Scalable and Flat Controls for Reliable Power Grid Operation with High Renewable Penetration

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Abstract

This project envisions a fundamental shift in the approach to the electric power infrastructure with both a broadening of the electric grid to consider overall end energy use and a “flattening” of the control structure at all levels of the power grid the traditional control strategies. The proposed work focuses on the control and communication structure for the power grid. Coordination across wide areas is critical to ensuring that the future grid can enable efficient, low cost and reliable integration of renewables. As such, the work is a system development investigating several areas of control and communications, device technologies as well as electricity market structures. Commonalities arising across these diverse research tasks include the importance of new measurement technologies, increased functionality at the device level and managing uncertainty in both control systems and markets. More specifically, new phasor measurements are being used in this work to enable wide area control of the power grid and understand system limits more precisely. New power electronic functionality, both at the source and load, allow improved stability and voltage control. These functions mean will allow alternative sources to provide grid services to offset their higher costs. Investigations into incorporating reliability and risk considerations into market structures will properly allocate costs and better define contributions of renewables and controllable load to system performance. Managing uncertainty in the control systems, as for example we do with the proposed delay-cancelling approach, improves reliability and thus, allows greater penetration of renewables.

There has been continued rapid growth in renewable interconnections to the grid and the need for improved controls has become critical. The second year report details continued progress in understanding the fundamental controls, monitoring and communication structure needed to enable the needed wide area control. We also describe results on enabling new actuation functionality through power electronics. Other efforts have focused on the appropriate market structures needed for managing the variability of renewable supply. A notable achievement this past year has been the establishment of a new NSF/DOE research center stemming from the research done in the initial stages of this work.

1. Introduction

Frequently overlooked in discussions on energy problems is the central role that the electric power system infrastructure must play in any viable solution. Power generation plants are among the largest sources of greenhouse gas (GHG) emissions and in addition, many of the proposed solutions for minimizing emission – wind farms, solar roof-tops, plug-in hybrid cars, even the “hydrogen” economy – must rely heavily on the grid. Historically, energy systems have been engineered according to the separate industry sectors, i.e., transportation, heating, electric delivery, and thus, represent “frozen accidents.” Today, a comprehensive solution to the reduction of GHG requires a more general approach. This is not only to avoid shifting problems between sectors but also to take advantage of efficiencies that can only be realized through interaction among the subsystems. The electric power grid must function centrally to this system of systems. Global warming concerns, rising fossil fuel costs, and management of a carbon-constrained economy will require the development of a different type of electric power system.
infrastructure while electric energy resources based on renewable resources and storage are expected to be pervasive. Overall, energy delivery by electricity has great advantages in terms of ease of energy transformation, precise control capability and flexibility for end use – i.e., heating, cooling, lighting, consumer electronics, heavy industry, and so on. The modern electric power grid is extremely reliable and efficient in delivering bulk energy from large-scale sources to load distribution centers. At a high level, the interconnected power grid is reliable because system operators can depend on controllable equipment, e.g., generators, to supply power to meet relatively predictable loads. Unfortunately, many of the renewable technologies pose great operational difficulties because the present system is a centralized control structure with a limited amount of storage and control options that requires a precise balance between load and generation to be maintained at all times.

The main challenges of operating a power grid with a high proportion of generation based on renewable resources include that these resources: (1) are less predictable than traditional fuel-based power plants, (2) may be far from load centers so power may have to flow through congested transmission paths, (3) do not generally match the daily cycle of load variation, (4) suffer from unusual operating constraints, such as, rapid variation or complicated weather dependence, and (5) need to be tightly coupled to storage, which may be mobile. To respond to this challenge, this research envisions two fundamental shifts in the approach to the electric power infrastructure, namely

- A broadening of the electric grid to consider overall end energy use, so that electric power generation and delivery does not merely respond to load demand but actively controls energy delivery for plug-in vehicles, the production of fuels (e.g., hydrogen), production of power versus commercially sold steam at thermal plants, energy storage, and end demand as needed.

- A “flattening” of the control structure that fully changes, at all levels of the power grid, the traditional control strategies. Existing energy systems today are characterized by multiple, largely autarchic control systems, including such systems as transient stability control, load frequency control, voltage control, power quality control, and distribution protection. These need to be replaced by a simpler, flatter structure with a local control operating within a more global context for the system.

1.1 A Systems Approach Centered on the Electric Grid

As illustrated in Figure 1-1, the PIs believe that a broad integrated energy systems approach is crucial to achieving goals of reduced GHG, adequate performance and low economic cost. Some researchers have suggested a highly distributed approach with, for example at one extreme, extensive roof-top solar and wind units with local storage. This concept is attractive in that it does not rely on the existing infrastructure and allows innovations to be driven at the consumer level. Still, it is not clear that this approach can achieve desired reliability or low economic costs without major technological breakthroughs. The viewpoint taken in this work does not preclude such an eventuality, but focuses instead on taking advantage of economies-of-scale and the value of sharing resources over a wide area. New transmission must be added, but depending entirely on extensive new transmission is risky and costly. Thus, our vision of an expanded electric delivery system is one with greater load and expanded control tools available to operators.
Underlying this new framework for reliable power system operation is our proposed concept of “flat” control. We use the term both in the sense of reducing the levels of hierarchy in existing control systems and in the formal sense of flat differential systems. Existing energy systems are characterized by multiple, largely autarchic control systems, including such systems for control of transient stability, load frequency, voltage, power quality, and protection. Within each control system, coordination is achieved through a multi-layered hierarchy at substations, power plants, independent system operators (ISOs), and regional power pools. Such control systems are often myopic with regard to system needs and emphasize protection of individual components rather than protection of energy delivery and are already stretched to their practical limits. We envision a simpler structure that consists of only two levels at each scale:

- Local control in which individual components and individual loads operate in a manner that tends to support the best interests of the overall system, for reliability, speed, and robustness of control actions.

- Contextual control in which larger-scale controllers select one of a finite number of system-level control goals, such as efficiency maximization, cost minimization, stabilization, network recovery, or other goals that best reflect needs based on overall system status at a given moment.

Flat control approaches must be implemented at many different scales, given the multi-scale nature of the overall energy system. For example, a roof-top solar installation would have a local control that might alter its energy behavior in response to local frequency or voltage variation. A shopping center would have a contextual controller to serve the many local controllers within its domain. Each version requires support through information exchange and a communication
layer that support this exchange. Flat control supports concepts of aggregation, in which a new type of business offers sophisticated contextual control that serves the power grid operator while supporting local control and its economic benefits down to the customer level.

An electric power system is an extremely complex dynamic system that relies on regular patterns of operation. Even though system characteristics cannot be completely understood, high performance can be assured as long as system limits are respected. A power system with high renewable energy penetration is far more dynamic and subject to greater uncertainties than the present system. Successful operation cannot be realized following current design and decision-making paradigms. The control system and communication methodologies to realize a flat control framework have not been established in a large-scale practical system. Once a framework is established, with published rules and standards, all participants can contribute to the overall system goals. This work seeks to establish a structure where capabilities can be added incrementally at various levels and by different technologies, players, and localities. The focus is primarily on defining this infrastructure but we also investigate specific implementations to establish validity of the approach. The remainder of the report breaks down the results to date and plans for the current year by the research tasks identified in the original proposal.

1.2 Project Highlights

This project began in the summer of 2010 for most of the participants. The initial work has primarily focused on establishing the fundamental framework for the proposed approach. We are now moving into more extensive simulation of the concepts on a larger system. To date, there have a number of notable successes that support the on-going work. Specifically:

- The “flat” control concepts explored in this GCEP proposal helped the PIs to compete successfully for an NSF/DOE funded engineering research center entitled CURENT. Initial funding for the center is $18.5M for five years. CURENT states as its vision “a nation-wide or continent-wide transmission grid that is fully monitored and dynamically controlled in real-time for high efficiency, high reliability, low cost, better accommodation of renewable energy sources, full utilization of energy storage, and accommodation of responsive load.” The center will allow us to more fully evaluate the concepts developed in this proposal.

- A total of 41 publications and one patent application supported by this work.

In addition, we note the following recent trends in the electric power grid that highlight the need for enhanced grid controls.

- The rapid introduction of Phasor Measurement Units (PMUs) will enable the wide area controls developed in this work. On-going efforts supported by the DOE will be install an additional 850 PMUs in the US by 2013.

- The continued growth of large-scale wind farms has led to an installed wind generation capacity in the US at the end of 2011 of 46.9 GW.

- Rapidly falling cost of PVs have brought them far closer to cost competitiveness.
2. Research Results and Future Plans

This project consists of the following five primary tasks:

1. Flat control and information system methodologies
2. Intelligent device interfaces
3. Optimization with multi-scale energy sources and demands
4. Transmission grid management and operation
5. Test and verification

The annual report is organized around these five tasks with detailed descriptions of the results. Section 2.1 focuses on the formulation and modeling issues for the proposed controls. This is not only the needed controls but the monitoring and communications issues. Section 2.2 describes results on devices that will enable the controls. The main issue here is to design the functionality so that interconnected components have the ability to respond to assist system performance. Section 2.3 deals directly with resource management and system operation. Here the main issue is determining the appropriate mix of generation to ensure reliable and economic performance in the face of greater source uncertainty. Section 2.4 addresses issues of transmission operation. The grid must be operated in a more robust manner to withstand disturbances and uncertainty in the generation and depends. Section 2.5 begins to address issues related to overall test and verification of the developed methods.

2.1 Flat Control and Information System Methodologies

Flat systems were first introduced by Fliess [1] and it is an indication that the nonlinear structure of the system is well characterized and one can exploit that structure in designing control algorithms for motion planning, trajectory generation, and stabilization. One major property of differential flatness is that the state and input variables can be directly expressed in terms of the flat output and a finite number of its derivatives [2].

The flatness property may be very useful when dealing with trajectories: from the flat output, y, trajectories, system state variables, x, and system input, u, trajectories are immediately deduced. These properties permit a straightforward open loop path tracking. The equivalence of the flat system with a controllable linear system via an endogenous feedback yields a feedback stabilization of the desired trajectory. Precisely, according to the flat output properties, system trajectories joining a collection of points with given velocities, acceleration, jerks, etc., are easily generated, thus replacing difficult dynamical computations by statistical interpolation techniques [3].

Due to flat outputs properties, all trajectories \((x(t),u(t))\) satisfying the system differential equation can be interpreted in terms of the flat output and its derivatives. Considering the problem of steering from an initial state to a final state, the components of the flat output \(y_i, i = 1, \ldots, m\) are parameterized by:
\( y_i(t) = \sum A_{ij} \lambda_j(t) \)  

where \( \lambda_j(t), j = 1, \ldots, \alpha \) are basic functions. Thus, the problem of steering from an initial state \( x(t_i) \) to \( x(t_f) \) reduces to find the \( A_{ij} \) coefficient through simple algebra equations. The multi-dimensional case follows by repeatedly applying the approach to one-dimensional cases, since the algorithm is decoupled in the component of the flat output [2, 4].

