Electric Energy Challenges of the Future

Future Grid Thrust Area 1 White Paper

Power Systems Engineering Research Center

Empowering Minds to Engineer
the Future Electric Energy System

Thrust Area 1 White Paper

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Power Systems Engineering Research Center

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Executive Summary

This is a white paper on research related to the future power grid in the United States. The objective period is through the year 2050. The central theme is the inclusion of high levels of renewable resources, principally wind and solar energy. The intent is to give an over The Horizon view of the evolution of the transmission grid emphasizing new technologies, applications of system theory and algorithms, and considering new infrastructures. The elements of this research area focus on electric energy challenges of the future through four critical areas:

- Transmission system design
- Substantive changes in power distribution system design
- Dynamic balancing of load and generation
- Wide area controls, including integrative controls in the transmission and distribution systems.

The significance of this effort in the context of the stated U. S. Department of Energy "Scientific Discovery and Innovation" Strategic Theme #3 includes:

- The assessment of advances in basic energy science to utilize selected technologies
- The impact of the use of those technologies in a power engineering context
- Reduction of dependence on foreign oil
- The implementation of digital/computational science tools to realize a next generation power system.

Relating to fundamental overhead and underground transmission, a wide range of eventual technologies is studied. These include ultra-high voltage (e.g., > 1000 kV): six phase transmission and related polyphase designs: high voltage DC (including expansion of existing facilities, routing of circuits in Mexico, multi-terminal DC, and meshed DC systems); and variable frequency concepts. The new advances in high temperature low sag overhead conductors, and compact overhead designs appear to yield from 100% to nearly 200% improvement in transmission characteristics. It is possible that the main element in future systems with high levels of renewables shall be the study, development, and ultimate implementation of high levels of energy storage.

Transmission overlay plans are discussed for the United States. It is likely that the present transmission system shall evolve into a system that uses a portfolio of technologies. Illustrations of transmission capacity needs for a renewable-heavy generation portfolio are given.

An important feature of the future system with high levels of renewable resources is the provision of generation reserves. This is the case since many renewable resources are variable in nature. A discussion is given for the calculation and alternatives for reserve requirements. Also, the real time control of the system in the new environment is important. Accordingly, the concept of wide area controls is applied to take advantages of new digital and communication technologies. The challenge of wide area controls is to develop the correct mix of substation controls, voltage stability controls, power grid controls, and their concomitant hardware and communication requirements.

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Introduction

Electric power engineering is often viewed as a mature topic since the inception of this field dates back nearly 100 years. However, one can identify distinct milestones in the field that have become ‘game changers’ in the sense that these critical milestones have caused a radical change in design and operation. As examples, the concept of networking the transmission system was at first deemed impossible – because it was thought that synchronizing AC generation over long distances was not feasible. However, large scale networking has become a design hallmark of contemporary transmission systems. Another example of a transmission design milestone was the use of digital computers to evaluate alternative designs (as well as alternative operating scenarios). The *game changing* features that face contemporary electric energy engineering include the utilization of renewable energy resources (including both design and operation issues), and maximizing the automated features of the system so that operation makes maximal use of the assets available. Also, the expanded use of electric energy in the transportation sector will alleviate dependence on foreign oil. The added load and its impact on the grid is another game changing eventuality.

In this paper, several key electric energy engineering challenges are addressed by bringing innovative engineering technologies [1] to bear on: the integration of renewable resources into the system; the direct digital control of the system; and the maximization of the use of sensory information to use the assets available. The intent is to use newly available information in mathematics and statistics, instrumentation and control, communications and computing, and advanced concepts of transmission engineering to achieve the objectives of renewable resource integration, maximal system operability and reliability, and making use of digital technology where it is warranted and human operator skills where they are needed.

The elements of this thrust area focus on electric energy challenges of the future through four critical areas:

- Transmission system design
- Substantive changes in power distribution system design
- Dynamic balancing of load and generation
- Wide area controls, including integrative controls in the transmission and distribution systems [2].

The intent of the paper is an ‘over the horizon view’ of the segment of the electric energy field, accounting for eventualities in hardware, digital technologies, political actions, public participation, and the growth of electric energy use. Fig. 1 shows a pictorial of the concept of long range forecasts of the infrastructure of electric energy 2012 – 2050. The intent of the pictorial is that assumptions and forecasts made in 2012 may result in an increasing ‘cone of uncertainty’ as the years evolve, and uncertainties may be realized. The uncertainty relates to fuel costs, environmental issues, mandates for renewable resource penetration, technological developments and a host of other factors. At points in the future, e.g. in 2031, actual scenarios could be used to evolve other forecasts of scenarios. It is expected that a 19 year forecast would be more accurate in its predictions and approximations as compared to, for example, a 38 year forecast. This is shown pictorially in Fig. 1.

In 2012, celebrating the centennial of the Institute of Electrical and Electronic Engineers, a special centennial issue was issued which addressed both the future electrical grid [42] and observations on the present grid [43].

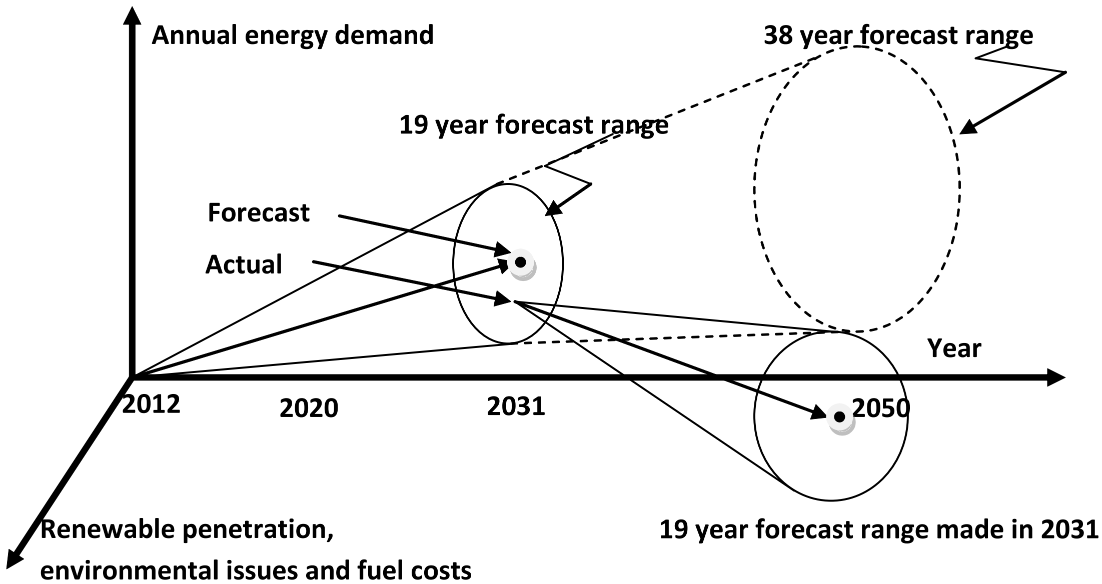

Figure 1: A conceptual diagram indicating long term forecasts of technologies and the configuration of the electric energy infrastructure

1. The Opportunity and the Challenge

1.1 Research Opportunities in Transmission Engineering

In many instances, engineering designs focus on the applications and the bottlenecks to implement given technologies. However, the long term view and the long term (to year 2050) impact assuming full implementation may be overlooked. In this task, the objective is to assume that a given application is implemented, and then apply rigorous research depth to the assessment of the impact of that implementation. The significance of this effort in the context of the stated U. S. Department of Energy "Scientific Discovery and Innovation" Strategic Theme #3 includes:

- The assessment of advances in basic energy science to utilize selected technologies
- The impact of the use of those technologies in a power engineering context
- Reduction of dependence on foreign oil
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Figure 2 illustrates the concept and 'systems approach' in examining these research approaches.

