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Market-Based Indian Grid Integration Study Options

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ABSTRACT

The Indian state of Gujarat is forecasting solar and wind generation expansion from 16% to 32% of installed generation capacity by 2015. Some states in India are already experiencing heavy wind power curtailment. Understanding how to integrate variable generation (VG) into the grid is of great interest to local transmission companies and India's Ministry of New and Renewable Energy.

This paper describes the nature of a market-based integration study and how this approach, while new to Indian grid operation and planning, is necessary to understand how to operate and expand the grid to best accommodate the expansion of VG. Second, it discusses options in defining a study's scope, such as data granularity, generation modeling, and geographic scope. The paper also explores how Gujarat's method of grid operation and current system reliability will affect how an integration study can be performed.

1. TRADITIONAL GRID MODELING

Conventional transmission planning studies focus on specific points in time when the grid is stressed, usually during periods of high demand. Disturbances or contingencies (i.e., the loss of individual grid components like a generator or transmission line) are then simulated to check the reliability of the grid. These studies look at several aspects of the system including line loading, bus voltages, voltage stability, transient stability, dynamic stability, short circuit, frequency, harmonics, and other system performance characteristics. These studies are carried out for present and expected future (e.g., 5 years forward) generation and load conditions. The aim is to identify weak points in the grid that will become the subjects of further analysis and mitigation.

2. VARIABLE GENERATION INTEGRATION MODELING

Variable generation (VG) grid integration studies have been developed to answer a different set of questions than conventional transmission studies regarding the grid's ability to operate reliably and cost effectively at progressively larger percentages of VG, with the associated variability and uncertainty. VG studies assume the existence of multiple technical solutions for periods of high grid stress and challenging operation; therefore, they focus on identifying the solutions that are most economical by considering a larger number of variables in both operation and system expansion as they dynamically interact over time. As such, different data, tools, and analytical techniques are used in an integration study.

2.1 Databases for a VG Study

To correctly assess the combined variability and uncertainty of load, wind, and solar requires time synchronized load, wind, and solar data. The load data may be based on historical data of both actual and forecasted load scaled to the desired future scenario. With an absence of significant measured data, the wind and solar databases will need to be synthesized from historical weather data. Development of these resource databases is non-trivial and can be a large part of the cost of a VG integration study.

A typical approach to synthesizing a year of wind data would include the use of a mesoscale Numerical Weather Prediction (NWP) model of the study area with a consistent time (e.g., 10-min) and grid (e.g., 2-km) resolution. To simulate a large region at such a high spatial resolution may require division into separate or nested geographical domains that are run independently. The simulations may also be broken into multi-day segments to allow for re-aligning the simulation with the observed historical weather data. Then these separate spatial and multi-day segments are merged into a full year of wind speed data. Another step is required to convert wind speed (or solar irradiance) into wind (or solar) plant power output. This conversion will incorporate selected hub heights, wind turbine characteristics, and plant sizes.

Validation is required to ensure that the synthesized data, both forecast and actual, correctly represent the variability and uncertainty. This can be accomplished by comparing the synthesized data to measured data from facilities in the same region, under similar weather conditions, and at the same time of year. Such a comparison could include characterization of the forecast error, magnitude and frequency of various wind or solar ramps, and spatial and temporal diversity of individual plants when combined into larger aggregate profiles.

2.2 Scenario Development

Next, the desired study scenarios need to be defined. These scenarios will be based on specified penetration levels of wind and solar energy generation, transmission system topology, conventional generation expansion, and/or retirement plans, as well as grid operating procedures and market policies. Variations on each of these items may result in a significant number of study scenarios. Hence, a compromise must be reached between comprehensiveness, and study cost and duration.

2.3 Analytical Methods

Once the input data sets are developed and the study scenarios defined, the analytical work may begin. VG integration studies commonly include two types of analysis: a statistical evaluation of variability and uncertainty, and an operational simulation of the grid's ability to respond to that variability and uncertainty. A third type of analysis that maybe done is capacity value analysis. Under this umbrella, a number of questions can be asked and answered about the impact of VG on reserves, balancing area size, the conventional generation fleet, transmission system, emissions, operating costs, use of forecasts, and need for various mitigation options.