In a flat system tracking the desired trajectory is ensured using the fact that the flat system is equivalent to a trivial system \((y)^{\alpha} = v\) by endogenous dynamic feedback. By setting \((y^*)^{\beta} = v^*\), it suffices then to set:

\[
v = v^* - \sum_{j=1}^{\alpha-1} K_j e^{(j)}
\]

with appropriate gain matrix \( K = K_1, \ldots, K_{\alpha-1} \) and \( e = y - y^* \) the error term in this equation. Standard linear control methods can be applied to find \( K \) coefficients. Similar to trajectory generation for multi-dimensional case, trajectory tracking follows by repeatedly applying the approach to one-dimensional cases [2, 4-5].

### 2.1.1 Flatness based Automatic Gain Control (AGC)

System frequency deviates from the nominal setting whenever there is any imbalance between generation and load. The imbalance will be drawn from the kinetic energy stored in the rotating masses of the generators. Local governor control is the primary control loop to ensure balance. In order to maintain system frequency at the nominal value and schedules between control areas, a secondary control loop, AGC, coordinates the unit raise and lower signals. The control center gathers the relevant frequency and power flow information and sends the appropriate set point adjustments for each of the units on AGC [6]. Considering the governor-prime-mover-rotating mass/load model block diagram in [7], the multi-machine system to analyze AGC performance is described by a fourth-order model and wind generation dynamic [8-9].

\[
\delta_i = \omega_i - \omega_s
\]

\[
\dot{\omega}_i = \frac{1}{2H_i} \left[ (P_m - D_i(\omega_i - \omega_s)) - \frac{E_i V_i}{x_{di}} \sin(\delta_i - \theta_i) \right]
\]

\[
\dot{p}_{gvi} = \frac{1}{\tau_{gi}} \left( p_{ref} - \frac{\omega_i - \omega_s}{R_i \omega_s} - p_{gvi} \right)
\]

\[
p_{mi} = \frac{1}{\tau_{gi}} (p_{gvi} - p_{m})
\]

\[
p_{wi} = \beta_1 p_{wi} + \beta_2 v_{wi} + \beta_3
\]

where \( \delta_i \ [\text{rad}] \) is the rotor electrical angle, \( \omega_i \ [\text{rad/s}] \) is the rotational speed of rotor, \( \omega_s \ [\text{rad/s}] \) is the machine electrical synchronous speed, \( P_m, P_{gvi}, P_{wi} \) and \( P_{ref} \ [\text{pu}] \) are the turbine and generator powers, wind generator power and speed changer position, respectively.
$V_i$ and $E_i$ [pu] are the machine terminal voltage magnitude and voltage behind reactance respectively, $\theta_i$ [rad] is the machine terminal voltage angle, $D_i$[s/rad] is a damping constant, $H_i$ [s] is the machine inertia constant, $\tau_{ti}$ and $\tau_{gi}$[s] are the turbine and governor time constants, respectively, $R_i$ [pu] is the slope of the machine speed-droop characteristic, $\beta_1, \beta_2, \beta_3$ are parameters of wind power model and $v_{wli}$ is the wind speed.

$p_{ref}$ is conventionally calculated through integration of ACE. The frequency bias setting, $B_f$, is multiplied by $10\Delta f$ to obtain frequency bias. The frequency bias is subtracted from the deviation of tie flows to obtain ACE. The main challenge in this method is the design of the integral controller. This becomes more challenging in the presence of wind farms in the system as the energy generated by these units varies rapidly.

The suggested flat-based control method is implemented on AGC of a multi-area system including wind power penetration. Based on (2-3) (2-7), $\delta = [\delta_1, \ldots, \delta_i, \ldots, \delta_n]$ is considered as the flat output vector. The algebraic relations between the state variables, input, flat outputs and their derivatives, verify that $\delta$ is the flat output in this system. The compensator for each generator can be defined as:

$$\delta_i^{(4)} = u_i$$ (2-8)

According to (2-8), it is observed that the dynamics of a multi-generator system can be split into n linear controllable subsystems. The trajectory generation and the asymptotic tracking of the desired trajectory, rotor angle, are explained in the following.

Trajectory generation for multi-machine AGC system

An important role of AGC is to allocate generation so that each power source is loaded most economically [10]. Therefore, in this study economic dispatch is performed to find the desired operating points for each generator. The desired operating point has to be updated at frequent intervals in order to follow load changes and wind generation variations. A smooth trajectory is then planned to generate the optimum path, which will be followed by trajectory tracking control in each interval.

Trajectory tracking for multi-machine AGC system

Finding appropriate gain matrix, $K$, in (2-2) is an important task in AGC design to maintain system stability, restore the frequency nominal value, and track the scheduled net interchange. Tracking the generated trajectory guarantees the mentioned goals. The trivial system of (2-8) for each area is the key to achieve tracking of the desired trajectory in this system. The LQR method subject to trivial system constraints such as generator ramping rate is employed to find the appropriate $K$ in this study.

Simulation Results

The approach is implemented on a 3-machine, 9-bus system [11]. In order to evaluate the performance of the controller in presence of load changes and penetration of wind energy, two scenarios are studied: Scenario 1: a step load perturbation of 30% and Scenario 2: adding wind power generation unit. Performance of the controller is evaluated based on NERC balancing standard, CPS1 [12].
In the first scenario the perturbation is imposed on the system at $t = 500$ s. Fig. 2-1 displays the simulation results for rotor angle and frequency deviation of generators 1-3. As shown in the figures, the frequency deviation is in the acceptable range due to utilizing the proposed AGC. Moreover, since rotor angle tracks the planned trajectory, the net active power interchange for each generator follows the scheduled value. In this scenario, the calculated CPS1 is 200.00, 200.00 and 199.62 for areas 1, 2, and 3, respectively.

Fig. 2-2 displays the rotor angles and frequency deviations in scenario 2. As observed, the frequency deviations are in the acceptable range. Due to fast variation of wind generation output and ramping rate constraint for thermal units that limits the mechanical power changes, the rotor angle of these units is not able to track the trajectory as it does in hydro unit. However calculation of CPS1 for the three areas shows that the rotor angle deviations are in the standard range. CPS1 values are 200.00, 198.13, and 199.02 for areas 1, 2, and 3, respectively.

References
2.1.2 Measured Signals for Flat Control

An important aspect of flat control in a large system is the selection of the measured signal for control. In fact, if the desired signals are used for feedback control, a control system would either already be in the feedback linearized form, or readily be transformed into a linearized system. In power system control, remote machine angle and speed measurements allows a system to be in the feedback linearized form such as controllers to improved system performance can readily be obtained.

The use of remote signal can be readily facilitated by synchronized phasor measurement. Fig. 2-3 shows an embellishment of such a control scheme based on synchronized high-sampling rate power system voltage and current phasors measured by PMUs (phasor measurement units). In this advanced control system, there is several main sources of latency: (1) the time to compute the phasors, (2) the computation time for collecting phasor data, and (3) the time for data to travel several hundred to a thousand miles. However, with the data time tagged by GPS signals, the time delay can be known quite accurately. Due to potential network congestion the total delay time for the PMU data will not be constant. Thus, an adaptive control shown in Fig. 2-4 can be useful where the controller $G_c$ is a function of the time delay $T_d$. This adaptive control scheme is illustrated for using a TCSC (thyristor-controlled series capacitor) to damping the Interarea oscillations between two coherent areas in a 4-machine system (Fig. 2-5). Fig. 2-6 shows that performance of the control system with and without latency in the feedback signal. The results summarized here are described in [1]. Currently, we are developing a stability proof based on switching control.
Fig. 2-3. Phasor data communication path and control system

Fig. 2-4. An adaptive control scheme

Fig. 2-5. Four-machine, two-area power system
Fig. 2-6. Performance plots: (a) control system performance, (b) control action

References

2.1.3 Estimation and Control over Networks
Communication delay is one of the unavoidable side-effects of using a computer network to interconnect sensors, actuators and control centers/nodes. In general, increased delay in a
feedback control system often results in instability or reduced performance [1]. In [2], we have proposed a delay compensation approach based on time-stamping of transmitted signals, which can successfully mitigate the destabilizing effects of delay. By “time-stamping” we mean that every signal sample $x(t)$ is transmitted over the network as an ordered triplet $(x, t, k)$, consisting of the sample value “$x$,” the corresponding sampling time instant “$t$,” and the identity of the source of the signal $x(t)$ (e.g., which sensor). Time stamping is enabled by the availability of precise time signals derived from the Global Positioning System (GPS) in various nodes of the power system. Such signals are part of Phasor Measurement Units (PMUs) that are increasingly being deployed as a key ingredient of system-wide monitoring and control.

For illustration, we show the performance of our robust estimation scheme for the case of a 2.5 kW induction motor with an uncertain model. Fig. 2-7 shows the signal to estimation error ratio as a function of the network delay for the accurate model (top trace) and for two models with parametric uncertainties (1% and 5%, two lower traces). In comparison, we note that the system without delay compensation becomes unstable for a 50 ms delay.

![Signal to Error ratio with the Inaccuracy of system parameter](image)

**Fig. 2-7.** Networked estimation/control configuration

Time-stamping of transmitted information can also be used to overcome random, time-variant, delays in the observation path between sensors and estimation/control centers. It can be used with any state-estimation method and any feedback-control strategy, not just Kalman filtering and LQG state-feedback control. In particular, robust estimation and control methods (see, e.g., [3-6]) may be required to accommodate significant uncertainty in system parameters (and models). Endowing such robust estimation and control techniques with delay mitigation capability will be the key to successful implementation in spatially-extended power systems. We are currently developing an extension of our delay mitigation technique to the robust Kalman filter algorithm described in [5].
Previous analysis of the effects of observation intermittency have mostly addressed the problem of dropped communication packets [7-8], which result in an irregular (random) inter-sample interval with a Bernoulli (i.e., geometric) probability distribution. We have recently extended these results to the case of arbitrary (non-Bernoulli) sensor sampling patterns [10]. In contrast to the formulation in [7], our results do not rely on coordination between the individual sensors, since we assume the cyber-physical power system to be geographically-distributed over a wide area. Uncoordinated (i.e., statistically independent) sampling and transmission of sensor observations result in enhanced resilience to communication packet loss and cyber-security attacks. In particular, we have demonstrated that staggered sampling - i.e., displacing the sampling instants of individual sensors with respect to each other so as to reduce the variation of the combined multi-sensor inter-sample intervals - results in a reduction of the average estimation error covariance [9].

We established a necessary condition for stability of a continuous-discrete Kalman filter with irregularly sampled observations [10]. Our stability condition extends [7] and relates the location of system poles to the region of convergence of the characteristic function (a.k.a. moment generating function) associated with the random multi-sensor inter-sample interval. Recently, we have extended these results to include the effects of both irregular sampling and delay in the measurement path [11].