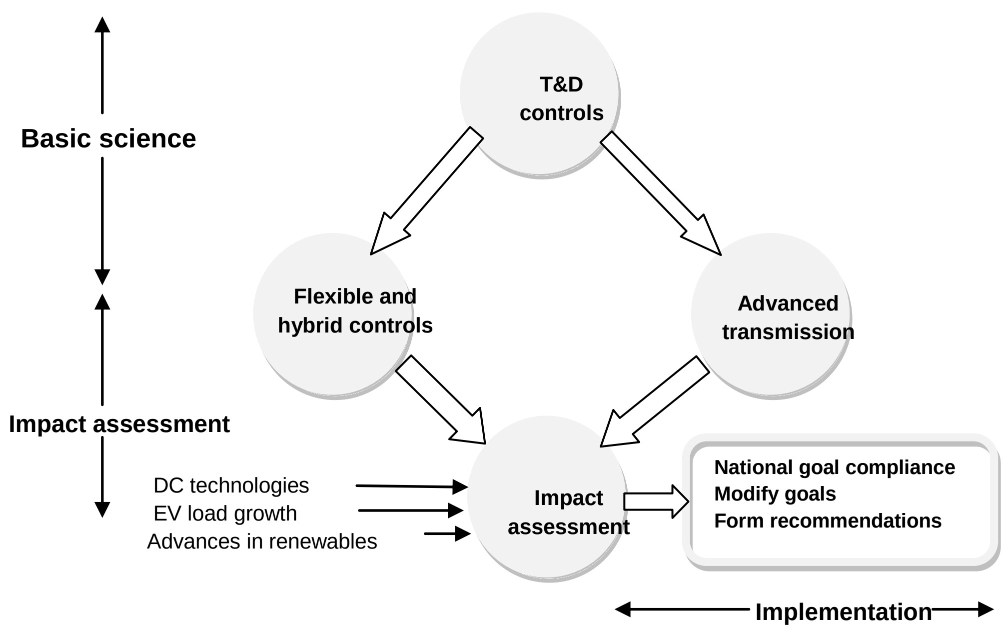

Figure 2: Research on integrating transmission and distribution engineering eventualities

1.2 The Research Issues

The main research issues addressed in this area are:

Fundamental Transmission Engineering Challenges

These challenges and research issues include high voltage DC technologies (including voltage source converter technologies, multi-terminal HVDC, networked DC, limitations imposed by DC circuit interruption limitations and difficulties): new technologies in overhead transmission such as high temperature low sag conductors, non-circular cross-section conductors, compact phase spacing designs, new insulation concepts, ultra high voltage (e.g., > 1000 kV), high phase order (e.g., six phase and higher phase order): the role of energy storage and transmission expansion and design: underground cable technologies. It is expected that through the year 2050, continental transmission connections are likely (including the connections already made between Canada and the United States, but also considerably enhanced connections between Mexico and the United States).

The Role of Energy Storage

In the integration of renewable resources into interconnected power systems, a key consideration is the role of energy storage. This is the case because of the variability of wind and solar energy resources. As convenient storage is augmented into the systems, the energy available system wide may be stored or discharged based on need (i.e., based on the price of one megawatt-hour). The role of storage includes alleviating transmission expansion, reducing generation reserve requirements, maximizing the use of variable generation resources such as wind and solar. The negative side of this observation is that energy storage generally involves multiple energy conversions (e.g., DC/AC), consideration of losses in the energy storage and conversion processes, and the cost of energy storage devices. Concomitantly there is the issue of the inconvenience of large scale energy storage devices. The main elements of energy storage deployment, in the 2012–13, time frame are that any one specific advantage of energy storage may not have a favorable cost to benefit ratio, and the commercial unavailability of large scale storage units may not favor their use. Pumped hydro is an obvious solution, but this technology has limited applicability due to the land, topography, and water resources required. Moving to the time frame 2033, one can envision breakthroughs in energy storage and its commercial viability. The main breakthroughs needed are:

- Resolution of unfavorable cost to benefit ratios, either by advances in storage technologies, acceptance of governmental subsidies, consolidation of benefits, or otherwise realizing the benefits of storage.
- Realization of electric vehicle technologies that include distributed storage of energy in the distribution system.
- Increases in renewable penetration with the percentage of variable resources being high enough to render the cost to benefit ratio of energy storage to favorable ranges.

In addition to the hardware oriented issues of energy storage, there are also needed system theory breakthroughs. This is the case since the scheduling of charge/discharge regimes requires the optimization of a nonlinear objective function (namely service cost over a specified time horizon) constrained by equality constraints (e.g., conservation of power at all buses, conservation of energy over a given charge cycle), and also inequality constraints (e.g., transmission line and component loading limits, various operating limits, compliance with energy storage device ratings). The scheduling problem is made more complex by including system losses, storage unit and converter losses, energy price uncertainty. One approach is the use of quadratic programming to minimize the constrained cost to deliver energy to specific system buses, and another approach uses a modification of quadratic programming by adding Kuhn-Tucker terms to the objective function. Reference [44] addresses some of these points with regard to stored energy scheduling.

Transmission Overlay Plans

Research into a coordinated national transmission plan and overlay is important to the long term future of power engineering in the United States. The basic design of such an overlay is the main element of this area. Included is the development of an associated design process to facilitate the growth of wind, solar, nuclear, geothermal, and clean-coal generation over the next 40 years. Research in this area includes: model development: evaluation and development of future alternatives (e.g., about 7 significantly different "futures" in terms of load growth and generation investment). The generation investment "future" will depend on which generation technology is emphasized (relative to a reference case): reference, high wind, high solar, high geo-thermal, high nuclear, high clean-coal, and high natural gas: the evaluation of alternative transmission technologies including HVAC overhead (500 kV, 765 kV), HVDC overhead (600 kV, 800 kV), HVDC under-ground (including standard cable, gas insulated cable, and superconducting high-temperature); optimization (e.g., using NETPLAN software will be used to identify the most effective (cost, resiliency, and emissions) transmission plan for each future); and robust testing of alternative plans. Important to this area is the determination of which plan is most robust to future uncertainties.

