2019 Electricity Industry Technology and Practices Innovation Challenge

Winners' Abstracts

Southern California Edison (Tier I, Gold)

Submission Title: Machine Virtualization in the Bulk Power System

Abstract: As the electric industry undergoes dramatic transformation, California is at the forefront, continuing to take a leadership role in addressing climate change and air pollution while driving disruptive technologies. This has resulted in aggressive clean energy policies as well as innovations to create a more flexible and efficient power grid.

In this new energy paradigm, Southern California Edison (SCE) is on a journey to develop an electric grid that increases reliability and supports the transition to a clean and sustainable energy future. We are continually reviewing our operations, identifying opportunities to improve existing practices, and leveraging new and emerging energy technologies to strengthen and modernize the grid.

One technology that offers tremendous promise for increased grid reliability and system resilience is machine virtualization in the bulk power system (BPS).

BPS Challenges

A BPS is a large interconnected electrical system comprised of generation and transmission facilities and their control systems. A critical component of this system is the substation, which steps down high voltage electricity from the transmission system to lower voltage electricity so it can be supplied to customers through distribution lines.

Each substation has a control room that houses various components, such as protection relays and automation (P&A) devices. Relays contain secondary voltage and current inputs to protect the power system from abnormal system faults while automation devices automatically restore power to the grid.

Traditional P&A systems, which have long relied on proprietary hardware, have been reliable, but there are considerable challenges with their operation. They currently face high construction costs and long deployment times due to the hard-wired connections and trenching required to terminate and route wires to these P&A devices.

A single substation consists of thousands of wires and terminations, and a control room must be large enough to accommodate this equipment and perform safe cable terminations and maintenance. Modifications to these systems can also result in long and costly scheduled outages as a result of the complex relay connections and wiring. In addition, their design makes it difficult to assess threats and weaknesses and comply with future regulatory and cybersecurity requirements.

Furthermore, the maintenance of these systems is largely a manual process, which drives the need to explore new ways to automate and alert when device failure is approaching. When devices fail, it can be expensive and time-consuming to upgrade them with the latest technology, so the short-term solution is to retain legacy technology. Unfortunately, this patchwork approach does not promote a more reliable and resilient grid.

U.S. DEPARTMENT OF ENERGY | OFFICE OF ELECTRICITY

Machine Virtualization

Traditional P&A systems are inflexible, but with technological advancements, there is an opportunity for change through machine virtualization.

Machine virtualization simulates physical hardware devices in a software environment. Now commonplace in IT enterprise and data center environments, machine virtualization can simplify P&A systems and solve their current challenges.

A key component of the virtualized P&A environment is IEC-61850, the international standard for substation automation systems. IEC-61850 enables the integration of all protection, control, measurement, and monitoring functions within a power system network at the field or process and station control levels. It is an open standard accepted overseas and gaining widespread acceptance in the U.S.

Traditional relays contain hardwired current, voltage, contact inputs, and outputs. Virtualization using IEC-61850 offers a simplified electrical design layout, allowing relays to accept these inputs via a digital network interface and perform the analog and binary to digital conversion.

Our innovation involves a cluster of two or more redundant servers that contain virtual relays, Human Machine Interfaces (HMIs), which are widely used in manufacturing, and programmable logic controllers (PLCs), often employed to monitor and control processes and systems.

Each cluster has network interface to connect to both the station and process bus networks. The former contains controls for opening and closing breakers and analog information from power lines, such as currents and voltages, and the latter has IEC-61850 sampled values (SV) and generic object-oriented substation event (GOOSE), a mechanism to transmit substation events, including commands and alarms.

Among the benefits of incorporating this technology in substations: reduced overall costs, including hardware, installation, engineering, and maintenance; fewer wiring and terminations, which minimize electrical hazards; server redundancy; automated self-monitoring and alerting; and enhanced cybersecurity.

In addition, transitioning relays and automation devices to virtual ones would decrease the number of relay racks in the control room, thereby reducing the footprint. The time required to design these systems would also be shortened as wire connections are replaced with network fiber connections. Failure or replacement of devices would require minimal design changes, as the relays are virtual, requiring no wiring or changes to relay rack design.

Virtualization technology offers efficiencies by making use of existing IT methods, including automated backups and remote configuration downloads. Updates can be made remotely through software rather than physical changes, reducing the need to send personnel to substations for maintenance and troubleshooting.