We have also shown that estimation performance depends primarily on the average length of the sampling interval, with a very minor dependence on the variance and a negligible dependence on higher order moments of the (time-varying) sampling interval (see Fig. 2-8, where $\xi$ is the normalized variance of the random sampling interval and $\lambda$ controls kurtosis). These observations lead to a simple design rule: the average sampling interval $T_{av}$ can be adjusted to achieve an acceptable level of state estimation error. Further research is needed to extend these findings to robust Kalman filter method [5], with special focus on estimator stability.
The sensing, communication, and processing resources available in each hub can also be used to detect and locate faults in power lines, using the technique proposed in [12] and [13]. In this approach, arrival time differences of signals from the fault point to the synchronized monitoring instruments are used for accurate fault location. When a fault occurs, electromagnetic waves which originated at the fault point travel along neighboring transmission lines. Since these traveling waves follow different paths, they arrive at distant recorder locations with distinct time delays. Referring to these wave-arrival delays of a certain fault transient at various locations in the network, the fault location can be determined. The previously proposed methods assumed either a single recorder at one end of the faulted line, or a pair of synchronized recorders at both ends of the faulted line. In this work we take advantage of sparsely distributed available synchronized recorders throughout the network. The captured waveforms are processed together in order to identify the exact location of the fault under study [14].

2.1.4 Modeling and Control via Dynamic Phasors
Dynamic phasors are finding increasing use in analysis and control of electric energy components and systems. Applications of the dynamic phasor framework are numerous, and include power systems (analysis of unbalanced faults and protection), electric drives (analysis of unbalanced electric machines and of position-dependent loads, torque ripple minimization) and power electronics (model reduction in DC/DC converters, analysis of resonant and high-power converters, control of active filters). While dynamic phasors are intended for near-to-periodic operation, they have a number of useful features: (i) models are time-invariant (autonomous); (ii) inputs and consequently states tend to vary slowly compared to the driving frequencies; (iii) they achieve "simultaneous demodulation" in that all variables are constant ("dc") in a steady state;
(iv) they are very effective in revealing dynamic couplings between various quantities, as shown in derivation of novel equivalent circuits for unbalanced ac machines [15].

Recently we have shown that such dynamic phasor expressions are a special case of a broader family of customizable signal transforms that we called Phasor Banks [16-18]. The need for compact dynamic phasor representations that can be efficiently communicated across a spatially distributed cyber-physical energy system mandates customization that focuses on frequency selectivity. Similarly, dynamic phasors for fault detection and location applications require a customization focused on time selectivity. For instance, we have developed an efficient procedure for customization of the pre-detection filter used in fault location in power grids [19]. Our customized pre-detection filter is superior, in terms of both peakedness and group delay, over the currently used (Daubechies-based) discrete-wavelet transform processing of fault waveforms (Fig. 2-9).

![Customized pre-detection filter vs. wavelet transform (Daubechies)](image)

In [18], we presented a method for application-specific customization of dynamic phasors, intended for use in wide-area monitoring and control of electric power networks. In particular, we proposed frequency-selective customization for accurate tracking of time-variant harmonic content under both steady-state (nearly-periodic) and transient operating conditions. We provided an explicit compact characterization of the optimally-robust reconstruction stage of this transform, which can be used with any (customized) choice of its analysis stage. Since the phasor bank transform allows causal delay-free perfect reconstruction of any input waveform, it is perfectly suited for (closed-loop) control applications.
In this project, we continue to explore the advantages of matching phasor bank transforms to different applications, such as fault detection and location, power decomposition, adaptive compensation and networked estimation. We also intend to explore the use of such descriptions in model-based detection and neutralization of cyber intrusions [20].

2.1.5 Dynamic Power Analysis and Control

Our approach to dynamic characterization of power quality, motivated by our steady-state decomposition [21], uses a novel dynamic (i.e., time-variant) 7/11-component power decomposition [22]. Our approach is based on dynamic phasors, and relies on the fundamental, cyclic mode of operation of all energy conversion systems (periodic in the idealized steady-state) and applies naturally to any number of phases. It includes explicit models of components, and reduces to well-known quantities (such as harmonics) in steady state. Such quantities are often the subject of binding regulations (e.g., the power factor or the harmonic content). The quantities that we define dynamically can be used both in simple integral controllers and in more ambitious model-based control schemes. In addition, dynamic phasors can be customized to optimize specific properties in transients (e.g., frequency separation), as shown in [16]. Our dynamic power decomposition, viz.

\[
S^2(t) = P^2(t) + N_s^2(t) + N_u^2(t) + Q_B^2(t) + Q_s^2(t) + Q_u^2(t) + S_L^2(t)
\]

(2-9)
captures transient behavior, while reducing to the standard (constant phasor) characterization in steady-state [23]. Here, \(P\) denotes the real (active) power, \(Q_B\) is the reactive (Budeanu) power, \(N_s\) (respectively \(Q_s\)) is the co-active (resp. co-reactive) power due to the spread of (incremental) conductances (resp. susceptances) in various phases over frequency, \(N_u\) (respectively \(Q_u\)) is the co-active (resp. co-reactive) power due to the spread of (incremental) conductances (resp. susceptances) in various phases across phases, and \(S_L\) denotes a component due to system responses (typically currents) at frequencies or phases when there is no driving term (caused by circuit nonlinearity). The use of dynamic phasors makes it possible to enforce \(P(t) = S(t)\) (with negligible line impedance) even during transients, by employing the adaptive compensator of [24-25], which we describe below.

The role of compensation in controlling power flow in cyber-physical energy systems is to reduce the power consumption of the Thevenin equivalent source (or "line") impedance, so that most of the generated power is delivered to the load. This impedance represents the combined effect of all power sources, loads and transmission/distribution lines in a power network. With the dispersion of energy sources to lower-voltage networks, the line impedances are bound to increase. They will also vary much more, as the topology changes are much more frequent is such networks. In addition, many renewable sources are inherently single phase (e.g., small rooftop photovoltaics), and their intermittency will lead to increased unbalances in polyphase networks. Together with increased injection of harmonics by new loads and sources, this will result in modes of operation that are qualitatively very different from the ones assumed traditionally for network compensators such as active and passive filters and shunt capacitors.

Traditional compensation methods, such as Fryze compensation, lose their effectiveness when the equivalent line impedance is no longer negligible in comparison with the load impedance. Moreover, constantly changing network conditions require continuous readjustment of the
compensator current in order to ensure continuing efficient operation of the power system. Recently, we have introduced an adaptive near-optimal compensation scheme that relies only on measurements of the load voltage and current or, equivalently, on the phasor description of these waveforms [23-24]. Our compensator tracks variations in both network and load conditions, continuously adjusting the polyphase compensator current so as to reduce the power dissipated in the source impedance, for both linear and nonlinear loads.

We show in Fig. 2-10 an example of the performance of our adaptive near-optimal compensation method: $P_{\text{line}}$ are the line losses, $P_{\text{cloud}}$ is the power supplied to the compensated load, and $P_{\text{comp}}$ is the (real) power supplied by the compensator (which is zero on the upper parabolic cross-section curve). The nonlinear (electrical) load to be compensated is an induction machine rated at 25 kW, connected to a mechanical load with a quadratic torque-speed characteristic, and supplied over a long, unbalanced line [24]. The solid line in the figure connects the points obtained by our iterative algorithm. We use the cross-section curve, which indicates the theoretical optimum (dash-dot line in Fig. 2-10) achievable with exact knowledge of network and load characteristics, as a benchmark for comparison. Due to the near-optimal characteristic of our compensator it is observed that the steady-state points (white circle markers in Fig. 2-10) lie very nearly on the optimum cross-section curve.

![Fig. 2-10. Convergence trajectory of the adaptive compensator.](image)
In the current project year, we have demonstrated the stability of our adaptive compensation technique in the presence of linear loads, as well as a special class of nonlinear loads. Future research is needed to validate our approach with a wide variety of nonlinear loads, to establish the boundaries of stable operation, both in steady-state and in the presence of network transients, and to develop safeguards against loss of stability even under the most compromising conditions. Our ultimate goal is to develop a methodology of collaborative adaptive networked power flow control that can use network status information, extracted from the information layer of a cyber-physical energy system, to improve overall energy delivery efficiency beyond what can be achieved with stand-alone (i.e., network-blind) adaptive compensators. In particular, network information can be used to speed up the convergence of our adaptive compensation scheme, as well as expand the region of its stable operation.

References

2.2 Intelligent Device Interfaces

Under the concept of flat control, a key property for development of an inclusive power grid infrastructure is effective local control. In general, the objective is to seek control approaches at each level of hierarchy that acts in accordance with limited information, but in such a way that the overall system performance in enhanced. This implies requirements for communications and device interfaces. An implication of the local control approach is that many types of electrical loads will participate as active entities at the lowest level of grid control. This task focuses on device interfaces to realize the local control. A control system that allows “plug-and-play” capability for a STATCOM in order to enhance voltage stability is described. A patent application has been submitted for this work. We also investigate a new converter design to facilitate grid-connected PV. A developed interface for offshore wind power systems using HVDC transmission are described. We continue to investigate the role of PHEV charging and how operation they can support the overall system.

2.2.1 STATCOM to Enhance Voltage Stability

Voltage stability is a critical consideration in improving the security and reliability of power systems. The Static Compensator (STATCOM), a popular device for reactive power control based on gate turn-off (GTO) thyristors, has gained much interest in the last decade for improving power system stability [1]. Various control methods have been proposed for STATCOM control [2-8].

In many STATCOM models, the control logic is implemented with the PI controllers. The control parameters or gains play a key factor in STATCOM performance. Presently, few studies have been carried out in the control parameter settings. In many practices the PI controller gains are designed in a case by case study or trial-and-error approach [9-11] with tradeoffs in performance and efficiency. Generally speaking, it is not feasible for utility engineers to perform trial-and-error studies to find suitable parameters when a new STATCOM is connected to a system. Further, even if the control gains have been tuned to fit the projected scenarios, performance may disappoint when a considerable change of the system conditions occurs, such as...
as, when a transmission line is upgraded or retires from service [12]. The situation can be even worse if such transmission topology change is due to a contingency. Thus, the STATCOM control system may not perform well when mostly needed.

Different from the previous works, the motivation of this paper is to achieve a control method that can ensure a quick and desirable response when the system operation condition varies. In other words, the change of the external condition will not have a negative impact, such as slower response, overshoot, or even instability, to the performance. Thus, a plug-and-play feature will be achieved such that utility operation will be much simplified.

Based on this fundamental motivation, an adaptive control of STATCOM for voltage regulation is presented. By this adaptive control method, the PI control parameters can be self-adjusted automatically and dynamically under different disturbances in a power system. When a disturbance occurs in the system, the PI control parameters for STATCOM can be computed automatically in every sampling time period and can be adjusted in real time to track the reference voltage. Different from other control methods, this method will not be affected by the initial gain settings, changes of system conditions, and the limits of human experience and judgment. This will make the STATCOM a plug-and-play device. In addition, this research work demonstrates a fast, dynamic performance of STATCOM in various operating conditions.