Robust and Dynamic Reserve Requirements

There are opportunities to greatly improve upon today's methods of determining reserve levels and reserve zones. There is a need for more systematic ways to determine the optimal reserve requirements. Also contemporary practices do not reflect the true flexibility that exists in the grid and they do not account for the uncertainty of future resources (wind, solar, PHEVs). Zones today are static and do not change with the operational conditions of the grid. Research objectives in this area are: the examination of contemporary practice in calculating reserve requirements: analysis of the impact on reserve requirements due to the integration of new resources and proposing of necessary changes: analysis of the impact on reserve requirements due to the development of a more flexible transmission grid and proposing of necessary changes: optimal determination of reserve zones and analysis of *dynamic* reserve zones; and the risk assessment of reserve requirements and the proposed changes.

Wide Area Control

The main research areas in wide area control are: future wide-area controls and benefits; voltage controls; wide-area oscillatory controls; and wide-area angle stability controls. Subtopics for wide area control research are:

1. Control framework and formulation in the future power system
2. Merits of different controllers and recommendations

3. Substation level voltage controllers
4. Coordinated wide-area voltage controllers
5. Formulation of real-time designs for oscillatory controls
6. Distributed formulations of oscillatory controls
7. Coordinated designs for oscillatory controls
8. Formulation and first investigation of coordinated wide-area angle stability controls.

The research horizons in each of these areas are discussed in the subsequent sections. The time horizon used is to year 2050.

2. The Future Grid

In this section, a discussion of a view of the future grid in the United States through year 2050 is discussed. The intent is an 'over horizon' view of the future grid. The discussion is organized into four subsections which are correlated to the four areas discussed in the previous section.

2.1 Fundamental Transmission Engineering Challenges

Fundamental transmission engineering challenges facing the United States at this time include:

- Integration of renewable resource generation.
- Maintaining reliability at historical levels despite restrictions in transmission expansion and the variability of wind resources.
- The utilization of newly developed transmission technologies which include high temperature, low sag overhead conductors: ultra-high voltage transmission cables suitable for high population density locations and marine applications.
- Utilization of compact transmission designs, and potentially developing new standards for overhead conductor spacing to attain high power use of rights of way.
- Investigation of the relaxation or modification of design standards to obtain the best tradeoff of reliability, safety, cost, and land use. This area includes the potential loosening of the tight frequency standards in North America. Another area is the relaxation of some protection practices, e.g. protection of certain transmission system components.
- Rendering the transmission system robust to problematic conditions. This area is a wide area which exceeds the bounds of traditional transmission engineering. For example, how would the transmission system react to a large earthquake in California or the central Midwest? There are some transmission designs which are more robust than others to accommodate natural occurrences, and these need to be examined to include more extensive use of underground technologies, wider disbursal of transmission facilities, decentralization of substations.
- The full development of transmission expansion technologies, including multi-objective optimization of cost.

As an example of the foregoing discussion, high temperature low sag (HTLS) overhead conductors may be used to improve the loadability of circuits. Mainly, HTLS designs have been used to alleviate thermal problems with existing circuits. A typical HTLS conductor can handle 1.6 to 3 times the current of a similar conventional conductor [3]. This increase in current rating comes at a dollar cost of up to 6.5 times that of a conventional conductor (see Table 1.1). Comparing the alternatives of a single HTLS circuit versus a *double circuit* conventional line, HTLS may have higher I^2R losses as a consequence of the higher current but comparable resistance. Table II contains representative values of HTLS conductor resistance values with the resistance of similar conventional conductors shown for comparison. Apparently the impact in phase angle security rating of HTLS circuits is very low; however, if the HTLS design is augmented with compact spacing of conductors, there could be a substantial increase in the security limit of a line.

Table 1: Increase in current and cost for HTLS conductor compared to conventional conductors [6-8]

Conductor type	*Relative ampacity**	*Relative cost**	*Manufacturer*
ACCC	2.0	2.5-3.0	CTC Cable
ACCR	2.0-3.0	5.0-6.5	3M
ACSR	1.6-2.0	2.0	J-Power
ACSS/TW	1.8-2.0	1.2-1.5	Southwire
ACSS/AW	1.8-2.0	1.2-1.5	Southwire
ACIR/AW	2.0	3.0-5.0	LS Cable

*Compared to conventional conductors [3], for typical commercially available HTLS conductors

Table 2: Resistance of HTLS conductor compared to conventional conductors[4-8]

HTLS / Conventional	*Conductor type*	*Type*	*Resistance (Ω/mi)**
← HTLS →	ACCC	← Drake →	0.1088
	ACCR		0.1300
	ACSR		0.1148**
	ACSS/TW		0.1355
	ACSS/AW		0.1320
	ACIR/AW	Cardinal	0.0951**
↑ Conventional ↓	ACCR	←Drake →	0.1300
	ACSR		0.1389
	ACAR		0.1280

*at 75^{o}C 60 Hz except as specified
**At 20^{o}C DC

Other transmission possibilities include high phase order. For example, there is a significant improvement of conversion of a double circuit three phase line to a six phase line from the security point of view. This is due to the exploitation of the mutual coupling of phase conductors which has the effect of reducing the positive sequence reactance of the circuit. The lower positive sequence reactance results in a directly proportional increase of cos ($\Delta\Theta$) where $\Delta\Theta$ is the phase angle difference in voltage across a line. Thus the voltage phase angle across a circuit can be operated at large levels, and this results in a higher power rating (security rating) of the line. This progression increases further with even higher phase order, and there are some other environmental benefits to phase order greater than six. The main hobbles of six phase designs are the much more complex protection of the line, and the required transformer costs. Concepts of basic transmission topology that are less considered that six-phase designs include: true polyphase designs, e.g., twelve phase or higher in which electromagnetic field cancellation occurs better than lower phase order, but transformer connections and protection become problematic: non-standard frequency designs, e.g., line frequencies higher than 60 Hz for short runs and few magnetic components but lower than 60 Hz for longer runs and instances of many magnetic components: truly variable frequency designs in which the line frequency is adjusted in time according to loading and injected power operating conditions. Some of these concepts may have application in wind farms where nonstandard frequency or phase order are possible because of the use of electronic converters.

High voltage DC advances may play a significant role in transmission engineering in the future. High voltage DC (HVDC) transmission technologies have been recognized as effective in transmission systems for long distance, bulk energy applications, and also in back-to-back interconnection of asynchronous AC transmission systems. There are innovative HVDC designs that have not been widely applied in transmission engineering, however, and these include:

- Multiterminal HVDC systems
- Meshed (networked) systems
- Voltage source converter (VSC) applications in HVDC.

Motivation for examination of these technologies include: paucity of viable rights-of-way for added transmission paths; expected added generation resources far from load centers (e.g., renewable resources such as wind and solar); continued improvement in system reliability by employing asynchronous connections of large interconnection areas.