With more components in a virtualized environment, electric utilities can have far greater monitoring capabilities, leading to greater situational awareness and self-diagnostics than currently available.

Potential Impact

Machine virtualization in the bulk power system can have a major impact on electric utilities' operations. The technology offers a more flexible, cost-effective, and lasting solution to a long-standing problem with P&A devices. By using standard IT practices, these systems become more redundant, more automated with system and device backups, and more stable with minimal physical engineering.

The potential for machine virtualization in the bulk power system is strong. SCE recently migrated to the IEC-61850 standard, which further makes this innovation more feasible. Additionally, we are collaborating with a vendor to develop a design specification and have begun discussions with various utilities and vendors to promote our idea. We are also piloting our first IEC-61850 process bus project and working on designing a full digital substation.

Through our work to date, we have found there is keen interest in the industry toward moving away from today's hard-wired, traditional substation architecture to a virtualized one.

George Washington University (Tier I, Silver)

Submission Title: Smart Measurement Units for Online Situational Awareness in Power Grids

Abstract: With the increasing trend in deployment of sensors in mission-critical cyber-physical power grids and a widespread interest in best utilizing the streamed data for online situational awareness, there exists an urgent need to equip the network protection and control functions with robust high-fidelity, high-resolution algorithms for online monitoring and threat detection. Following the catastrophic Northeastern U.S. blackout in 2003, the American Recovery and Reinvestment Act (Recovery Act) of 2009 supported $4.5 billion for the Smart Grid Investment Grant (SGIG), Smart Grid Demonstration Program (SGDP), and several other U.S. Department of Energy (DOE) smart grid initiatives, which offered a new impetus for the development of advanced sensors and monitoring infrastructure facilitated by synchrophasor technology. Since synchrophasor technology was introduced, developed, and now deeply integrated into the electric power systems, it revealed significant advantages and improvements in power grid monitoring and control, early-stage detection of the network abnormalities and violations, as well as the enhanced security, reliability, and stability of the system. Such improvements can be mainly attributed to its ability in providing high-resolution, time-synchronized measurements.

The existing technology, i.e., the synchrophasor technology through Phasor Measurement Unit (PMU) sensors located in power substations, measure the voltage and current phasors continuously and report them to the control centers through communication channels. The control center applications then utilize such data to analyze and monitor the power grid and to make informed decisions. This current practice heavily relies on the accurate synchrophasor measurements from the PMU sensors; these outputs are obtained from synchrophasor estimation algorithms (SEAs), which are primarily driven by mathematical approximations. In most cases, and irrespective of the focused application, marketplace PMUs are typically furnished with "only one" SEA tool, each unleashing distinctive advantages and limitations, solely valid in one or a few certain applications. Typically, the waveforms fed into PMUs have variant behaviors; for instance, phasor magnitudes and phase angles go through step changes during faults, and the waveform measurements could be noisy. Besides, unbalanced load, voltage surge or sag, harmonics, and frequency drift are also common phenomena in electrical power networks. Laboratory tests and field observations have revealed how inefficient the PMU measurements could be, if this "one-size-fits-all" SEA is applied to capture both static and dynamic features and peculiarities, when facing different operating states in the grid. To meet the growing demand for high-speed, low-latency, and yet absolutely accurate measurements in PMUs, a more efficient mechanism that provides online event detection and assists selecting the right SEA at the right time is desired. Moreover, the current measurement and monitoring practice relies on reliable and secure communication gateways: if the communication channels are lost (due to failures or attacks) or have delays, then the control center analytics and application trustworthiness will be compromised or will be attributed a latency.

Going beyond the traditional measurement settings and the existing monitoring technologies, we propose a paradigm shift for advanced observability (event detection, event classification, and measurements) in power grids by adding levels of smartness in the existing sensors or having it as a stand-alone measurement units for deployment, i.e., "smart measurement units." The project's principle objective is to develop an innovative hardware and software tool set for online surveillance of power systems. We focus on the online event detection, classification, and decision-making in power systems using big data analytics and advanced machine learning

technologies within the distributed smart measurement units. Within these units, we introduce (i) advanced sensor-embedded signal processing analytics for online feature extraction and pattern recognitions on the inputted signals; (ii) machine learning analytics that get the extracted features and perform an accurate event detection and classification, and (iii) an estimation mechanism that adaptively select an appropriate SEA based on the detected events to achieve higher phasor measurement accuracy in the face of various operating conditions in the grid.