The traditional control diagram of STATCOM is shown in Fig. 2-11. The phase locked loop (PLL) provides the basic synchronizing signal which is the reference angle to the measurement system. Measured bus line voltage $V_m$ is compared with the reference voltage $V_{ref}$ and the voltage regulator provides the required reactive reference current $I_{qref}$. The droop factor, $K_d$, is defined as the allowable voltage error at the rated reactive current flow through the STATCOM. The STATCOM reactive current $I_q$ is compared with $I_{qref}$ and the output of the current regulator is the angle phase shift of the inverter voltage w.r.t. the system voltage. The limiter is the limit imposed on the value of control with the consideration of the maximum reactive power capability of the STATCOM.

![Fig. 2-11. Traditional STATCOM PI control block diagram.](image-url)

In traditional STATCOM control, fixed PI control parameters are used. However, this approach may not reach the desired and acceptable response when the power system operating condition (e.g., loads or transmissions) changes.
In the proposed adaptive control method, in order to obtain the desired response and to avoid performing trial-and-error studies to find suitable parameters for PI controllers when a new STATCOM is installed in a power system, dynamical self-adjustment of PI control parameters are implemented. An adaptive control block for STATCOM is shown in Fig. 2-12. In Fig. 2-12, the measured voltage \( V_m(t) \) and the reference voltage \( V_{ref}(t) \), the \( q \)-axis reference current \( I_q^{ref} \) and the \( q \)-axis current \( I_q \) are in per unit values. The proportional and integral parts of the voltage regulator gains are denoted by \( K_{p_V} \) and \( K_{i_V} \), respectively. Similarly, the gains \( K_{p_I} \) and \( K_{i_I} \) represent the proportional and integral parts, respectively, of the current regulator. In this control system, the allowable voltage error \( K_d \) is set to 0. The \( K_{p_V}, K_{i_V}, K_{p_I} \) and \( K_{i_I} \) can be set to an arbitrary initial value such as simply 1.0. One exemplary desired curve is an exponential curve in terms of the voltage growth, shown in Fig. 2-13, which is set as the reference voltage in outer loop. Other curves may also be used than the depicted exponential curve so long as the measured voltage returns to the desired steady state voltage in desired time duration. The main strategy of adaptive voltage control method for STATCOM is described as follows:

- The bus voltage \( V_m(t) \) is measured in real time.
- When the measured bus voltage over time \( V_m(t) \neq V_{ss} \), the target steady-state voltage (which is set to 1.0 per unit (p.u.) in the discussion and examples), the measured voltage is compared with \( V_{ss} \). Based on the desired reference voltage curve, \( K_{p_V} \) and \( K_{i_V} \) are dynamically adjusted in order to make the measured voltage match the desired reference voltage, and the \( q \)-axis reference current \( I_{ref} \) can be obtained.
- In the inner loop, \( I_{ref} \) is compared with the \( q \)-axis current \( I_q \). Using the similar control method like the one for the outer loop, the parameters \( K_{p_I} \) and \( K_{i_I} \) can be adjusted based on the error. Then, a suitable angle can be found and eventually the DC voltage in STATCOM can be modified such that STATCOM provides the exact amount of reactive power injected into the system to keep the bus voltage at desired value.

![Fig. 2-12. Adaptive control block for STATCOM](image-url)
It should be noted that the current $I_{\text{max}}$ and $I_{\text{min}}$ and the angle $\alpha_{\text{max}}$ and $\alpha_{\text{min}}$ are the limits imposed with the consideration of the maximum reactive power generation capability of the STATCOM controlled in this manner. If one of the maximum or minimum limits is reached, the maximum capability of the STATCOM to inject reactive power has been reached. Certainly, as long as the STATCOM sizing has been appropriately studied during planning stages for inserting the STATCOM into the power system, the STATCOM should not reach its limit unexpectedly.

**Simulation Results to Verify the Proposed Adaptive Control**

In the system simulation diagram shown in Fig. 2-14, a +/-100 MVAR STATCOM is implemented with a 48-pulse VSC and connected to a 500kV bus. This is the standard sample STATCOM system in Matlab/Simulink library [9-11]. Here, the attention is focused on the STATCOM control performance in bus voltage regulation mode. In the original model, the compensating reactive power injection and the regulation speed are mainly affected by PI controller parameters in the voltage regulator and the current regulator. Fig. 2-15- Fig. 2-17 show simulation results with the original control and the adaptive control after a disturbance is assumed to cause a voltage drop at 0.2 sec from 1.0 to 0.989 per unit at the source (substation). The original control may have significant problems under different operation conditions as shown in Fig. 2-15- Fig. 2-17. Fig. 2-15 shows that the original control cannot bring the voltage back to nominal value under different control gains. Fig. 2-16 shows that the original control performs much slower under different load levels. Fig. 2-17 shows that the original control leads to unnecessary overshoot under a different transmission network. In contrast, in all simulation studies, the adaptive control performs consistently well and follows the desired curve via the dynamic adaptive adjustment of control gains. This shows the plug-and-play characteristic of the proposed adaptive control.
Fig. 2-14. The studied system.

Fig. 2-15. Voltages with changed $K_p$ and $K_i$ in the original control.

Fig. 2-16. Results of measured voltage with change of load.
Fig. 2-17. Results of measured voltage with change of transmission network.

References


2.2.2 Multilevel Converters for Solar Panels

Since power generation plants are among the largest sources of greenhouse gas emissions, many solutions are proposed to minimize emission, including wind farms, solar roof-tops, and plug-in hybrid cars. Among the different renewable energy sources possible to generate electricity, solar energy has been one of the most attractive areas. Photovoltaic (PV) systems are ideally distributed generation (DG) units, and they offer many advantages such as no fuel costs, no
pollution, no noise and little maintenance. Solar photovoltaic has been among the fastest growing energy sources in the world, with annual growth rates of 25-35% over the last ten years. The growth is mainly due to grid-connected applications. In the US, the top 10 ranked utilities integrated 561 megawatts (MW) of solar electricity capacity in 2010, representing 100 percent growth over one year.

In grid-connected systems, the panels needed to reach the required power levels are usually arranged in strings. The cascaded H-bridge multilevel inverter requires a separate DC source for each H-bridge; thus, the high power and/or high voltage from the combination of the multiple modules would favor this topology in grid-connected PV applications [1-2]. As shown in Fig. 2-18, the cascaded multilevel inverter topology consists of \( n \) H-bridge converters connected in series, and each DC link is fed by a short string of PV panels. By different combinations of the four switches in each H-bridge, three output voltage levels can be generated, \(-v_c\), 0, or \(+v_c\). A cascaded multilevel inverter with \( n \) input sources will provide \( 2n+1 \) levels to synthesize the AC output waveform. This \((2n+1)\)-level voltage waveform enables the reduction of harmonics in the generated current, reducing the output filters. In addition, the multilevel inverter also presents the advantages of reducing the device voltage stress and being high efficiency [3]. The cascaded multilevel inverter topology can be used in both single-phase and three-phase grid-connected applications. A three-phase cascaded H-bridge multilevel inverter for a grid-connected PV system is shown in Fig. 2-19.

![Fig. 2-18. Topology for grid connection.](image-url)
At higher penetrations, the impact of PV systems may accumulate and affect power quality. The nonactive power control of PV inverters provides an opportunity to maintain good power quality in the grid and optimize the performance of distribution circuits. In Fig. 2-19, the photovoltaic cascaded H-bridge multilevel inverter is connected to the grid through an inductor L. A generalized nonactive power theory is applied to generate the nonactive current reference [4]. In addition to providing the active power, the multilevel inverter could also provide the reactive power required by the local load to realize power factor correction and minimize distribution losses [5].

An 11-level cascaded H-bridge inverter prototype has been built, as shown in Fig. 2-20. Each of the five H-bridges has its own 195 W PV panel connected as an independent source. The MOSFET IRFSL4127 is selected as inverter switches, and the control signals to the H-bridge inverters are sent by the dSPACE ds1103 controller. The experimental result is presented in Fig. 2-21. It can be seen that the load current is lagging the voltage, however, the grid current has the same phase as the voltage, which means the grid has unity power factor. To maximize the solar energy extraction, an individual maximum power point tracking (MPPT) control scheme has been studied, which allows the independent control of each dc-link voltage. Simulation is carried out in Matlab/Simulink to verify the individual MPPT control scheme.
Fig. 2-20. Solar panels and experimental setup.

Fig. 2-21. Experimental voltage and current waveforms.

(a) DC-link voltage of module 1.
(b) DC-link voltage of module 2.

Fig. 2-22. DC-link voltage of two modules (T=25 °C).
The 5-level inverter is operated in two different conditions. First, two PV panels are operated under the same irradiance $S=1000 \, \text{W/m}^2$ and temperature $T=25 \, \text{˚C}$. At $t = 3s$, the solar irradiance over the second panel decreases to $600 \, \text{W/m}^2$. The dc-link voltage waveforms of two modules are shown in Fig. 2-22. As the irradiance changes, the second dc-link voltage decreases, tracking the new MPP voltage of the second PV panel. The lower irradiation affects the current in the second PV panel, so the lower ripple of the dc-link voltage can be seen.

The voltage and current waveforms are shown in Fig. 2-23, which shows that the power factor correction is also realized. The output voltage of the multilevel inverter is shown in Fig. 2-24. The 5-level voltage helps to reduce the output filters. In a grid system with high renewable penetration, the grid-connected PV systems should provide both the active power and reactive power to improve grid power quality. The cascaded H-bridge multilevel inverter is suitable for grid-connected PV applications, and the separate DC links in the multilevel inverter make independent voltage control possible. Thus, individual MPPT control in each string can be achieved, and the energy harvested from PV panels can be maximized.

Experimental tests will be carried out next to validate the individual MPPT control scheme. A prototype of three-phase grid-connected PV system will be built and tested. Besides reactive power compensation, other auxiliary functions, like harmonics compensation, will be also considered in grid-connected PV systems.
References


2.2.3 Analysis and Control of Offshore Wind Farms with HVDC Transmission

Two offshore wind power systems with HVDC transmission to the onshore power grid were defined in the first year of the project. One of the systems uses line-commutated converters (LCC), while the other uses voltage-source converters (VSC). Fig. 2-25 shows a simplified diagram of the system studied, where each wind turbine with its generator and rectifier is modeled as a dc power source, $P$. The STATCOM (Static Compensator) is used when LCC HVDC rectifier is used. Detailed simulation models were developed for each system and simulated in Saber to understand the control and stability characteristics. Preliminary small-signal models were also developed using harmonic linearization methods [1], and system stability analysis method using impedance models was presented.

![Fig. 2-25. A simplified diagram of the offshore wind power system with HVDC connection to onshore power grid.](image)

The second-year effort has focused on 1) control revision and refining for each of the two HVDC systems; 2) impedance-based small-signal modeling and analysis of each system based on the method outlined in last year’s report.