The Western interconnection in North America contains many examples of potential applications for HVDC technologies, both in the milieu of long, bulk energy transport and in asynchronous ties. By no means is the Western interconnection unique in this regard, but it does serve as a valuable test bed for applications. A stylized, simplified portion of the Southern California – Arizona part of the Western interconnection is shown in Fig. 3. One of the best known HVDC systems is the Pacific HVDC Intertie (PDCI) which spans Celilo, Oregon to Sylmar, California, a total distance of about 1354 km. The PDCI takes advantage of the different seasonal load peaks between the Northwest and Southwest of the U.S. and therefore helps to exchange energy between the two regions. However, because Sylmar converter station is located near Los Angeles area which is considered as a significant load center and because of the excess in hydro power generation in Northwest, the flow of power is mostly from north to south.

The main attractors in HVDC technology would include multi-terminal lines (e.g., the addition of an Arizona – California HVDC line to the stylized system shown in Fig. 3 – connecting to the Sylmar southern terminal of the PDCI). Three terminal HVDC is a proven technology, but a hobble in this regard is the availability of a HVDC circuit breaker. The same hobble occurs for meshed HVDC networks. As an example of such a possibility, consider the ‘triple point’ of AC interconnected systems located near the southeast border of New Mexico where three asynchronous AC systems converge (Comisión Federal de Electricidad (CFE) in Mexico, the WECC, and the Eastern Interconnection). Another similar point exists with two asynchronous AC systems at the southern border of Arizona where the CFE Mexican systems converge. A potential meshed HVDC system in southern Arizona and adjacent Mexico and California is shown in Fig. 4. The Tres Amigas project [9] is an example of a more recently commissioned HVDC project with a different objective: the interconnection of the three asynchronous 60 Hz AC power systems in North America (the Eastern, Western, and Texas interconnections) in a back-to-back scheme. Voltage source converters are to be used in a 5 GW application which is scalable up to 30 GW. This connection would be a 'merchant' operation in which power from the three interconnections would be bought and sold in a power marketing venture. The construction of this project is expected to commence in 2012, and operation of the 'super substation' near Clovis, NM is expected by 2014 [10-12].

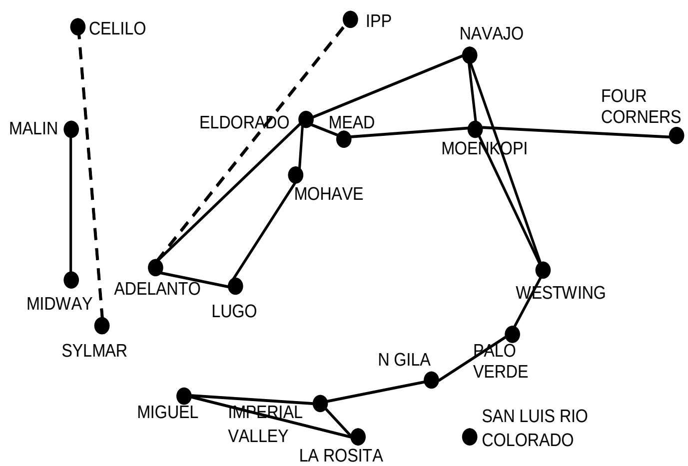

Figure 3: Stylized, simplified southern portion of the Western interconnection in North America. Dotted lines are existing HVDC lines. Solid lines are AC. Note that San Luis Rio Colorado and La Rosita are in Mexico. The PDCI is shown dotted (Celilo–Sylmar).

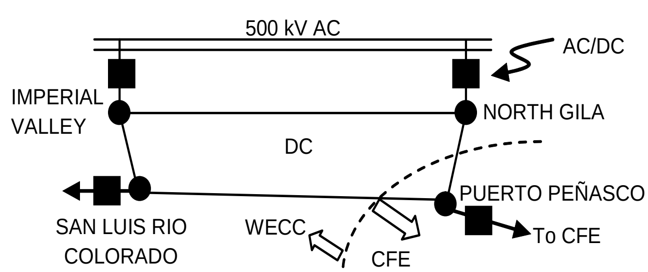

Figure 4: Simplified schematic of a meshed HVDC network joining WECC and mainland CFE (Mexico)

The possibility of an overhead transmission corridor in northwest Mexico in the states of Baja California and Sonora should not be overlooked: in this region, a transmission connection from Arizona to California on the U.S. side of the border, and CFE on the southern side of the border offers distinct high capacity transmission connections not only for the United States but also for Mexico. This is the case since CFE has asynchronous systems in Baja California and Sonora, and thus these segments of their system may not be connected directly: and the U.S. states of Arizona and California are facing a dearth of transmission rights of way. A connection across the border joining the several systems and augmenting the WECC system seems prudent. This is discussed in some detail in [31, 32] which include a discussion of HVDC ties in this region. The same issues occur near El Paso TX – Ciudad Juarez, Chihuahua where the Texas interconnection, CFE, and WECC converge.

2.2 Transmission Overlay Plans

The levelized cost of energy production for renewables (e.g., wind, solar, and deep geothermal) varies dramatically from one part of the country to another, and unlike energy in coal, natural gas, and uranium which may be moved electrically or in other ways (e.g., by rail and truck for coal, and by pipeline for natural gas), the only way to move renewable energy is by electric transmission. These two attributes of renewables, the heavy influence of location on their economic viability and their complete dependence on electric transmission for energy transfer, increases benefits derived from interregional transmission in future scenarios where renewables comprise an increased percentage in the national generation portfolio. Yet, today, the ability to move electric energy interregionally is limited to the capacity of the existing transmission system, a system designed largely to serve intraregional needs from fossil- and nuclear-based generation for which production costs are relatively flat from one region to another. Our nation's ability to utilize renewables with least cost depends on the existence of high capacity interregional transmission. This point was illustrated in [35] where optimization software was used to show that if generation resources were restricted to wind, photovoltaic (PV), concentrated solar thermal (CST), and geothermal over the next 40 years, the most economic resource allocation would require over 170 GW of interregional transmission to move electric energy from the most attractive renewable resource locations to the load centers. Figure 5 illustrates the locations for this capacity, its flow direction, together with the generated (left-hand bars, with green indicating renewable energy) and demanded energy (right-hand bars) in each region, in units of quads (1 quad=1×10^{15} BTU=293,080 GWh). An effectively designed high-capacity transmission overlay would also bring benefits in terms of operational resilience to unforeseen events and in terms of future planning flexibility.