Our experiments demonstrate that the proposed analytical solution achieves high accuracy for real-time event classification and phasor measurements, outperforming the existing technologies with at least an order of magnitude higher accuracy. The proposed smart measurement unit is equipped with a suite of advanced analytics distributed and much closer to where the data is generated and measurements are captured, i.e., at the substations and embedded within the units. This solution makes it possible to achieve an online surveillance, observability, and monitoring of the distributed sections of the grid or the large-scale power grid in real-time and with minimum latency (if they communicate), as it is less susceptible to communication failures and vulnerabilities. Our proposed smart measurement unit is featured with the following key advantages: (i) online observability (event detection and classification) in power grids of different sizes and characteristics; (ii) online detection of almost all fast- and slow-dynamic events that can happen in power grids (different types of faults—e.g., single-line-to-ground, three-phase, double-line-to-ground—surges, voltage sags, power swings, load changes, topology changes, rare events, etc.); (iii) more accurate and adaptive synchrophasor measurements in different operating conditions; (iv) analytics designed in such a way that can work either in a stand-alone device or embedded within the existing sensors in power grids (meeting interoperability requirements) and can be achieved with minimum additional cost.

Minimizing the disastrous consequences and maximizing the resilience to emergencies, this undertaking is essential since disruptive events are expected to be more frequently realized in power grids with potential to result in hundreds of billions of dollars in annual costs. Therefore, even modest improvements in situational awareness, monitoring, resilience, and recovery efficiency in power grids could lead to sizeable monetary savings and an enriched social welfare.

University of Houston (Tier I, Silver)

Submission Title: Enhancing Energy Management System With Stochastic Optimization, Flexible Transmission, and Responsive Networked Microgrids

Abstract: Electric power must be produced, transferred, and consumed at the same time. This creates serious challenges for real-time operations of electric power systems. Thus, energy management systems (EMS) are used to help system operators monitor, manage, and optimize power system real-time operations. However, existing EMSs do not model and utilize the flexibility in the transmission network. In addition, current deterministic optimization-based dispatching strategy is inefficient to accommodate high penetration of variable renewable generation in the grid; today's control framework is unable to monitor and manage behind-the-meter distributed renewables. Therefore, this idea proposes a practical EMS upgrade strategy that can overcome these hurdles and operate future renewable power systems efficiently and reliably; the proposed EMS procedure requires minimal changes to existing operational tools.

Though various types of generation reserves are enforced in the dispatching application, system N-1 reliability is not guaranteed. Additionally, reserve deliverability may be restricted by network congestion. Thus, independent system operators (ISOs) conduct real-time contingency analysis (RTCA) successively every few minutes and identify the critical contingencies that may cause network violations, which are used to determine the network constraints that will be included in security-constrained economic dispatch (SCED). Then, SCED will execute to eliminate those potential violations. Both RTCA and SCED are key modules of EMS. This idea will first develop an RTCA-based SCED that is consistent with industrial practice. The RTCA is based on full AC power flow model, while SCED is based on the simplified DC power flow model. The proposed model conversion scheme will seamlessly connect AC RTCA and DC SCED.

Network congestion is a key factor affecting system reliability and operational efficiency. It prevents low-cost units from producing cheap power; it is also a major obstacle to reserve sharing and deliverability between different areas. Thus, it is very important to develop advanced techniques to relieve network congestion. Although prior efforts show flexible transmission can provide various benefits including violation reduction and congestion mitigation, the flexibility in the transmission network is not modeled and utilized in existing EMSs. In addition, the effectiveness of flexible transmission has not been demonstrated in a complete EMS procedure. To bridge this gap, this idea proposes an enhanced EMS procedure that can practically incorporate flexible transmission into current EMSs without any major changes. The proposed EMS procedure enables RTCA-based SCED to utilize the flexibility in the transmission network and achieve reliability enhancement and operational efficiency improvement. Most previous studies on flexible transmission target at a single application only; the proposed EMS procedure can utilize flexible transmission for a suite of coordinated EMS applications. This idea will develop a systematic decision support function that can be smoothly integrated into current EMSs to help operators make the optimal switching decision.