2.3.1 Statistical Analysis

The statistical analysis characterizes several different system variables: load, wind, and solar variability, both individually and in combination; and load, wind, and solar forecast errors, both individually and in combinations. It commonly evaluates variability and uncertainty in multiple time frames, from the highest time resolution in the data (e.g., 10-min) to hours to days to seasons and years. The year-to-year timeframe is addressed by evaluating multiple years of synchronized data (e.g., 3 years or more). The statistical analysis identifies both the expected level of variability and uncertainty (e.g., 90% of the time, 1-min aggregate wind power changes will be less than X MW), as well as when coincident, large magnitude, variable events happen (e.g., high wind output coincides with low load). How they can be economically managed through operational and infrastructure changes is addressed via operational studies using production simulation tools.

2.3.2 Operational Simulation

Operational studies are intended to emulate real grid operations. Grid operators in the U.S. use security constraint unit commitment (SCUC) and security constrained economic dispatch (SCED) tools to assist them in meeting load with the least expensive combination of generation assets. The SCUC tool enables operators to commit sufficient generators to meet forecasted load the next day. The SCED tool gives the real-time signals to the committed generators to meet actual load, or net load (load minus wind and solar). These tools take into account the physical constraints of each generation asset and transmission characteristics while solving for the least-cost line up of generators to meet load and reserves. Generator constraints include startup times, minimum down times, minimum and maximum output limits, and ramp rates. Transmission flows are also modeled to confirm that capacities are not exceeded and reliability is maintained.

These operating tools, as well as the market policies and procedures, are simulated for a VG integration study using production simulation software. Most commonly, the simulations are performed for an entire year with an hourly interval. Looking forward, researchers are working on sub-hourly, high-resolution production simulations; improved methods for determining optimal economic solutions; and creating resource databases with more realistic key characteristics (e.g., coal plant cycling costs, minimum power output for hydro plants that reflect external constraints such as wildlife conservation or irrigation).

2.3.3 Capacity Value Analysis

A third type of analysis commonly included in a VG integration study is a capacity value analysis. This analysis measures system reliability in terms of the probability that there will be sufficient generation to meet load. Hence, it focuses on periods of peak load, which will likely occur on hot summer afternoons or evenings. However, wind generation is likely to peak at other times: at night after load has begun to decline, or in the spring and fall. Solar generation has better coincidence with load, but may peak at mid day before the load has reached its maximum. Therefore, the ability of wind and solar generation to provide capacity at peak load periods will be less than that of a conventional thermal plant. As an example, a thermal plant with a 10% forced outage rate would have a 90% probability of availability during peak load periods and therefore a 90% capacity value. If a wind plant is generally producing 12% of its rated output at peak load, then it would have a 12% capacity value. If a solar PV plant is generally producing 30% of its rated output at peak load, then it would have a 30% capacity value. (See "Western Wind and Solar Integration Study," published by the National Renewable Energy Laboratory, http://www.nrel.gov/wind/systemsintegration/wwsis.html.) There are a number of approaches to performing this analysis, including loss of load probability, loss of load expectation, and effective load carrying capability.

2.4 Testing of Mitigation Options

Integration of significant levels of VG will put new demands on most grids. Therefore, testing of mitigation options for both effectiveness and cost is a key component of most studies. Rewarding and therefore increasing the flexibility of conventional generation can help accommodate VG generation. Increasing balancing area (BA) size or inter-BA cooperation increases the ability of the system to integrate variability and uncertainty. Sub-hourly electricity markets respond quicker than hourly or longer markets to changes in the balance between generation and load, which also increase system flexibility. Incorporating VG forecasts into system operation has significant benefits. The addition of transmission capacity can allow access to areas with strong wind and solar resources, and reduce transmission bottlenecks in getting power to loads. Greater geographic diversity within the VG portfolio will result in relatively less variability. Because grid system operation is a balance between generation and load, variability in generation can also be mitigated by actively adjusting load, known as demand response. Energy storage can offer services to the grid, such as energy arbitrage, capacity, or regulation. And, curtailment of VG power during extreme events is also effective.