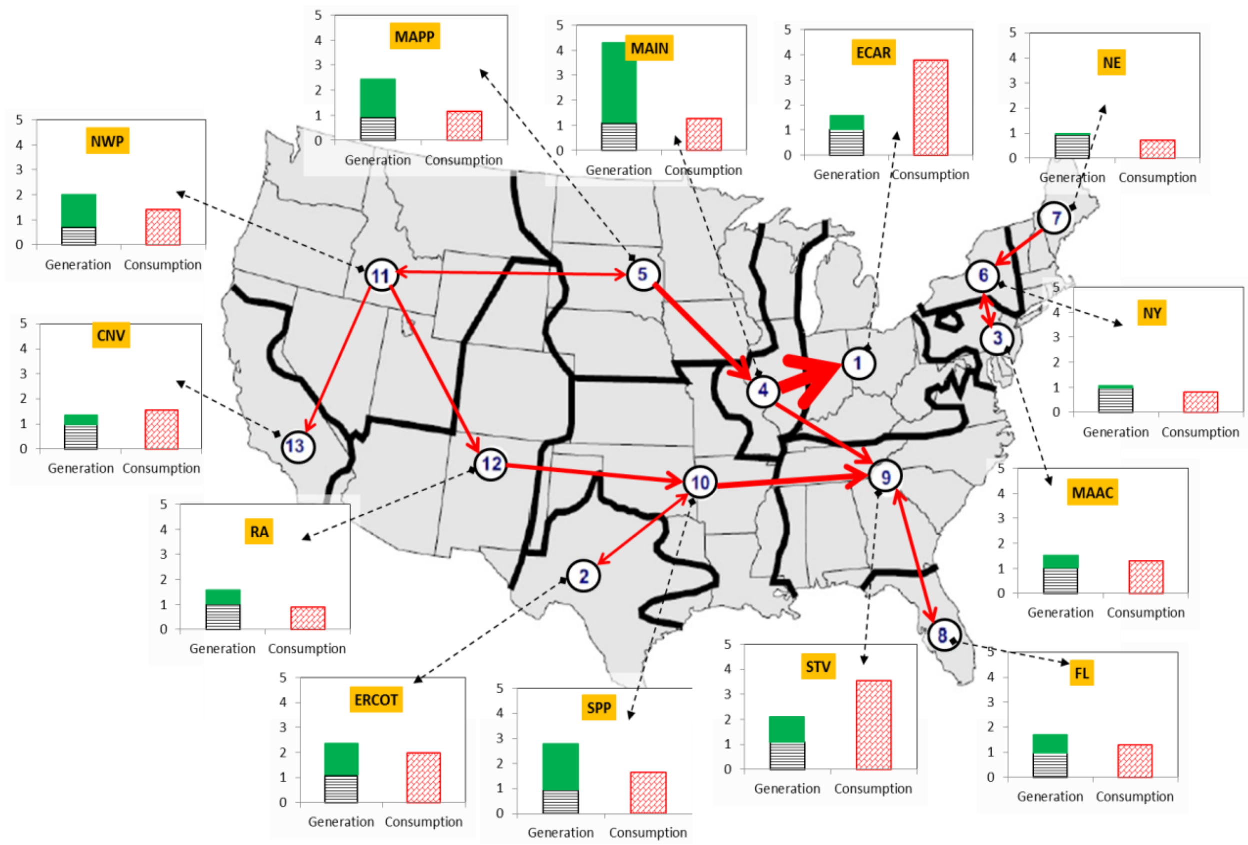

Figure 5: Illustration of transmission capacity needs for a renewable-heavy generation portfolio

Building transmission at an interregional or national scale will require use of high-capacity transmission technologies. There are two proven technologies that are operational and can be purchased and built today, 765 kV AC and ±800 kV DC. If a 765 kV line is equipped with adequate capacitive compensation every 200 miles or so, it can reach capacities of 3100 MW. DC at ±800 kV provides about 6400 MW capacity per bipole configuration. A third technology is superconducting DC; though a ±200 kV DC system is being marketed having capacity of 5000 MW or more per bipole configuration, it is yet to see commercial implementation. Although there is one instance of an AC transmission line built at 1150 kV in Russia and another built at 1000 kV in Japan, both of the lines are now being operated at 500 kV. Today, the only AC transmission operated above 765 kV is a 640 km, 1000 kV line, with capacity 5000 MW, in China which began commercial operation in January, 2009.

Although DC applications require high-cost converter stations at the terminals, the per-mile line cost is well below that of an equivalent capacity AC circuit. Therefore, in overhead applications, for relatively short distances, high capacity transmission is usually more economic with AC. DC transmission becomes more economic for distances beyond about 400 miles. High capacity underground AC transmission is generally not feasible because of the high charging currents generated. Therefore, any high capacity underground application today must be DC.

Although overhead transmission is generally much less expensive than underground, it may be that public resistance to overhead transmission significantly limits use of overhead for interregional transmission design. A DC (either ±800 kV or superconducting ±200 kV) underground design could meet capacity needs while incurring much less public resistance. The main problem with such a design, referred to as a multi-terminal DC line, is that interconnection between the line and the AC grid at locations other than the terminals significantly increases its cost because additional converter stations are required. Thus, today's high voltage (HV) DC designs generally have poor "on/off-ramp" capabilities, a feature which is of some concern in order to provide that the transmission yields value to intermediate locations along its path, an issue of importance because future renewable plants are likely to be distributed within a region.

There are two types of solutions to this problem. An obvious approach is to bring down the cost of the converter stations. Many researchers are actively pursuing this approach, and significant progress has been made using voltage source converters (VSC). The major difference between VSC-based and thyristor-based HVDC is that the latter is line-commutated whereas the former is forced-commutated via control circuits driven by pulse-width modulation. A primary limitation which must be overcome for VSC-based multi-terminal DC lines is to develop an economically attractive means to increase their power handling capability which is presently limited by the power ratings of the insulated gate bipolar transistors (IGBT) on which they depend.

It is likely that long-distance bulk transmission design at the interregional level would necessarily include an integration of both HVDC transmission, to take advantage of its lower cost per GW-mile, and extra high voltage (EHV) AC transmission, to obtain the flexibility AC provides in facilitating the numerous interconnections of new generation projects and load centers, and that systems will be designed so that the two are complementary assets. This perspective is consistent with conclusions made in two recent studies [36, 37] which demonstrated that hybrid 500-765 kV AC and HVDC systems were effective solutions for a 20% renewable energy penetration in the Eastern Interconnection. Various network topologies should be considered, including those with multi-terminal DC lines, to identify those integrated HVDC/EHVAC designs which have low investment costs and effective performance. For example, one or more three-terminal DC lines (either ±800 kV DC or ±200 kV superconducting) could be built in parallel with a single high capacity AC overhead circuit. Similar discussions on this issue include a European supergrid [38, 39] and a design for a North Sea DC network [40].

There is also need for an intermediate stage of transmission which, in the case of wind energy, can be called a multi-farm collection network, interconnecting the turbine collection networks to the interregional transmission system. Transmission at this level would collect the energy produced from multiple plants for transmission along a backbone system. This conceptualization, as illustrated in Fig. 6, provides for a three-level network hierarchy. The need is to identify cost-effective, reliable, and flexible transmission designs in terms of topology and technology to collect energy onto the backbone transmission system. For example, a topology consisting of concentric rings has been proposed [41].