*Wind Turbine Inverter and Control*

The control strategy for the wind turbine inverter is to regulate the dc bus voltage through d-axis current control and to inject the required reactive power to the ac bus through q-axis current
control. Design of current controller follows a similar procedure as used for the HVDC rectifier. The dynamics of turbines dc bus are given as

$$C_0 \frac{dv_0}{dt} = i_0 - \frac{3}{2}(d_{dw}i_{dw} + d_{qw}i_{qw})$$

(2-10)

where \(i_0\) is the current flowing the turbine rectifier into the dc bus capacitor, \(ddw\), \(dqw\) and \(idw\), \(iqw\) are averaged inverter duty ratios and output currents in the dq-domain respectively. Ignoring \(iqw\) and considering \(i0 = P/v0\), where \(P\) is the power captured by the wind turbine, PI control for \(v0\) is achieved through d-axis current control. The angle of the rotating dq reference frame is generated by the PLL which tracks the phase angle of the ac bus voltage. Fig. 2-26 depicts the circuit model and control blocks of the wind turbines, where \(P0\) is the power command of converters, \(idw\) and \(iqw\) are the converter output currents \(iaw\), \(ibw\) and \(icw\) in dq frame, \(v0\) is the converter dc bus voltage and \(V0\) is rated dc bus voltage. Table 2-1 shows the key design parameters of wind turbines.

![Fig. 2-26. Circuit and control block diagrams of a wind turbine inverter.](image-url)
Table 2-1. Wind Inverter and control Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>Units</th>
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<tbody>
<tr>
<td>Dc Bus Voltage</td>
<td>1500</td>
<td>V</td>
</tr>
<tr>
<td>Filter Inductance</td>
<td>0.5</td>
<td>µH</td>
</tr>
<tr>
<td>Filter Capacitance</td>
<td>0.207</td>
<td>F</td>
</tr>
<tr>
<td>Reactor Inductance</td>
<td>0.526</td>
<td>µH</td>
</tr>
<tr>
<td>Dc Bus Capacitance</td>
<td>0.160</td>
<td>F</td>
</tr>
<tr>
<td>MV Cable Inductance</td>
<td>30.59</td>
<td>µH</td>
</tr>
<tr>
<td>MV Cable Resistance</td>
<td>1.155</td>
<td>mΩ</td>
</tr>
<tr>
<td>XMFL Leakage Inductance</td>
<td>0.1</td>
<td>p.u.</td>
</tr>
<tr>
<td>Current Controller $H_{lw}$</td>
<td>$0.88<em>10^{-6} + 1.10</em>10^{-6}/s$</td>
<td></td>
</tr>
<tr>
<td>Dc Voltage Controller</td>
<td>53.56 + 10097/s</td>
<td></td>
</tr>
<tr>
<td>PLL $H_{pll}$</td>
<td>$(0.233 + 45/s)/s$</td>
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</tbody>
</table>

**VSC HVDC Rectifier and Control**

The control objective of HVDC rectifier is to maintain the voltage amplitude, frequency and phase angle at the ac collection bus. Dynamics of rectifier reactor current are represented by

\[
L_{ds} \frac{di_{dm}}{dt} = v_{ds} - v_{dm} + \omega_{1}i_{qm} \quad (2-11)
\]

\[
L_{ds} \frac{di_{qm}}{dt} = v_{qs} - v_{qm} - \omega_{1}i_{dm} \quad (2-12)
\]

where $i_{dm}$ and $i_{qm}$ are dq components of the reactor currents, $v_{dm}$, $v_{qm}$ and $v_{ds}$, $v_{qs}$ are dq components of the converter terminal voltage and the filter bus voltage respectively and $\omega_{1}$ is the constant rotating speed of the reference dq frame which determines the voltage frequency. The dc bus voltage is considered to be constant. Based on this model, decoupled dq averaged current controller is designed by assuming ideal ac filter bus voltage with rated amplitude $V_{m}$. Fig. 2-27. Circuit and control block diagrams of a VSC HVDC rectifier, defines the variables related to the HVDC rectifier model and shows the local control architecture using dq-domain dual-loop control. To simplify the design of the outer voltage loop, the inner current control loop is assumed to be much faster so that its dynamics can be ignored in voltage loop design. The dynamics of filter bus voltage are shown as

\[
C_{ds} \frac{dv_{ds}}{dt} = i_{ds} - i_{dm} + \omega_{1}v_{qs} \quad (2-13)
\]

\[
C_{ds} \frac{dv_{qs}}{dt} = i_{qs} - i_{qm} - \omega_{1}v_{ds} \quad (2-14)
\]
where the ac filter is represented by their dominant capacitance $C_{1s}$ at low frequency. $i_{ds}$ and $i_{qs}$ are dq components of the current ($i_{as}$, $i_{bs}$, $i_{cs}$) going from the wind farm into the rectifier and the current feed foreword helps to cancel the effect of current variation of the ac bus.

The filter of the HVDC converter is designed to absorb high-frequency harmonic components of the voltage and help to stabilize the ac collection bus voltage. The cut-off frequency of the filters is designed at the switching frequency of HVDC converters, that is, 2000 Hz. Table 2-2 lists the key design parameters of the HVDC rectifier and the ac bus filter.

**System Operation and Stability**

Operation of the HVDC system under different conditions was simulated to provide a basis for comparison with small-signal analysis. Two representative cases are presented here to highlight the characteristics of the system. Fig. 2-28 shows stable operating of the wind farm system. In this case (Case I), the HVDC rectifier was able to maintain stability of the ac bus and the wind inverter operated stably with a unity power factor. The THD of offshore ac voltage is below 1% without any harmonic resonance. The dc bus voltage was regulated at the rated value. Saber simulation shows that system is stable in both start-up condition and under gust wind conditions when wind power increases greatly within a short period of time.

Fig. 2-29 shows an unstable operation of the system (Case II) when the PLL bandwidth is increased from 30 Hz to 120 Hz. It can be observed that there is high-frequency resonance at both ac collection bus voltage and wind turbine output current, which indicates that wind inverters and the VSC HVDC rectifier interact with each other and this interaction causes the harmonic resonance.
Table 2-2. VSC-HVDC Rectifier and Control Parameters

<table>
<thead>
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<th>Parameters</th>
<th>Values</th>
<th>Units</th>
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<tbody>
<tr>
<td>Filter Inductance</td>
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<td>Filter Resistance</td>
<td>10.0</td>
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<tr>
<td>Filter Capacitance</td>
<td>14.471</td>
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<tr>
<td>Output Reactor</td>
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<td>mH</td>
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<td>DC Bus Capacitance</td>
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<td>μF</td>
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<td>XMFL Leakage Inductance</td>
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<td>p.u.</td>
</tr>
<tr>
<td>Current Controller $H_{iH}$</td>
<td>$1.825 \times 10^{-3} + 0.233/s$</td>
<td></td>
</tr>
<tr>
<td>Voltage Controller $H_{vH}$</td>
<td>$0.150 \times 10^{-3} + 0.188/s$</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2-28. Simulated time-domain responses of three-phase currents (upper trace) and voltages (lower trace) of the offshore ac grid for Case I.

Fig. 2-29. Simulated time-domain responses of three-phase currents (upper trace) and voltages (lower trace) of the offshore ac grid for Case II.
**Small-Signal Impedance Modeling**

Small-signal impedance models have been developed for each converter of the two HVDC systems defined above. Each converter is modeled by a positive-sequence and a negative-sequence impedance.

**Wind Inverter:** Each wind inverter is modeled as current source in parallel with the following output impedance:

\[
Z_{ip}(s) = \frac{H_{iw}(s-2\pi f_1)V_0}{2\left(1 - \frac{1}{2}T_{p\text{ll}}(s-2\pi f_1)\right) \left[1 + H_{iw}(s-2\pi f_1)\frac{l_1V_0}{2V_1}\right]} + (s - 2\pi f_1)L_{1w}
\]  

(2-15)

\[
Z_{in}(s) = \frac{H_{iw}(s+2\pi f_1)V_0}{2\left(1 - \frac{1}{2}T_{p\text{ll}}(s+2\pi f_1)\right) \left[1 + H_{iw}(s+2\pi f_1)\frac{l_1V_0}{2V_1}\right]} + (s + 2\pi f_1)L_{1w}
\]  

(2-16)

\[
T_{p\text{ll}}(s) = \frac{V_1H_{p\text{ll}}(s)}{[1 + V_1H_{p\text{ll}}(s)]}
\]  

(2-17)

**STATCOM:** The STATCOM is modeled as voltage source in series with the following output impedance:

\[
Z_{sp}(s) = \frac{k_sL_{1s} - \frac{V_{dc}}{2}[kH_1(s-2\pi f_1) + jkK_{ic}]}{H_1(s-2\pi f_1)V_{ac}T_p(s) - \frac{1}{k} - kY_p(s)L_{1s}}
\]  

(2-18)

\[
Z_{sn}(s) = \frac{k_sL_{1s} - \frac{V_{dc}}{2}[kH_1(s+2\pi f_1) + jkK_{ic}]}{H_1(s+2\pi f_1)V_{ac}T_n(s) - \frac{1}{k} - kY_p(s)L_{1s}}
\]  

(2-19)

where

\[
T_p(s) = -H_\nu(s-2\pi f_1) + jK_{vc} - k^2Y_p(s) + \frac{jk^2K_{ic}Y_p(s)}{H_1(s-2\pi f_1)}
\]  

(2-20)

\[
T_n(s) = -H_\nu(s+2\pi f_1) + jK_{vc} - k^2Y_p(s) + \frac{jk^2K_{ic}Y_p(s)}{H_1(s+2\pi f_1)}
\]  

(2-21)

**LCC HVDC Rectifier:** The LCC HVDC rectifier is modeled by its input impedance as the load for the system. The input impedance is developed by using double Fourier integral method to avoid the need for assuming commensurability between the ac bus fundamental frequency and the perturbation frequency [2]. Following is the positive-sequence input impedance of a 12-pulse LCC rectifier that uses a phase-locked loop to generate gate control signals.

\[
Z_{p12}(s) = \frac{\pi^2}{18} \sum_{n=-\infty}^{\infty} \frac{-1}{j(12n-1)} + A_p(s)V_1 \cos(\alpha) e^{-j\alpha} + \frac{e^{-j\alpha}}{j(12n-1)Z_{dc}[s + j2\pi(12n-1)\pi] + jZ_{dc}[j24n\pi f_1]} + \frac{1}{12n-1} + \frac{1}{12n+1}A_p(s)V_1
\]  

(2-22)
where
\[
A_p(s) = \frac{-je^{-j\alpha} - T_p(s) V_1 \cos(\alpha)}{Z_{ac,\phi}-j2\pi f_1\pi \over 6\sqrt{3}c(s-j2\pi f_1)} - V_1 \cos(\alpha) \\
T_p(s) = V_1 H_{pl}(s) / [1 + V_1 H_{pl}(s)]
\] (2-23)

**Small-Signal Stability Analysis**

Fig. 2-30 shows a small-signal representation of the offshore wind farm system with HVDC transmission, where \(Z_s\) is the input impedance of the VSC HVDC rectifier, \(Z_g\) is the offshore ac grid impedance including the transformer leakage inductance and impedance of the cables, and \(Z_i\) is the output impedance of wind turbines. Based on this representation, response of the grid current can be written as
\[
I(s) = \left[ I_i(s) - \frac{V_r(s)}{Z_i(s)} \right] \frac{1}{1 + \frac{Z_g(s) + Z_r(s)}{Z_i(s)}}
\] (2-24)

Based on the stability criterion presented in [3], the ac bus is stable if the ratio of the total impedance of VSC HVDC rectifier input impedance in series with the grid impedance to the output impedance of the wind turbine meets the Nyquist criterion.