3. STATE OF GRID AND OPERATIONAL METHODS IN GUJARAT

The electrical system in Gujarat is divided into three divisions: electricity generators, transmission, and distribution companies. Transmission in Gujarat is primarily controlled by Gujarat Energy Transmission Corporation (GETCO) and operated on a daily basis by the State Load Dispatch Center (SLDC). There are some nationally owned and operated (Power Grid) transmission lines but they are primarily used to transport power across state lines and to deliver allotments of power from central generation assets within a state and to different states. The distribution companies are called discoms, and there are four public and two private discoms in Gujarat.

The transmission system in Gujarat is one of the most stable and reliable in India. Transmission availability is 99.5% and losses are only 4.25%. AC transmission is from 66 kV to 400 kV. Voltage is stepped down to 11 kV for distribution to the discoms. There is no load shedding as is common practice in other states.

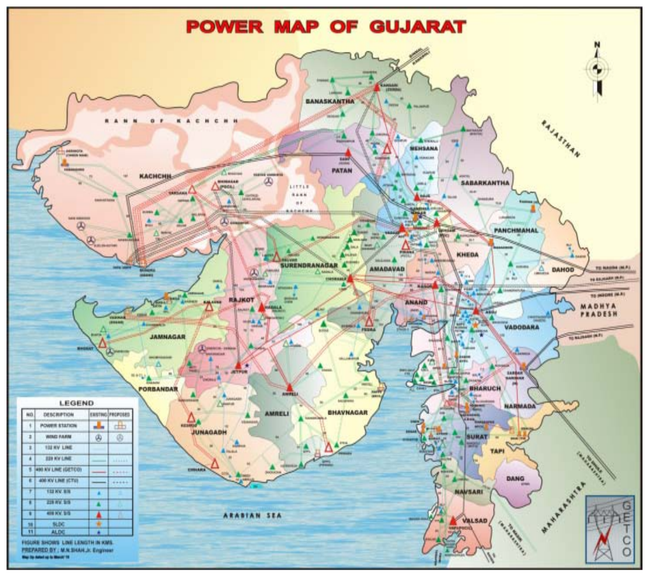

Fig. 1: Power map of Gujarat. Source: Gujarat Energy Transmission Corporation Limited.

3.1 Grid Challenges

As of August 2011, the total installed, conventional, electric generating capacity in Gujarat is 13,041 MW with an additional 2,119 MW of installed wind. The anticipated generation capacity expansion of the next 5 years is 18, 666 MW of conventional generation and 5,849 MW of wind and solar, which is a 162% increase. Much of the present and planned conventional generation is coal fired plants, which presently have a minimum operating point of 70% capacity and an average start time of 18 hours. The large planned increase of conventional generation assets is to help with contingencies during high loads, better serve the agricultural load, and export of power to neighboring states. Presently the expected increase in VG is not taken into account for transmission planning.

Loads for Gujarat can vary widely. On a high-demand day the load has varied from about 7,200 MW to 10,800 MW and on a low-load day from about 6,000 MW to 8,700 MW. At high-load conditions, the system does experience low voltages (e.g., 378 kV on a 400 kV line) and high voltages (e.g., 431 kV on a 400 kV line) when demand is low. The system cannot handle contingencies when demand is high. Much of the load shape is defined by agricultural irrigation water pumping during the non-monsoon season. Presently, the system is only able to handle 8 hours/day of agricultural load. This load is supplied by power lines that are separate from other loads, and there is a rotating schedule for users to draw power from this line. Because this load is undersupplied, a VG study could look at load shifting or other measures to understand how VG generation could increase the energy serving agricultural load.