2.3 Robust and Dynamic Reserve Requirements

The US electricity grid, and many national and regional grids globally, are experiencing or will soon experience an unprecedented penetration of variable renewable resources, such as wind and solar. California has established a Renewable Portfolio Standard (RPS) goal of 33% by 2020 and some regions are aiming for even loftier goals in future years, up to as much as 50% renewables. With such high penetration levels of variable renewable resources, the existing methods to manage uncertainty in unit commitment decision problems do not provide for adequate reliability and market economics. Assuring uninterruptable supply in unit commitment problems based on traditional methods to determine adequate levels of operating reserve is not economically sustainable at high renewable penetration levels because these approaches undermine the economic and environmental benefits of the renewables.

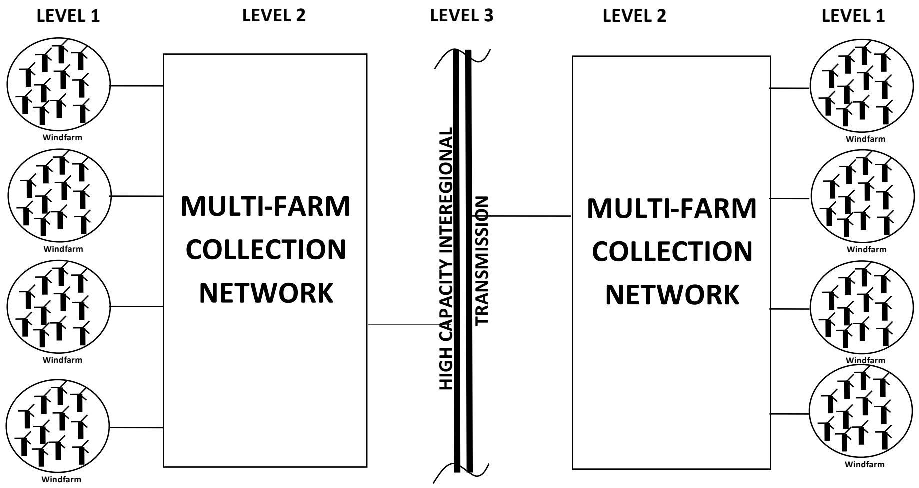

Figure 6: Multi-farm collection network

The increased reserve requirements for mitigating uncertainty imposed by renewable integration are compounded by stringent constraints on the placement of such reserves due to network congestion, which is exacerbated by the remote location of resources such as wind and concentrated solar power. Furthermore, since the electric power industry is roughly 0.5 trillion dollars a year (for the USA alone), there is a need for new technologies that can optimally manage variable renewable resources while maintaining reliability and ensuring economic efficiency. As a result, new innovative methods to manage uncertainty in the electric grid are necessary. The development of a systematic way to determine robust and dynamic reserve requirements offers a new paradigm for the determination of reserve zones and reserve levels for either day-ahead unit commitment or reliability (residual) unit commitment models.

Current reserve requirement practices

Reliability standards are necessary in order to guarantee continuous supply of energy and adequate operating reserves are essential to ensure reliability. Operating Reserves (OR) ensure that there is sufficient generation capacity available in case there are load forecast errors, area interchange errors, generator outages, or transmission outages [13]. The definition of OR may vary from including only spinning and non-spinning reserve to the inclusion of interruptible loads, voltage and frequency support, regulation reserve, and replacement reserve [13]. Spinning reserve generally refers to available capacity from generators that are on-line, in-sync with the grid and can provide the required output within ten minutes while non-spinning reserve refers to capacity that can come online within ten minutes; however, note that these definitions can vary by operator.

Today, reserve requirements for day-ahead unit commitment problems are based on a predefined set of rules. The California Independent System Operator (CAISO) states its requirement for operating reserve in [14]. The operating reserve requirement in CAISO is the maximum of OR1 and OR2, then plus 100% of the non-firm (interruptible) imports. OR1 is calculated for each reserve zone and is equal to 5% of the demand met by hydro resources plus 7% of the demand met by non-hydro resources. OR2 is based on the worst single contingency. The worst contingency is based on the largest committed generator or the largest net tie-line import. The Western Electricity Coordinating Council (WECC) establishes its own guidelines for contingency reserve, i.e., spinning and non-spinning reserve, in [15].

Historically, ad-hoc or rule-of-thumb methods have been used to determine reserve requirements. The most basic rule-of-thumb is that the amount of reserves must be at least as great as the single worst contingency, as can be identified by CAISO's OR2 rule above and this is the approach taken by the largest public utility in the USA, Tennessee Valley Authority (TVA). This rule is commonly adopted due to the N-1 requirements imposed on the electric power sector by the North American Electric Reliability Corporation (NERC), which is the appointed Electric Reliability Organization (ERO) as designated by the Federal Energy Regulatory Commission (FERC). While the N-1 requirement is a robust requirement, N-1 reliability is not explicitly enforced inside unit commitment and simply acquiring reserve equal to the largest single contingency falls short of guaranteeing N-1. Due to congestion, there is no guarantee that the reserve can be delivered when and where needed and, hence, simply procuring a quantity of reserve equal to the largest contingency does not guarantee N-1. As a result, one method to adjust the level of reserve is to rely on historical information that reflects system loading conditions in order to avoid involuntary load shedding. The problem with the use of historical information is that wide-spread load shedding is not a common event and it is not possible to determine the actual optimal amount of reserves based on historical information when the grid and resources are ever changing. Another common approach is to relate the level of congestion in the system to the level of reserve. The Electric Reliability Council of Texas (ERCOT) uses historical information to estimate the level of congestion as well as identify key congested transmission lines, Commercially Significant Constraints (CSCs), in order to define the reserve zones, [16]. Using historical information to estimate the level of congestion is imprecise because: a) the network topology changes as there are constant network outages, which affects the power flow; b) congestion can vary greatly over the course of a day let alone vary substantially in comparison to average historical information. Finally, future grid conditions will not be represented well based on current historical information. The addition of large amounts of variable renewable resources, new demand side resources and participation, e.g., PHEVs, and advanced technologies being developed for the smart grid will change grid operations and grid characteristics.

With high levels of variable generation due in the future, the National Renewable Energy Laboratory (NREL) suggest a new rule for operating reserves: 3% of load and 5% of variable resources (wind and solar) for spinning and non-spinning reserve. However, these numbers are again based on ad-hoc, rule-of-thumb procedures and it is a static, universal rule. To date there is no mathematical framework for the determination of reserve requirements in relation to the special characteristics of variable renewable resources. While it is understood that these currently proposed approaches are imprecise, there has not been enough attention given to improving the methods to determine reserve requirements and these past procedures will not suffice in future years.