Existing SCED functions are based on deterministic optimization that uses a simple "point forecast" and assumes the netload is "deterministic," which is ineffective to address the system uncertainty associated with load fluctuation and intermittent renewable generation. Though deterministic SCED is relatively easy to solve due to moderate computational complexity, it may

fail to provide quality solutions when forecasting errors are large. Moreover, significant growth of renewable penetration level introduces a great amount of uncertainty and worsens the inefficiency of existing “deterministic” dispatching paradigm, which poses serious risks on grid reliability. It is envisaged that a “stochastic” dispatching paradigm is necessary to efficiently utilize renewables and reliably facilitate their grid integration. Thus, this idea will develop a stochastic SCED model that leverages probabilistic information and co-optimizes energy and reserve; and it will be compatible with the proposed enhanced EMS procedures. Stochastic optimization algorithms will be constructed to decompose the original intractable stochastic SCED problem into multiple trivial deterministic SCED sub-problems that can be solved independently and simultaneously.

There has been an explosive growth of distributed energy resources (DERs). High penetration of variable DERs that are not monitored and controlled by system operators will substantially increase the system uncertainty, which challenges grid reliable operations. Though upgrading SCED from deterministic optimization to stochastic optimization can accommodate grid integration of utility-scale renewables, it cannot address the impact of high penetration of behind-the-meter distributed renewables on system reliability. It is impossible for the system operator to directly monitor and manage hundreds of thousands of DERs that widely spread over the entire network; thus, it would be practical to develop a hierarchical framework that includes an intermediate layer between the system operator and DERs. Since networked microgrids that reside at the load pocket can manage distributed renewables along with other types of DERs, they can serve as the DER aggregator at the intermediate layer.

The considerable growth of DERs results in a surge of interest in microgrid. With effective energy management schemes, a microgrid can dispatch its own resources with least cost while being able to keep the netload constant during a SCED period. By maintaining the microgrid netload constant, it will not cause negative impact on the bulk power system, and grid operators will no longer need to worry about the variable distributed renewables within the microgrid. This will significantly relieve the computational complexity of the bulk power system dispatching problem and thus, it can enhance system reliability and improve operational efficiency. This idea proposes a novel energy management strategy for networked microgrids so that they can operate as grid-friendly controllable and responsive loads from the perspective of bulk power systems.

With effective coordination between the bulk power system and networked microgrids, the impact of variable distributed renewables on system reliability can be relieved; moreover, the aggregated DERs via networked microgrid can provide grid services to support grid reliable operations. The proposed hierarchical framework is effective in managing and utilizing DERs to achieve real-time power balancing. Moreover, the proposed hierarchical framework is compatible with flexible transmission and stochastic SCED. To conclude, this idea can substantially enhance EMS with stochastic optimization, flexible transmission, and responsive networked microgrids, which will significantly improve system reliability and operational efficiency.

Siemens Corporation (Tier I, Bronze)

Submission Title: A Digital Companion to Ensure Grid Stability Challenged by Increasing Green Technologies

Abstract: Eleven percent of the energy consumed in the U.S. came from renewable energy sources in 2017. Two hundred thirty-four thousand electric vehicles and 3.3 million hybrid vehicles are currently in use in the U.S. The raising numbers of renewable energy sources for electric power generation and electric vehicles for electric power consumption increase the volatility for the electric grid. These facts call for a system that will support grid operators and grid users to keep the electrical grid stable. The electric grid needs to be in balance at all time in order to ensure uninterrupted service.

This document proposes a Green Technologies Digital Companion that combines semantic technologies, machine learning, and augmented reality. This will provide grid operators with all available data, information, and derived knowledge about the grid's status. Grid operators will be able to focus on grid stability while counteracting the volatility introduced by a raising number of renewable energy sources and electric vehicles. The Green Technologies Digital Companion will use different information sources such as smart meter data, weather updates, event information, and charging infrastructure. The results of collecting and combining different data sources through semantic technologies, the application of different machine learning technologies for prediction of imbalance, and the suggestion of charging controls will enable grid operators and consumers to keep the grid stable. Through this approach, the prediction results will be displayed in an operator's field of view. Critical predictions and mitigation plans could be simulated on a virtual map, and different solution scenarios could be tested. Furthermore, the system could communicate with a consumer app and suggest or tell electric vehicle users where, when, and how to charge their electric vehicles.