![Fig. 2-30. Small-signal representation of the offshore wind farm with HVDC transmission.](image)

To apply this criterion, Fig. 2-31 shows the frequency response of \(Z_g(s) + Z_i(s)\) and the inverter output impedance for the two cases simulated before. It can be found that in Case I with a slower PLL, the phase margin is about 40 degrees, which indicates stable operation of the system. In Case II with a faster PLL, on the other hand, the phase margin is only 15 degrees, indicating an unstable operation. The simulation results in Fig. 2-28 and Fig. 2-29 confirmed this analysis. In particular, it can be seen from Fig. 2-29 that a 180 Hz harmonic resonance exists. This resonant frequency correlates well with the intersection frequency of the two impedances plotted in Fig. 2-31.
Fig. 2-31. Small-signal impedance analysis of offshore ac grid. Dashed lines: inverter impedance with fast 120 Hz PLL; solid lines: inverter impedance with 30 Hz PLL; dashed-dotted lines: offshore ac bus impedance.

References

Related Contributions - Plug-in Vehicle Infrastructure and Interoperability
We have been exploring various strategies by which plug-in electric and hybrid vehicles can interact in useful ways with the power grid. Among the findings are the following:

- Bidirectional energy flow (which can discharge batteries as well as charge them) is not a necessary condition to gain nearly all vehicle-to-grid (V2G) operating benefits. Unidirectional devices can provide reactive power support, and by virtue of controlled flow can mitigate dynamic changes in renewable resource or provide “virtual reserve capacity” based on the ability to turn charging off quickly.
• Dynamic pricing and control strategies are essential, and it appears that these will be most effective if they emphasize customer choice, easy use, and simple charger programming.

• Vehicle users are likely to seek an “energy guarantee:” requiring a certain energy storage level to be achieved by a defined target time. Subject to this guarantee, with unidirectional charging there is time flexibility that can be employed to the benefit of an aggregator or utility operator.

2.3 Optimization with Multi-scale Energy Sources and Demands

The highly random variability of wind speeds results in major challenges in scheduling. As the penetration of wind increases, the variability issue becomes more pronounced. This has a direct impact on electricity prices as can be seen today with price spikes occurring during fast ramp up or ramp down time periods. When the effects of wind speed forecasting errors are also considered, the combined effects of the various sources of uncertainty create major challenges for unit commitment and dispatch. Without sufficient controls and storage, the operators can only manage the uncertainty by increasing the level of reserves -- spinning and stand-by -- to have the appropriate “insurance” in place. This insurance policy incurs costs for running the increased reserves and the associated start-up costs with the reserves. We are developing optimization methods to schedule loads, generation, and storage dynamically while respecting system limits and considering a broadening of the system to new loads, such as, might exist for hydrogen production. A significant challenge is developing computationally tractable methods for optimization under these uncertainties. We have developed several approaches to quantify the reserves needed to allow reliable operation without sacrificing reliability or imposing high costs on producers. We are also developing modeling tools to allow studies of longer term impact on the system as well as investigating new algorithms to improve computational efficiency. Finally, in these and other efforts, the importance of establishing market incentives for integration of renewables is emphasized.

2.3.1 Quantifying Spinning Reserve for Systems with High Penetration of Wind

With the increasing penetration of wind power in many systems, the traditional unit commitment (UC) with deterministic spinning reserve requirements is inadequate due to the variability and limited predictability of wind power. As wind power cannot be predicted with great accuracy, additional spinning reserve needs to be carried to guarantee the operational reliability [1,2]. Therefore, developing new UC methods capable of taking account of probabilistic characteristics of wind power, load and generators to quantify spinning reserve is of fundamental importance.

Various methods have been presented in the past few years. Gooi et al. [3] integrate a probabilistic reliability assessment with the traditional reserve constrained unit commitment function. A dual objective formulation considering EENS is transformed into a fuzzy optimization problem in [4]. In [5], Wang and Gooi proposed a method for estimating spinning reserve requirement in microgrids considering uncertainties caused by load and non-dispatchable units, such as wind turbines (WTs) and photovoltaics (PVs). Various uncertainties are discretized.
then combined into an aggregated uncertainty distribution. Doherty et al. [6] use the number of load sheds per year as the reliability criterion to quantify the spinning reserve in a system with large wind power penetration. The net load forecast error is modeled as a normal distribution, but this criterion does not consider the extent that supply fails to meet the demand. In [7], Bouffard and Galiana use both EENS and LOLP as constraints in a market clearing scheme. The model is solved by mixed integer linear programming. The wind power penetration is considered later in [8]. The normal distribution of net load forecast error is discretized. In addition, a scenario tree is introduced to simulate the intra-period transitions. However, the model will have a heavy computational burden when all possible scenarios are considered. Ortega-Vazquez et al. [9] use a cost/benefit analysis to determine the optimal spinning reserve level for each time interval. These optimal spinning reserve levels are set as constraints in reserve constrained unit commitment. In [10], they add the uncertainty of wind power generation into the model. The Gaussian distribution of net demand forecast error is approximated by seven intervals. A capacity outage probability table (COPT) [11] is used to calculate the EENS of system. In [12], an Artificial Neural Network model for wind generation forecast is presented and integrated in UC. The probabilistic concept of confidence interval is used to account for the wind forecast uncertainty, but determining the optimal confidence level is another problem difficult to specify. In [13], adequacy of flexibility is used to guarantee the security of system in case of wind power volatility. Benders' cuts are created and added to the master UC to revise the commitment solution for iterations with violations. Another stochastic optimization scheduling model considering wind power production as stochastic input is presented in [14], which makes use of a scenario tree tool to commit the scenario reduction and reschedules based on the most up-to-date forecast information.

The main contribution of this work is to propose an approach to determine the additional spinning reserve required over the next few hours or days due to the integration of wind power generation. A new formulation of expected energy not served (EENS) taking account of the probability distribution of forecast errors of wind and load, as well as outage replacement rates (ORR) of various generators is presented. Based on it, a new model of SCUC, which minimizes the cost of energy, spinning reserve and EENS is proposed and solved using MILP technique.

EENS is the expected energy not served while the net demand forecast error plus the output of unavailable generators is larger than the available spinning reserve. The net demand forecast error is a continuous random variable, while the uncertainties of generators are a set of binary random variables. In order to combine these binary random variables with the continuous random variable, the formulation of EENS is divided into two steps. In the first step, a set of scenarios is constructed based on “\(n-I\)” contingency rules. In the next step, the probability distribution of net demand forecast error is combined with the realization of uncertainties of generators in each scenario, and then discretized into \(NL\) intervals. The EENS in a scenario is calculated by summing the expectation of all intervals giving rise to load shedding. The summation of all EENS weighted by probabilities of corresponding scenarios is the total EENS of the system.

Taking scenario \(s\) during period \(t\) for example, we calculate the redundant or deficient power of generators according to the realization of them in this scenario as
\[ \mu_{s,t} = \sum_{i \in A_{s,t}} R_{i,t} - \sum_{j \in u_{s,t}} P_{j,t} \] (2-25)

Then, we subtract \( \mu_{s,t} \) from the net demand forecast error \( e_t^d \) to find the total system forecast error for scenario \( s \) as

\[ x_{s,t} = e_t^d - \mu_{s,t} \] (2-26)

Next, the probability distribution of \( x_{s,t} \) is divided into \( NL \) odd number intervals with \( a_{s,t,l} \) as the probability of interval \( l \). The width of each interval is \( \sigma_{t}^d \). The mid-value of each interval is taken as the value of the whole interval. A seven-interval approximation is shown as in Fig. 2-32.

Fig. 2-32. Seven-interval approximation of probability distribution of total system forecast error since we only need the intervals satisfying

Since we only need the intervals satisfying

\[ \left( \frac{NL + 1}{2} - l \right) \sigma_{t}^d - \mu_{s,t} > 0 \] (2-27)

Another binary variable \( b_{s,t,l} \) is introduced to distinguish intervals satisfying the above equation from others. Hence, the EENS in scenario \( s \) during period \( t \) can be formulated as

\[ EENS_{s,t} = \sum_{l=1}^{NL} \left( \left( \frac{NL + 1}{2} - l \right) \sigma_{t}^d - \mu_{s,t} \right) a_{s,t,l} b_{s,t,l} \] (2-28)
Each of these binary variables $b_{s,t,l}$ is associated with one realization of the total system forecast error, such that

$$b_{s,t,l} = \begin{cases} 1 & \text{if } \left(\frac{NL + 1}{2} - l\right)\sigma_t^d - \mu_{s,t} > 0 \\ 0 & \text{otherwise} \end{cases} \quad (2-29)$$

This expression implies that the new binary variable is equal to 1 if and only if the associated realization of total system forecast error falls on the right side of the $f(x)$ axis as in Fig. 2-32. The nonlinear conditional expression of $b_{s,t,l}$ can be recast into an equivalent MILP form by constraints

$$\begin{cases} b_{s,t,l} \leq b_{s,t,l+1} \\ \frac{NL + 1}{2} - \frac{\mu_{s,t}}{\sigma_t^d} > \sum_{l=1}^{\overline{l}} b_l \geq \frac{NL - 1}{2} - \frac{\mu_{s,t}}{\sigma_t^d} \end{cases} \quad (2-30)$$

Finally, the summation of $EENS_{s,t}$ weighted by probabilities of corresponding scenarios is the total EENS of the system during period $t$

$$EENS_t = \sum_{s \in S} EENS_{s,t}p_{s,t} \quad (2-31)$$

Right now, the EENS is formulated as the summation of products of two binary variables and a continuous variable, which can be linearized as reference [7] did.

In the proposed formulation of SCUC, the spinning reserve requirements are determined by simultaneously optimizing the production cost, start-up cost, reserve cost and expected cost of load shedding (ECLS). The ECLS is expressed as the value of lost load (VOLL) multiplied by an approximation of the EENS as developed before. This approach has the advantage of being self-contained in the sense that it does not need another EENS target or spinning reserve constraint because the spinning reserve provision is based on an internal cost/benefit analysis. The objective function of SCUC is stated as

$$\min \left\{ \sum_{t=1}^{T} \left[ \sum_{l=1}^{L} \left[ c_l(u_{i,t}, P_{i,t}) + s_{i,t}(u_{i,t}) + q_{i,t}(R_{i,t}) \right] + EENS_{t} \cdot VOLL_t \right] \right\} \quad (2-32)$$

The objective function must be optimized subject to a number of constraints including power and generation balance, the upper and lower output constraints, minimum up and down time constraints, initial condition constraints and ramp-up and down constraints.