Stochastic and Robust Optimization Approaches to Endogenously Determined Reserves

Much of the current research that aims to address the future concerns of variable renewable resources focuses on the use of stochastic optimization, which endogenously determines reserves. Multiple stochastic optimization approaches have been proposed, including, but not limited to, scenario selection techniques to reduce the number of scenarios as well as chance-based constraints, [17]-[25]. While stochastic unit commitment approaches have the benefit of ensuring reliable solutions relative to the modeling complexity, the drawback is the high computational complexity that is required to ensure highly reliable solutions. Therefore, the computational challenges of stochastic programming limit the level of potential modeling detail and, hence, limit the reliability of the solutions. Robust optimization is another approach that has been recently proposed as a method to improve the robustness of unit commitment solutions. Robust optimization guarantees a feasible solution for any possible realization in the modeled uncertainty set. With robust optimization, instead of assuming a probability distribution for uncertain parameters, an uncertainty set is predetermined to cover the possible realizations. Recently, more attention has been given to the application of robust optimization in the power systems sector by Bertsimas *et al.,* [26], Jiang *et al.*, [27], and Mejia *et al.*, [28]. However, similar to stochastic optimization, robust optimization today is still too computationally challenging for large-scale unit commitment models.

Balancing Stochastic Approaches with Deterministic Reserve Requirements

While stochastic and robust optimization techniques are preferred since they endogenously determine reserve, today, and in the future, these methods are, by themselves, incapable of ensuring efficient and reliable unit commitment solutions. Due to the computational complexity of stochastic approaches, there will continue to be a reliance on reserve requirements due to the necessity to balance model complexity with proxy methods that are computationally tractable. As demonstrated by the curves in Fig. 7, solution quality can increase with added stochastic modeling; however, this comes at the cost of modeling complexity, i.e., computational time. The development of robust and dynamic reserve requirements can be used in conjunction with scenario selection of stochastic programming or uncertainty set definition of robust optimization, in order to provide the best solution attainable with the existing computational capability to date. Furthermore, with a novel mathematical framework to determine more reliable and economically efficient reserves, our ability to deal with uncertainties will improve and, thus, it will increase the maximum penetration level of variable renewable resources.

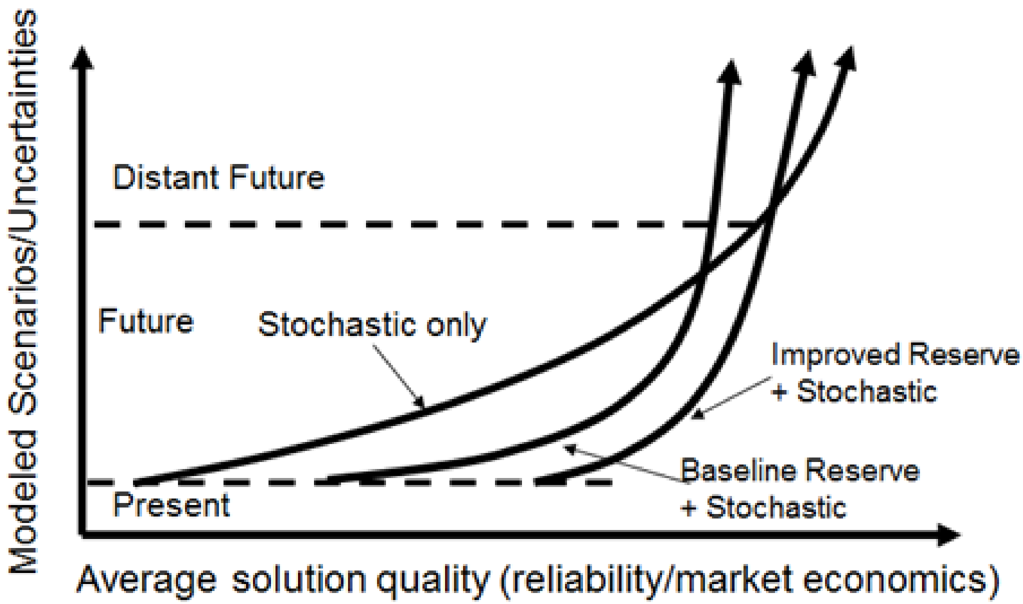

Figure 7: Impact due to improving reserve requirements

Future Innovations: A Mathematical Framework to Determine Reserve Zones

Reserve zones are used today to ensure that there is sufficient reserve within a particular region of the grid; reserve zones are necessary due to network congestion and they act as a way to improve the deliverability of reserves. While reserve zones are important as they help ensure that reserves are spread out over the network, little attention has been given to the determination of reserve zones. Due to future high levels of renewable resources, the placement of reserves will be critical. With mathematical programming frameworks for the determination of reserve zones, operators can ensure proper placement of reserve, which will be crucial for the integration of renewable resources based on their common remote location (wind and concentrated solar). Mathematical programs that determine network partitions for reserve zones will exist along with methods that allow for reserve sharing between zones, nested zones [28], and overlapping zones.

Co-optimization Framework for the Determination of Reserve Levels and Reserve Zones

With the advent of mathematical models for reserve zones, there will also be the development of methods to co-optimize the reserve level along with the reserve zone. Instead of using static requirements across the grid, methods to continually update reserve requirements will further improve system reliability and facilitate the management of variable renewable resources.

Smart Grid Technologies

Future smart grid technologies will also impact reserve requirement determination and our ability to facilitate the integration of variable renewable resources. Recently, the Advanced Research Projects Agency – Energy (ARPA-E) gave out roughly $35 million in grants under the Green Electricity Network Integration (GENI) call. These projects include, but are not limited to, the development of new Flexible AC Transmission System (FACTS) devices and the use of topology control. For instance, the company Smart Wire Grid Inc., [29], is developing a smart grid device that is attached to a transmission line to increase the reactance of the line when it approaches its thermal limit. There is also the Robust Adaptive Topology Control (RATC) project, [30], that will investigate the utilization of transmission assets to control, via transmission switching, the flow of power. These technologies will enable operators to have more control over the flow of power across the grid. Such technologies increase our ability to further utilize transmission infrastructure by mitigating congestion and, thus, these technologies will improve the deliverability of reserves, which will further facilitate the integration of renewables and will bring down the cost imposed on system operations due to renewables. Future mathematical frameworks for the determination of reserve requirements should be capable of incorporating such smart grid technologies when determining reserves.

2.4 Wide Area Control

The nature of the power system is expected to undergo dramatic changes in the next four decades. Owing to environmental concerns and possibly economic reasons, a significant portion of electric power generation is expected to be from renewable generation sources by 2050. Bulk synchronous generators which produce most of the generation in present day power system will play lesser roles, though nuclear energy may still play a substantial role that will be represented by bulk synchronous machines. On the demand side, the nature of the consumer loads will likely undergo dramatic changes where each consumer residence may serve as energy source or energy sink at different times of day with flexible interface with the bulk power system. In the future power system, substations may play crucial role in managing thousands of complex residential loads (or sources) along with other local energy sources that lessen the dependence on the power transmission grid. Therefore, each substation of the future power system may play the role of present day control centers.