There are several expected challenges as the rapid increase of installed renewable generation connects to the grid. Wind power generation increases during the monsoon season when the large agricultural load drops as natural precipitation precludes the need for pumped irrigation water. It is expected that there will need to be additional interstate transmission to export this wind power out of Gujarat. The geographical areas of large wind and solar resources are not collocated with the load centers they would supply, necessitating intrastate transmission expansion. The present challenge with expansion of interstate transmission is that Power Grid is responsible for interstate transmission expansion but it only has been concerned with transmission of central generation plant power. VG integration for Gujarat will partly depend on national level planning and cooperation.

3.2 GETCO Planning Process

GETCO presently does 5-year planning studies. GETCO has done traditional load flow and short circuit studies for the 18.7 GW of planned conventional generation expansion in the next 5 years. Costs for system upgrades, maintenance, and operation are submitted to the state regulator who decides the tariff. With regard to the expected 5,849 MW of new wind and solar generation capacity, GETCO is looking for help with VG-integration grid operation studies to understand what the challenges will be and how different technologies can be use to manage the system.

3.3 Gujarat Grid Operation

Daily operation of the Gujarat electrical grid is done through a system of day-ahead scheduling, real-time (15 minute) dispatch and post facto scheduling (i.e., account settlement). Day-ahead scheduling is done for both generation (i.e., unit commitment) and load. Note: load is forecast in the U.S. but not scheduled. Generators bid into the market the day before to supply a specified amount of power at specified times for a specific price. The discoms also schedule their loads or power draw from the transmission system for each time block of the following day. There are 96 time blocks in a day, with each block being 15 minutes. The market is cleared based on economic dispatch—in other words, generation is scheduled in order of cost from the cheapest to most expensive until the scheduled load is met. There are no scheduled operating reserves and system frequency is allowed to fluctuate. After each day, costs are calculated and accounts settled.

The structure of the tariff paid by discoms for power provided by GETCO is an availability-based tariff (ABT). The structure is divided into three parts: fixed, variable, and deviation. Fixed cost is based on a generating plant's fixed cost. Variable cost is based on the marginal operating cost. The deviation or unscheduled interchange (UI) is a charge for discom power draws above what was scheduled. The UI is designed to support the system frequency at 50 Hz. If the system frequency is 50 Hz during a discom overdraw, there is no UI. The UI charge increases non-linearly as the system frequency drops, causing the price of power to quickly climb to 10 times the scheduled price as frequency drops. On the other hand, the UI reduces the cost of power for overdraws as the system frequency rises above 50 Hz.

Presently there is renewable energy generation (2 GW of wind) that is connected to the grid. All renewable generation is currently accepted into the grid. As the amount of VG power accepted into the grid increases there will be times that generation will exceed load, and the export of power will need to be accommodated as well as tariffs determined.

4. OPTIONS FOR GUJARAT VG STUDY

Expected VG capacity expansion in the next 5 years is 4,881 MW of wind and 968 MW of solar, which has raised GETCO's concern regarding several aspects of wind and solar generation and what their impact will be on its grid and grid planning. Some questions that need to be answered are how variable are wind and solar generation and how will they affect the grid at planned levels of penetration? Are present transmission plans adequate to handle expected increases of wind and solar generation?

The usefulness of a grid-integration study is based on the clear definition of study goals and translating them into a well-designed study. Primary goals for a study can include, but are not limited to, developing data for the basis of future transmission planning, defining operational requirements for new generation being brought on-line, recommending changes to system operation and markets, and estimating the costs and benefits of integrating variable generation into the grid. The desired goals will become the drivers for study scope development. As such, an initial scoping study to define overall objectives, desired study scenarios, types of analyses, data requirements, software availability, and more would be a reasonable first step. Various aspects of such a scoping effort are discussed below.

The types of analyses performed in previous VG integration studies were discussed above. They focus on operational and statistical analyses, rather than traditional transmission planning studies. Traditional planning studies (e.g., voltage stability, transient / dynamic stability, oscillation study, frequency stability, etc.) still need to be completed to ensure a reliable system. They will be informed by the systemic and operational results of the VG integration study.