The combination of operator and consumer app will ensure a reliable and resilient grid. The proposed Green Technologies Digital Companion builds upon a previous research project funded by the California Energy Commission called Developing a Distribution Substation Management System (Grant Number EPC-15-046), in which a dashboard for the management and control of future secondary substations was created.

International Business and Technology Service Corporation (Tier II, Gold)

Submission Title: Remote Sensing Technology for Situational Awareness of the Grid

Abstract: International Business and Technology Service Corporation (IBT) in collaboration with Magnetic and Spintronic Sensor Group at the University of Nebraska, Lincoln (UNL), is pleased to submit: Remote Sensing Technology for Situational Awareness of the Grid, to participate in the U.S. Department of Energy (DOE), Electricity Industry Technology and Practices Innovation Challenge (EITPIC), tier 2 competition.

We are pleased to demonstrate the feasibility of remote sensing for grid (RemG) technology as a new sensing technology option to complement existing sensing technologies, transform the U.S. grid, and help to bring Grid Modernization Initiative (GMI) to a new level.

The key technical metrics that impact bulk power system (BPS) include:

1. High accuracy: RemG has very high sensitivity and good linearity, with field sensitivity at three orders of magnitude higher than the existing technology most utilized in the field.
2. Low cost: RemG provides ultimately the lowest cost, in terms of installation, operation, and maintenance. This significant reduction of cost enables a much higher number of sensing devices to be use for BPS, particularly when installing in existing facilities.
3. Safety: RemG installation, operation, and maintenance are not in contact with Grid facilities, and do not interfere with the Grid operations, providing a unique benefit for safety. Additionally, this allows continuous monitoring, even in emergency situations, further improving safety during emergency response and repair.
4. Low/no latency and high sampling rate: RemG sensor latency is less than 1 ns, and a sampling rate well exceeding 100 MHz can be achieved. RemG is suitable to monitor Grid current waveform (with sampling rate at kHz or 10s of kHz) and monitor generator or wind turbine operation (with sampling rate at MHz as needed).
5. Remote sensing: RemG provides measurement results while placed in a meter away from the facilities or devices. It is able to continuously provide data on the condition of operation. This enables both real-time decision and offline big data analytics and optimization study for the Grid.
6. Small size, weight, and power consumption: The total weight and size for the RemG sensing module is projected to be the size of a fingernail, with a sensor size less than 0.01 cm3 and power consumption less than 3 mW demonstrated.
7. Large dynamic range: RemG is able to measure remote current from 1 to 10,000 A. Short damage to the Grid line or lightening will not cause damage to the RemG sensor or its operation.
8. Large temperature range and suitable for harsh environment: RemG can operate between 60 to 150 degrees Celsius.
9. Long lifetime and high reliability: The projected sensor lifetime is very long and the failure rate is very small, at the ppm level per year. The technology has a low failure rate, and maintenance and replacement cost is much lower than the conventional approach.

RemG is the fundamental technology for sensing, which provides critical information for the Grid facilities, enabling situational awareness to reach a new level. The implementation of RemG will have broad impact to several areas of interest in this competition. Some of the applications are:

1. RemG can be utilized to monitor BPS facilities, such as power generation and transmission facilities, wind turbines, and generators.
2. RemG can be embedded into existing devices (such as in PMU or micro-PMU) to provide accurate measures of Grid condition.
3. RemG technology can be used to build a stand-alone device by adding energy supply and communication modules.
4. RemG can be utilized to monitor transmission Grid condition (primarily Grid lines) and serve as power monitor.