Controls and system protection in such a future power system will need to be thought out carefully. It is important that road maps be developed now for transitioning into the future power grid in a smooth fashion. The controls naturally divide into two kinds: a) substation controls and b) power grid controls:

a) Substation Controls: Substation controls can be expected to be mostly based on local measurements with supervisory guidance from regional control centers. The substation controller will need to manage local power balancing issues as well as ensuring stability and reliability of the local power system with no adverse effects on the large interconnected grid. Diverse power electronic controls in renewable power sources as well as in residential power systems will render the stability analysis of the substation dynamic models very complex. Traditional power system stability designs that assume the availability of detailed dynamic models of bulk power generators. These designs may need to be reformulated to be more of real-time observer based designs that estimate the essential dynamic features of the power electronic models of the generators and loads in the future power system. In managing the local resources at a substation, limitations of communication network will need to be included in the controller designs. It is also important to develop well-defined stability criteria or standards for local resources (such as power electronic controls) that ensure that the substation controls do not adversely impact on the reliability of the bulk power system.

Voltage stability controls will be more challenging because the power electronic devices may impose heavy burden on reactive power demands at the substation. At the same time, shunt capacitor banks and reactor banks as well as transmission line impedances may introduce challenging subsynchronous resonance issues affecting integrity of wind farms in the future power system. Analysis of these issues may require measurement devices at high sampling rates [34]. Each substation may be required to operate in islanded operation whenever needed, that may enforce special control designs on frequency control and angle stability issues at each substation especially in islanded configuration.

b) Power Grid Controls: Grid control center of the future will be responsible for ensuring reliable and efficient operation of the large power grid, much like in the present day power system. The complexity of the problem will however be much greater because of likely greater autonomy in the operation of the substations. The grid control center first needs to manage the overall power balancing of the power grid by coordinating the activities of the substations and other large energy sources in the grid including bulk energy storage. For ensuring the operational reliability, the grid controller will need to monitor the functioning of individual substations, anticipate potential problems by predictive controls, and initiate countermeasures as needed.

Substations may communicate local dynamic models to the control center which then may "compile" grid dynamic models in real-time by combining substation models with transmission models and other energy sources. Monitoring of subsynchronous resonance and other high speed phenomena may require complex dynamic grid models that need to represent the propagation features of the transmission grid itself. Angle stability controls may include capability to island specific substations as needed to preserve the integrity of the large system. The concepts of reactive power may need to be rethought out because of high speed phenomena and harmonics related to power electronic controls.

3. Conclusions

The main conclusions of this work include the observation that there are tangible transmission grid technology advances underway today to give North America substantial solutions to the integration of renewable resources into the grid. These technologies include overhead transmission designs, underground designs, advanced overlay concepts nationwide, and development of power operations practices and controls to make possible the integration of renewable resources into the grid. Innovative designs using HVDC technologies appear to offer considerable advantages and integration possibilities with existing HVDC installations.

Relating to *transmission overlay plans*, research in this area addresses the grand challenge of charting a 40 year investment path to bring CO_2 emissions to an acceptable level while maintaining low cost energy and an infrastructure that is price-resilient to major disturbances such as the Katrina/Rita hurricanes of 2005. There are a very large number of possible national transmission overlay designs. This research is expected to lead to a process by which “good” designs can be quickly separated from “bad” ones, in terms of cost, emissions, and resiliency and will put forth design strategies to help shape the development of a national transmission planning overlay. This work will also provide insight into the applicability of different transmission technologies, and it will characterize the aggregate effect of traditional electric loading and transportation-related loading (e.g., from electric and hybrid electric vehicles and trains).

With the impending and drastic changes that we will face in the future grid, there is a great need to better understand the modeling of reserve levels and zones as well as to explore the opportunities to improve and, perhaps, redefine reserve requirements. Developing robust and dynamic reserve requirements, optimally determining reserve requirements, and/or redefining reserve requirements will benefit future grid operations by being able to facilitate the integration of new resources. Furthermore, with more advanced modeling of reserve requirements, a system will be capable of handling greater levels of uncertainty while maintaining a reliable system. This will, therefore, allow for a larger penetration of such new resources, e.g., wind, to the electrical grid. Research on robust and dynamic reserve requirements not only addresses a contemporary need, to better understand how to optimally determine reserve requirements, but it extends beyond this need by examining how changes in future grid operations affect reserve requirements. This research is expected to be used by system operators to improve system reliability and efficiency.

Relating to wide area controls, it is recommended to rethink traditional controls, automatic generation controls, voltage control, and power system stabilizers to bring these controls up to the levels of emerging technologies (e.g., near real-time wide-area dynamic state estimation). In this way the new approaches are expected to handle unpredictable complex dynamic responses of large penetrations of renewable power sources in the future power system. Needed are new control paradigms on how next generation wide-area controls can be designed by utilizing wide-area real-time synchrophasor measurements. These measurements will be communicating with each other in a NASPInet-like infrastructure. In the uncertain operating environments of the future with rapidly changing power-flows and with large numbers of diverse power electronic equipment, the complexity of operational reliability problems will force the design of wide-area controls for real time control. Research in this area should address the formulation of such controls as well as specific controls strategies for mitigating voltage stability, oscillatory stability and angle stability issues in the new framework.

Relating to generation reserves, with the goal to substantially increase the use of renewable resources, operational uncertainty for the electric power grid will increase in the future. Instead of relying on ad-hoc methods to determine reserve requirements, future operations will involve systematic ways to determine robust and dynamic reserve requirements. With a mathematical foundation to determine reserve requirements, reserve zones and reserve levels will be continually adjusted to match grid operating conditions instead of relying on static rules for a dynamic grid. With future smart grid technologies, the need for systematic approaches to determine reserves will be crucial. Furthermore, future operations will incorporate methods such as stochastic and robust optimization to determine reserve requirements endogenously in order to improve system reliability and economic efficiency. However, while such stochastic approaches are preferred to deterministic reserve requirement rules, there will be a continued reliance on balanced approaches involving stochastic approaches and the use of deterministic reserve requirements.

Conclusions relating to wide area controls yield the following as an initial approach: it is possible to formulate new wide-area control designs for the wide-area power system by minimally assuming a PMU at every substation and by assuming suitable communication bandwidth between substations. Then it is logical to pose the question of what will be the most beneficial aspects of dynamic controls in the new framework and which controls should be pursued first and how.

- **Voltage Controls***:* Coordinated dynamic voltage controls may be well-suited to this framework because decisions can be made using dynamic measurements from a local area around the substation of interest. Substation level PMU measurements along with data from neighbors, as needed, will be used for voltage security monitoring and controls.
- **Wide-Area Oscillatory Controls***:* Modal properties of the real-time system can change quickly and abruptly in future power systems because of inherent system uncertainty. Oscillatory controls will be designed "on-the-fly" based on real-time estimation of poorly damped modes and their modal properties.
- **Wide-Area Angle Stability Controls***:* Because of large sudden fluctuations in power-flows across distant power systems, new generation of transient stability controls need to be designed that will likely be response based emergency control schemes. These controls will utilize wide-area power-flow and phase angle measurements to initiate fast power electronic controls and discrete control actions to stabilize the future system during large disturbances.

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