The proposed model is demonstrated on a modified IEEE Reliability Test System [15]. In this system, there are 26 thermal generators and the hydro units have been removed. For simplicity, the unit quadratic cost curves are converted into piece-wise linear cost curves. In order to show
the effect of wind power penetration on the system reliability, we add 6 wind farms, which each has 70 wind generators with capacity 1.5 MW. So, the total wind power capacity is 630 MW, 20.0% of the total conventional generation capacity. In addition, the wind speed forecasting error is set to be a Gaussian distribution with zero mean. The standard deviations fall within the range of 5%~20% in the examples. The model is coded in a MATLAB environment and solved using a MILP solver CPLEX 12.2. With a pre-specified duality gap of 0.5%, the running time is about 180 seconds using a Windows-based PC with 2.66 GHz and 4 G bytes of RAM.

Firstly, we solve the traditional UC maintaining the quantity of spinning reserve as the capacity of the largest generator in the system, which is 400 MW. Using this result, we calculate the EENS. Then, we solve the UC problem again by the proposed SCUC. The comparison of spinning reserve and EENS between traditional and the proposed method are shown in Fig. 2-33.

Fig. 2-33. Comparison of spinning reserve and EENS between proposed and traditional methods
Fig. 2-34. Comparison of generator schedules between proposed and traditional methods

Fig. 2-35. Spinning reserve under different VOLL values

<table>
<thead>
<tr>
<th>VOLL</th>
<th>Spinning Reserve (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2000/MWh</td>
<td></td>
</tr>
<tr>
<td>$4000/MWh</td>
<td></td>
</tr>
<tr>
<td>$6000/MWh</td>
<td></td>
</tr>
<tr>
<td>$8000/MWh</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 2-36. Spinning reserve under different wind speed forecast errors

Fig. 2-37. EENS under different wind speed forecast errors
The comparison of the resulting generator schedules are shown in Fig. 2-34. Then, we try different VOLLs and scaling factors of wind speed forecast error to demonstrate the relationships between them and spinning reserve. The results show the effectiveness of the proposed method. The relationships of uncertainties and required spinning reserves are verified.

References

2.3.2 Probabilistic Simulation Framework for Power Systems with Integrated Renewable, Storage and Demand Response Resources

We have completed the development of the basic framework of a probabilistic simulation approach capable of assessing the economics, reliability and environmental impact of a power system with integrated utility-scale energy storage units, demand response resources (DRRs) and wind/solar resources over longer-term periods. The methodology uses an hour as the smallest indecomposable unit of time and deploys a snapshot representation of the resources and the grid. We use the approach to assess the power system economic performance, capacity to serve the
load and the expected emissions in each hour of the week by clearing the associated transmission-constrained day-ahead market, which involves the solution to an optimal power flow or OPF problem. We have developed models for incorporating the wind/solar resources and the DRRs within the OPF formulation, so that the impacts of such resources on the market outcomes are appropriately represented. The proposed approach thus effectively emulates the dispatch decisions made by the IGO in each transmission-constrained hourly day-ahead energy market. As such, the methodology captures the time-dependent nature of intermittent resources and DRRs, as well as that of storage unit operations in a market environment, subject to the physical constraints imposed by the transmission network. In the approach, we represent explicitly the impacts of various sources of uncertainty, including those in the loads, the availabilities of the controllable supply sources and the variability and intermittency of the renewable resources. The resulting probabilistic models lead to the deployment of Monte Carlo simulation technique to perform the emulation. The approach uses systematic sampling techniques to determine the realizations of wind/solar power outputs, generator availabilities and loads to be used as inputs in the sequence of transmission-constrained hourly day-ahead markets. The samples of inputs for each hourly day-ahead market clearing results in realizations of the market outcomes of interest, such as electricity prices, total payments, congestion rents, reliability measures and CO2 emissions, which are used to construct approximations of the corresponding random variables and the evaluation of the sample means. In this way, we estimate the values of the means of the outcomes of interest for each simulated hour.

We will continue with the development of the effective representation of the storage plant operations scheduling in the hourly transmission-constrained day-ahead markets. In this regard, we plan to develop a methodology for identifying hours of the weeks during which a storage unit should charge, discharge, or remain idle in view of maximizing storage utility with respect to the system social surplus. We will also address the computational tractability issues in the Monte Carlo simulation. Reductions in the computational burden will be investigated by using representative weeks to be simulated and various variance reduction techniques.

Related Contributions
Power system optimization typically involves optimizing dispatches within a time period and also across time periods, as there are intra-temporal and inter-temporal constraints. As the penetration of renewable increases, the complexity of dispatch will increase significantly due to the variability of renewable resources, such as wind velocity. As a result, it is of interest to design simpler and yet more efficient and powerful algorithms for optimizing conventional system and renewable resources.

To address this need, we have developed a simultaneous perturbation approach embedded in the Lagrange relaxation (LR) approach [1-2]. A traditional iterative solution for the LR method would most likely be based on a gradient search approach or a pairwise adjustment scheme. The proposed simultaneous perturbation procedure provides a much faster converging solution to the LR method. The proposed iterative method not only takes into account the inter-temporal constraints of available resources over multiple time periods, but also simultaneously the intra-temporal economic dispatch. For optimization problems with quadratic fuel costs, linear resource constraints, and no losses, the LR perturbation method arrives at the exact solution in one step.

References
2.4 Transmission Grid Management and Operation

The transmission system of the future requires significant conceptual rethinking and physical reinforcement. The variability of renewable resources requires careful planning to avoid under utilization of transmission assets. In this task, we are investigating solutions for the transmission system to become more flexible. One objective of the transmission grid management and operation task is to assess the current grid’s ability to manage large amount of concentrated or distributed renewable resources with large amount of storages under normal daily operations and under sudden changes in the power flow associated with intermittent resources, such as shifting wind and isolation conditions. An important issue is assessing the state of the system through improved monitoring. As the system changes, violations of operating constraints must be quickly assessed. We are developing methods that address modeling issues as well as the use of phasor measurements to track grid topology changes and locate faults. A challenge to successful expansion of the grid is appropriate translation of the short-term market signals provided by the locational marginal prices or LMPs into long-term transmission investment signals. We are investigating methods to properly incentivize investments. We also are looking at expanding capacity through strategic use of power electronics.

2.4.1 Application of PMUs in Transmission Operations

Operation of the existing power grids is rapidly going through major changes due to the widespread deployment of synchronized measurement systems. These systems provide unprecedented advantages in wide-area monitoring of power grids due to the availability of synchronization among measurements at geographically remote parts of the system. So far, most of the investigations have focused on the use of synchronized measurements to improve applications, which require monitoring and control actions at relatively slow rates, i.e., slow enough to make treatment of slowly changing system conditions via phasors, which implicitly assume steady-state operation.

While effectiveness and benefits of synchronized measurements have been well documented for such applications, other applications requiring monitoring of the system conditions at a much shorter time span have not yet been fully explored. One of the challenges in secure and reliable operation of power grids is to rapidly detect, identify, and isolate faults, which occur due to unexpected equipment failures, lightning storms, accidental short circuits, etc. Such faults can cause significant damage if not cleared in a matter of fractions of a second. Hence, power grid protection systems have so far been designed as control systems that used local measurements as decision variables. In this regard, power transmission grids would fully exploit the potential of synchronized nature of the sampled voltage and current signals and the capability to access these synchronized values via system-wide communication infrastructure, enabling accurate and fast methods of fault location and removal.

This investigation aims to illustrate the use of “raw” synchronized measurements for a practical application, namely, for fault location. Many transmission grids do not have synchronized measurements at every bus, but at only a few selected buses. It is shown that it is possible to
locate faults accurately and reliably by using these few strategically located synchronized measurements. The broader impact will be a reduction in the duration of service interruptions, and consequently reduced loss of revenues for the industry and higher reliability for operation of transmission grids.

IEEE 30-bus test system whose one-line diagram is shown in Fig. 2-38 is used to illustrate the developed fault location algorithm [1]. Synchronized sensors are assumed to be placed at buses 1, 3, 5, 8, 11, 13, 14, 17, 18, 21, 26, 29, 30. A fault is simulated at 28 miles away from bus 10 on a 65-mile-long transmission line connecting buses 10 and 20. Aerial-mode wavelet transform coefficients (WTC) for each modal voltage are calculated. Four of these voltage measurements as well as the corresponding squared WTC waveforms of the aerial-mode voltages are shown in Fig. 2-39. Application of the developed algorithm accurately identifies the fault at 27.99 miles from bus 10. More examples and details of the algorithm development can be found in [1].
The fault location approach described above is extended to develop a method to optimally place these time-synchronized measurements in order to achieve fault-location observability over the entire transmission grid. The concept of fault-location observability refers to the unique localizability of any fault-occurrence point in a power grid using a set of readily deployed fault-recording devices. In general, a system is regarded as “fault-observable” if any fault occurring in the system can be uniquely located using the available set of measurements. Otherwise, the system is said to be “fault unobservable”. Those line segments which are constituted by points whose faults cannot be uniquely identified will be referred as “fault unobservable” line segments. Given the substation locations of the synchronized sensors, the analysis of determining fault observable and unobservable segments of the network lines will be referred as fault-location observability analysis. An optimal strategy for placing synchronized measurements in order to make the system fault-observable is developed. Developed strategy is applied to the IEEE 30-bus system shown above. The resulting locations of synchronized sensors are shown in Fig. 2-40. Details of the strategy and the associated optimization problem can be found in [2].

The successful performance of the existing fault-location algorithms is contingent upon the availability of accurate measurements. However, the reality is that the measurements are prone to errors, which may be caused by data conversion abnormalities, communication delays, sensor de-synchronization, etc. If the set of measurements involves large errors, the accuracy of devised fault-location methods may substantially be deteriorated. Therefore, it is of paramount importance to develop a fault-location scheme that is capable of successfully handling bad measurements.
In order to identify and subsequently eliminate bad sensor measurements, we utilize the test known as Largest Normalized Residual Test, steps of which are presented in the paper [3]. Synchronized measurement equations are set up and measurement errors are assumed to have a normal distribution with known variances and zero mean. Simulation results illustrating the performance of the bad measurement detection and identification can be found in [3].

The problem of tracking topology changes in the external network model has long been under investigation due to its impact on real time contingency analysis, an important application for maintaining system security. Our preliminary work uses an approach which can track line outages based on the real-time measurements from the internal system and GPS synchronized phasor data from the external system. The formulation of the problem uses the equivalent injection representation of line outages and converts the problem into an equivalent problem of tracking changes in injection pairs in the external system. An optimization problem can be set up in order to identify the most probable pair of injection changes. This is done by minimizing a norm of the difference between the observed and estimated signature of changes in injection pairs from the external system on the internal system real-time model. Simulated scenarios have shown that the approach may be useful when measurement scan rates are relatively faster than the rate at which the system load changes [4].