RemG is an innovative technology. The device-sensing element is based on modern MTJ spintronic sensors, and its manufacture processes use highly optimized, state-of-the-art magnetic and semi-conductor wafer processes. The design and integration include advanced signal processing, advanced characterization, and data analytics algorithms, as well as noise reduction, damage protection, and reliability improvement features. RemG is a transformative technology. RemG remote sensing provides a new dimension to be considered in terms of application. RemG is complementary to existing sensing technologies that were utilized and implemented in the field, allowing quick adoption and retrofit into existing (and sometimes century-old) facilities. RemG has high sensitivity, high sampling rate, small size and weight, and low power consumption, which enable reliable measurement of both Grid lines as well as facilities. RemG reduces costs, enables a large number of sensors to be installed throughout the Grid, and provides detailed feedback data when needed. In addition, RemG is safe to install, safe to operate, and safe to maintain. The data collected can improve safety and security of the Grid, particular during emergency response. Implementing RemG will allow Grid operators to collect the most relevant data regarding the Grid condition at high time and spatial resolutions, which is the foundation to improve Grid resilience and Grid ability against cyber and physical attacks. RemG operation can be independent to the Grid, and therefore can provide valuable data during emergency and recovery processes. Continuous monitor of the power generation facility and the power monitor capability from RemG also allows improvement of operation efficiency, and may be able to identify or predict device failure or damage, which improves reliability and resilience of the Grid. Using RemG for leakage current detection can improve safety for emergency response. RemG has high sensitivity, low latency, and a high sampling rate, which enables accurate measure of failure event and failure location, helping utility companies to prioritize maintenance tasks and reduce disaster events such as uncontrollable fire damage. RemG, as a fundamentally new technology, can be implemented with optimized design and integration. At IBT, we expect RemG to become a transformative technology that will help GMI reach a new level. In partnership with UNL, we are pleased to have the opportunity to participate with EITPIC.

Washington State University (Tier II, Gold)

Submission Title: QoS-Aware Data-Driven Analytics for Next Generation Synchrophasor Workflows

Abstract: Unprecedented quantities of data are collected from phasor measurement units (PMUs) across the nation's bulk electric power systems. A variety of robust data processing systems have been implemented for serving data-driven synchrophasor workflows to improve the efficiency, security, and reliability of power systems. For example, real-time analytics prefers BTrDB; near-real-time analytics normally choose Druid, KairosDB, or OpenTSDB; and offline analytics usually select Hadoop or Spark. However, the disparities of the diverse data processing systems lead to a computing environment that not only drastically increases the system management cost but also limits the performance, scalability, and quality of services (QoS) of PMU data analytics. Guided by preliminary results generated in the PIs' research group, we propose to develop a novel data processing system, called UPS, for supporting QoS-aware data-driven synchrophasor workflows. The system provides a runtime system to enforce QoS policies (e.g., latency bounds) across both compute layer and storage layer. We will use a program execution-time profiling and latency-aware model selection techniques to achieve the required computing time at the compute layer and use QoS-aware cache partitioning at the storage layer to achieve the desired I/O time. In addition, it provides a unified I/O layer so that heterogeneous data analytics can be serviced in-situ in-memory.

In the process of achieving our overarching goals, we propose three novel contributions in PMU data storage and analysis. First, existing PMU data processing systems were not QoS-aware and lack the runtime support for enforcing QoS policies (e.g., bounded execution time). We will develop the first QoS-aware workflow management system to provide performance guarantee across the compute layer and storage layer. Second, currently, system administrators need to maintain multiple dedicated storage clusters and manage complex synchrophasor workflows for learning data patterns in PMU datasets. We will devise a unified I/O layer to support data consolidation with predictable performance. It will significantly reduce system management effort and improve PMU data usability. Third, UPS leverages memory cache to support in-situ in-memory data analysis and avoid large-scale data movement between storage clusters. Consequently, it can achieve high throughput for offline analytics and low latency for real-time and near-real-time PMU data analytics.

University of Houston (Tier II, Silver)

Submission Title: Topology Control-Based Stochastic Resource Planning for Renewable Power Systems

Abstract: Electricity shortage may seriously affect the economy, social welfare, and public health and safety. To meet increasing electricity consumption in the future, independent system operators (ISOs) and electric utilities perform long-term planning studies. Power system long-term expansion planning (LTEP) aims to ensure continuous power supply to consumers in a reliable, efficient, and affordable way. There has been an explosive growth of renewable energy sources. The increasing deployment of renewable generation will dramatically change the system generating resources and power flow distributions in the transmission network, which requires ISOs and utilities to redesign their procedures for long-term planning.