4.1 Data Granularity

Developing appropriate wind and solar datasets is a significant effort, involving complex simulations with NPW models as described above. Data granularity, both temporal and geographical, also will be based on the desired goals of the study. If the study is only evaluating systemic operational analyses at an hourly resolution, then high-resolution data is not required. However, sub-hourly resolution input datasets for wind, solar, and loads are required to determine the grid's ability to operate reliably within the hour.

4.2 Scenario Development

The desired study scenarios are typically built around a high-level statement of VG penetration, their type (i.e., wind and solar), and location as well as a specific set of transmission system topology, generation expansion/retirement plans, market structures, and operating procedures that represent the expected future grid.

The geographic footprint of the study will need to be defined. Previous studies have shown that the behaviors of neighboring systems have an impact on any single balancing area and it is important to include them. Cooperation with neighboring states is dependent on Power Grid, which operates the interstate transmission. Due to the reliability difficulties experienced by neighboring grids, one assumption is that these states can absorb large amounts of excess power from Gujarat if transmission capacity and Power Grid operation will allow it. It should also be investigated to see if sub-hourly interstate transmission adjustments can be accommodated to assist with VG integration.

The methods and tools operators use to manage the grid will be key variables in a VG integration study. The size of the scheduling intervals or speed of the market can have a large impact on integration because the operator may not be able to adjust to system changes between time steps. Reserves can be carried to respond intra time step to load and VG variability as well as to the contingency loss of a conventional plant.

Currently, the SLDC operates the grid with no reserves and schedules both load and generation with day-ahead commitment and dispatches at 15-minute intervals within transmission constraints. Variable system frequency and punitive tariffs are used to keep the system balanced within acceptable ranges. Due to the fact that GETCO is synchronized with interstate transmission systems, study variables that look to change variable frequency operation are not an option. System operation variables that look at changing the mode of operation should be considered such as operating shorter time-step dispatch and operating with reserves as these have been shown to assist with VG integration.

Scenarios can be run assuming that generation can serve any load regardless of the locations of the transmission or load. This is sometimes called "copper sheet" analysis because power can flow any direction and ignores transmission constraints. This type of analysis will show how total generation and load coincide but not how the transmission system will operate. New transmission constraints will help define where new generation assets can be developed or where new transmission is needed.

Transmission analysis should explicitly model existing transmission assets, and allow for transmission capacity to be expanded. Scenarios are typically built around transmission expansion options such as expansion to the best resource areas and/or include additional interstate transmission.

Since wind and solar have very low to zero marginal cost for production, they are typically always dispatched and power accepted. At times of high solar and wind resource output and/or variability, there can be challenges in system operation. Mitigation options could include increased generation flexibility, energy storage, curtailment, and demand response. A scenario could explore the impact of greater conventional generation flexibility (e.g., minimum power output, ramp rates), especially assets that are in the planning stages to make them more accommodating to VG integration. Storage devices may be another means to ensuring reliable integration of high levels of VG. Other options can include demand response and VG curtailment.

If final actionable results are the desired goal, integration of traditional transmission planning models with the market-based VG integration study may be necessary. The VG study will identify conditions of high stress and provide output that can then be used by traditional tools (e.g., power flow and transient stability) to develop solutions to mitigate the stressed areas. Depending on the study, this could be an iterative process.

5. SUMMARY AND RECOMENDATIONS

GETCO is interested in results that are going to be actionable in a timely manner because their VG penetration projections are not giving them the time to do multiple studies of increasing granularity. Also, the GETCO's area of operation is limited to the state of Gujarat (196,077 km2), which is not a large geographic area compared to other studies and should not represent computational barriers. Therefore, an actionable and detailed study would be preferred.

It was hoped that a recommended study could be defined at the conclusion of this paper, but more work needs to be completed in defining and achieving mutual understanding with GETCO on the purpose and benefits of a VG integration study. This paper becomes the first step in this process. An initial scoping study to define overall objectives, desired study scenarios, types of analyses, data requirements, software availability, budgetary estimates, resource constraints, and more would be a reasonable next step. This would allow GETCO to develop the most appropriate study for their needs.

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