Related Contributions
We are initiating new work on the topic of evaluating and quantifying errors in PMU data. This includes monitoring measurement sensor error, device computation error, and communication transmission system error to determine the origins and scope of typical data error. We are pursuing cooperation with industry to obtain actual data at all stages of collection and concentration for use in EMS software. The goals are to: gain a fundamental understanding of phasor measurement challenges; characterize synchrophasor data quality (error, availability, reliability); identify methods for detecting and correcting faulty synchrophasor data; attribute defective synchrophasor data to synchrophasor data generation failure at the measurement site, losses in the data transmission process, or data processing errors at intermediate or final data storage locations.
References


2.4.2 Transmission System Adequacy Considerations

One of the biggest barriers to the deepening penetration of renewable resources is the state of today’s transmission grid. The grid was planned and built by utilities to connect the distant generation sources to the load centers so as to meet their customers’ demands reliably and efficiently. In the competitive environment of today, the legacy transmission grid is used to meet the open access transmission service requirements promulgated in various FERC orders since 1996 and so as to provide, in effect, “common carrier” transmission services. As the grid was designed for different purposes, its adequacy for the new role requires its expansion and modernization. Unfortunately, the lack of progress in the expansion and modernization of the grid has resulted in the creation of long queues of planned generation sources, including many renewable resource projects, with tens of thousands of planned MW capacity requesting interconnection into the network. FERC Order No. 1000 explicitly recognizes that transmission must be built in order to meet the needs of integration of the renewable generation sources. In light of the critical role of transmission in the integration of the deepening penetration of renewable resources, we are studying the key issues that need to be addressed in the expansion/upgrade of today’s transmission grid.

We have initiated a thorough analysis of the major impediments to the progress needed toward the creation of transmission resource adequacy for improving the ability to allow the timely integration of renewable resources to meet current and future electricity demands. The transmission planning problem has become in today’s environment a transmission investment problem. There is a major difficulty in the appropriate translation of the short-term market signals provided by the locational marginal prices or LMPs into long-term transmission investment signals. This reality complicates the complex cost allocation issues that must be resolved before any transmission expansion plans may be implemented. The transmission investors require a predictable stream of revenues for undertaking the required expenditures for the expansion projects. Thus, the need to develop regulatorily acceptable cost allocation methods that can also make transmission expansion projects attractive to investors is a major issue. We are analyzing the provisions of the FERC Order No. 1000 to create the incentives for transmission expansion and comparing them to those in use in the European Community. We continue with the investigation of the ability of the FERC Order No. 1000 to provide the “blueprint” for developing adequate conditions for the transmission buildout to occur. A particular area we will focus on is the creation of appropriate incentives. We will analyze past successes in the development of effective strategies implemented to integrate the renewable resources into the grid.
The transmission grid can also be reinforced with power-electronics based Flexible AC Transmission Systems (FACTS), without building new transmission lines. As more of these controllers are being built, the coordination of such controllers becomes important, in order to maximize their system benefits, such as power transfer. In [1], a dispatch system built on a mixed-integer programming approach to coordinate three separate shunt FACTS controllers (static var compensators (SVC)/static synchronous compensators (STATCOM)) located in a large city was described. In the next stage of this research, we intend to incorporate the simultaneous perturbation method the FACTS controller coordination problem, to provide more realistic dispatch with variable renewable resources.

References

2.5 Test and Verification
The control concepts developed in the tasks reported on sections 2.1-2.4 will be demonstrated in realistic power systems with various characteristics such as mix of renewable and non-renewable generation, locations of renewables, transmission system support, storage, loads, grid dispatch systems, power markets, communication infrastructure, and load management strategies. Scenarios will be developed for each system to test the efficacy of the proposed control methods and strategies. In terms of the task time line, these efforts need to follow on the other tasks and more effort will be placed on later years in the contract. Initial efforts have focused on improving the simulation tools, visualization of the system performance and meaningful assessment of the performance.

2.5.1 Improved Simulation Modeling to Support the Adoption of Sustainable Energy
Models of the electric power grids that cover the contiguous United States (eastern, western, and Texas) are important for achieving high penetration by environmentally sustainable energy technologies, for several reasons. First, such models can be used to estimate the effects of operational changes (including rate design changes) that may significantly help accommodate sustainable energy, such as those under development in this GCEP project. Doing so will help decide which operational changes are worthwhile and which are best. Second, such models can be used to show that the system can accommodate high penetration by such technologies in spite of the high local variability of wind and solar power. Third, if such models include the environmental costs of power generation (regional mortality, morbidity, and damages to natural resources, as well as damages from greenhouse gas emissions), they can show that environmentally sustainable energy technologies are the lowest-cost options. The environmental costs of power generation are real costs and are estimated to be large relative to the internal costs (construction, fuel, etc). For example, the estimated average mortality cost of just one pollutant, fine airborne particulate matter, is 3.2 or 9.6 cents per kilowatt-hour from US coal plants, depending on which estimated relationship between pollution and death rate one uses (National Research Council, The Hidden Cost of Energy, National Academies Press, 2010). By comparison, the average price of generation in the US in 2010, reflecting direct costs, was approximately 4.6 cents (Energy Information Administration, Today in Energy, March 4, 2011, accessed April 15, 2011 at http://205.254.135.7/todayinenergy/detail.cfm?id=370).

If models such as those described in the preceding paragraph were free or affordable, their use could be widespread. They could be used by governments, utilities, regional system operators,
academics, consultants, project developers, environmental groups, and other citizens’ groups to estimate the effects of proposed projects and their alternatives in a way that includes the environmental benefits of sustainable energy options and the ability of the grid to accommodate them. However, currently no suitable model exists. No model combines an electrical grid model with the damages from emissions, which vary greatly according to where those emissions occur. Additionally, no model combines an electrical grid model with the ability to predict future generation investment. That ability is essential for predicting the long-term effects of operational changes, sustainable energy policies, and sustainable energy investments. As a result, we are building such a model. It will have the additional advantages of being open-source rather and being either free or having a much lower cost than existing models (if the user prefers the highest-quality input data and some of it is not available to us or anyone else from public sources).

The development of these models is jointly supported by GCEP and the Center for Electric Reliability Technology Solutions of the US Department of Energy. The GCEP support is enabling us to include the crucially important health effects of generation technologies in the models. This involves several steps. First, we have obtained the proprietary estimated air pollution “transfer coefficients” that describe how much a ton of a pollutant emitted in one county increases the annual average concentration of fine airborne particulate matter in each county of the United States. There is one set of these for each combination of emission type (nitrogen oxides, sulfur dioxide, and directly emitted fine particulate matter) and smokestack height category. Second, we have also secured permission to share these, free of charge, with users of our model. Third, we are in the process of statistically extrapolating the missing transfer coefficients, such as those into, out of, and within Canada, and those from new US smokestacks not included in the provided set of transfer coefficients. Fourth, we have developed the method and software for using the transfer coefficients to calculate the estimated environmental cost per kilowatt-hour of each electric generation unit in the US and Canada. Fifth, we have begun to demonstrate the uses of the new modeling capabilities we are developing, as described below.

While we develop detailed models of the eastern, western, and Texas grids, we have begun demonstrating the new modeling capabilities by using a 36-node model of the northeast power grid, for upcoming journal submission. Fig. 2-41 below shows the estimated reduction in premature deaths per year under five scenarios, relative to the status quo. The red line shows the effect of charging each generation unit for its environmental damages (marginal damages or “MD”), taking into account its emission rate, smokestack height, and location. Figure 2-42 shows that this policy, which does not target carbon dioxide emissions, significantly reduces carbon dioxide emissions as a co-benefit. Figure 2-43 shows that it has these effects with little impact on the price of electricity.

Such models can be used to estimate the effects of operational changes that may significantly help accommodate sustainable energy, can be used to show that the system can accommodate high penetration by such technologies in spite of the high local variability of wind and solar power, and can show that environmentally sustainable energy technologies are the lowest-cost options once a more complete set of costs is included.
Fig. 2-41. Expected Number of Lives Saved Per Year Compared to the Base Case

Fig. 2-42. CO₂ Emissions Under Eight Scenarios
2.5.2 System Studies and Visualization

We have been working on developing equivalent models for system dynamic studies. The goal of the work has been to study frequency disturbance propagation in greater detail, and understand system level interactions with the use of equivalent models/small test cases to study post-fault dynamic behavior. The three key transient characteristics of interest are: (i) time delay of disturbance propagation, (ii) magnitude of maximum frequency deviation, and (iii) primary frequency response (i.e. governor response). A high penetration level of renewables will alter these three features. As a result, smaller power imbalances will cause larger frequency deviations, and new tools will be needed to access dynamic behavior of grid conditions.

On power system visualization an important challenge is how best to display time-varying information. Most techniques currently used display information at a single snapshot in time. Techniques such as contouring are useful for showing the current state of the system, but often these are insufficient to show the trends. Time-sequence animations can be used to show how a particular display has changed over a user specified time period but this requires time to see the display, so it cannot provide results at a glance. In this project, we have addressed the use of “spark-lines” to display time varying power system data. Another topic at the forefront of the electric power industry today is the need for advanced data analysis techniques for power system data. Methods need to be developed to deal with large volumes of power system operational data, typically collected by SCADA systems and more recently by PMUs. There is an immediate need for dedicated algorithms to extract useful information contained in a large data-set. In this
project we have also developed algorithms that can reduce the dimensions of a data set by identifying distinct patterns in a time varying data set. Groups of data points with similar patterns can be replaced by a representative data point depending on the application. We have applied the developed algorithms on transient stability run results on a simulated model of the WECC system.

### 2.5.3 Evaluation of Existing Transmission Systems to Handle 50% Renewable Penetration

We have been working on studying the impact of deep penetration of renewable-based electricity generation resources on power system performance. Since these resources are intermittent, variable, and difficult to forecast accurately, they introduce additional sources of uncertainty to power systems. This presents notable challenges in system operations across different time-scales---from day-ahead scheduling to automatic generation control. Furthermore, since renewable resources vary in rated power output and point of grid interconnection, they affect power systems at different voltage levels---from transmission to distribution. For example, wind farms are usually connected at the transmission level, whereas small-scale solar installations are usually connected at the distribution level. The focus of the work during the last year has been on the development of analysis tools to understand the impact of renewable-based generation on power system static performance. Specifically, we have developed an analytically tractable method to assess whether system static state variables, i.e., bus voltage magnitudes and angles, remain within acceptable ranges for all possible electric power generation profiles arising from renewable-based electricity sources.

In our methodology, uncertain variations in renewable-based generation can be viewed as forecast error, which can be bounded around the nominal forecast (this method is adopted by some system operators, e.g., BPA, to account for uncertainty in wind-based power). For example, the power produced by a wind power plant can be assumed to lie within some interval around a nominal power output value, which may be based on forecasted wind speed. Then, the set of all renewable-based power generation profiles can be described by a parallelootope (i.e., the generalization of a parallelepiped in three dimensions to any higher dimension). This parallelootope is then bounded by the intersection of a family of ellipsoids, each of which is tight to the parallelootope in a particular direction. Using set operations, each of these ellipsoids is propagated through a model of the power system, which is obtained by linearizing the nonlinear power flow equations. The result is a family of ellipsoids, each of which bounds the bus voltage magnitudes and angles. The intersection of this family of ellipsoids approximates the set that describes all bus magnitude and angle realizations arising from all possible (uncertain) power generation profiles. To determine whether renewable-based power generation variability has a significant impact on the power system static performance, we verify that the intersection of this family of ellipsoids is contained within the region of the static state space defined by system operational requirements, e.g., minimum and maximum bus voltage values.
Project Supported Artefacts

Publications


Patents
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