Existing LTEP technologies are based on deterministic optimization and assume the load is constant for each year or multiple years and annual load growth rates are the same for different areas. This indicates the uncertainty in load is not properly represented in the traditional LTEP model. Moreover, high penetration of variable renewable energy adds additional uncertainty and creates new challenges for power system expansion planning. Substantial increase in distributed energy resources will dramatically change the netload profile and increase the system uncertainty. To conclude, the traditional deterministic LTEP model is unlikely to overcome these hurdles. Thus, this idea proposes a scenario-based stochastic long-term expansion planning (S-LTEP) strategy to address uncertainties and achieve future renewable power systems.

The next generation smart grid includes many new features and products such as energy storage and demand response, which are not fully considered in existing planning studies. Energy storage is considered to be flexible resources that can provide multiple services. Particularly, energy storage systems can facilitate grid integration of variable renewables. For instance, it can alleviate the “duck curve” challenge associated with solar power. Thus, energy storage siting and sizing will be modeled in the proposed S-LTEP model. Traditional power systems are top-down oriented and only control resources at the generation side. However, demand response provides operators with an extra option to manage the grid. Demand response aims to reduce the total cost and enhance system reliability by encouraging consumers to modify their consumption levels and patterns. This can also promote the penetration of renewables and defer the need for new sources of power and network upgrade. Thus, demand response will be included in the developed S-LTEP model.

Existing power system planning tools do not acknowledge the flexibility in transmission networks and treat transmission elements as static assets in the planning models. This may not be optimal and incur unnecessary investment, especially in the context of system-wide penetration of variable renewables that follow different seasonal patterns. Past research efforts have demonstrated that utilizing the flexibility in the transmission network can benefit the system in various aspects such as congestion relief, reliability enhancement, and facilitation of renewable grid integration. However, very few efforts consider the transmission network flexibility in the power system expansion planning problems in the context of high penetration of renewables and energy storage. Thus, transmission network topology control will be considered in the devised S-LTEP model. The optimal network topologies for different seasons and years in the long-term planning horizon could be very different. Frequent transmission switching actions may cause system instability issues; thus, the optimized transmission network will remain the same for the

entire period of a season each year. This is often referred to as seasonal optimal topology control. In addition to existing transmission lines, the newly built lines can also be switched offline for specific seasons when their disconnection can facilitate the grid integration of renewables or relieve network congestion. This feature will be captured in the devised S-LTEP model.

Accurate representation of uncertainty should consider a large set of scenarios. Thus, this idea will implement scenario generation technologies to produce possible system scenarios. To reduce computational complexity, scenario reduction technologies will aggregate similar scenarios. The devised stochastic optimization will provide effective solutions to meet different scenarios. Since the proposed S-LTEP model considers energy storage, demand response, and topology control, it is not numerically trivial. Therefore, accelerating techniques are required to solve the proposed S-LTEP problem in a reasonable time. To conclude, the proposed idea for addressing new challenges of power system expansion planning consists of three phases that are presented as three tasks: (i) scenario generation and reduction; (ii) construction of a novel extensive model for scenario-based S-LTEP; and (iii) development of S-LTEP solution accelerating techniques.

Task 1 will conduct joint forecasting of renewable generation and load that captures their temporal and spatial correlation; then, Monte Carlo simulation will be performed to produce a set of potential scenarios; at last, scenario reduction techniques will be implemented to aggregate similar scenarios and determine the weighted scenarios for the proposed S-LTEP model. Task 2 is to construct an extensive formulation for S-LTEP with multiple salient features including energy storage system siting and sizing, utilization of demand response, and optimal network topology control. The developed extensive formulation will be very accurate as compared to the traditional planning model; however, it is intractable and may not be solvable in a timely manner. Thus, Task 3 will develop fast, effective techniques to relieve the computational burden and reduce the solution time. The devised accelerating technologies will make the extensive S-LTEP problem tractable while retaining high quality solutions.

This idea proposes an enhanced planning procedure that is practical, effective, and systematic, which goes beyond the state of the art. A salient and innovative feature of the proposed idea is the development of the stochastic optimization strategies that define a hierarchical framework including (i) Layer 1: data analysis and scenario selection for providing information required in the second layer; historical data will be processed and analyzed; with predictive information, advanced algorithms will be conducted to determine the weighted system scenarios; and (ii) Layer 2: scenario-based S-LTEP model and solution procedure for providing effective planning decisions. With information obtained from the first layer, the second layer will determine the location, capacity, and in-service starting time for each new asset.