Safety in Numbers

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Online Security Analysis of Power Grids with High Wind Penetration

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AS A GLOBAL TREND IN CLEAN AND RENEWABLE POWER, WIND POWER generation has significantly increased in the generation portfolios of many countries and is set for further growth over the next ten years. For example, the installed capacity of wind generation in Europe was near 84 GW (15% of peak demand) in 2010 and is planned to increase to 140–180 GW by 2015. Ambitious targets for renewable energy sources integration, with wind as their largest component, have been also set in Ireland and Northern Ireland. The aim is for 40% of electricity to be produced from renewable energy sources in 2020, with the majority coming from wind.

Planning and operation of a power system with a high penetration of wind generation face a number of technical challenges. These include:

- **Variability:** The output of wind generation frequently changes in time frames that range from seconds to hours.
- **Uncertainty:** The magnitude and timing of variable generation output is less predictable than it is for conventional generation.
- **Location:** Wind farms are often located in relatively unpopulated, remote regions that require long transmission to deliver the power to load centers.
- **New technologies:** New technologies are often needed for wind turbines, e.g., doubly fed induction generators (DFIGs). In general, wind turbines are not synchronized with the system; have insufficient voltage and frequency regulation capabilities; and require assessment of special problems and systems, such as harmonics, subsynchronous resonances, and protection systems.

Due to the characteristics mentioned above, as well as the increased need to cope with diversified operating conditions in many power grids, it is crucial to implement special tools so as to ensure the security of the grid under all system conditions, especially when a high level of wind generation is integrated into the system. Online dynamic security assessment (DSA) is one such tool.

Online DSA models the network topology and operating conditions obtained in real time, and it calculates the system security and stability limits using this data. Providing that appropriate modeling is used, online DSA results more accurately characterize existing system conditions than the off-line planning case, and thus they let the operator better evaluate the impact of wind generation and certain operating decisions with respect to changing operating conditions. Consequently, DSA conducted in a near-real-time setting greatly enhances the operational decision-making capability of an operator and significantly reduces the risk of cascading blackouts by evaluating stability limits based on real-time system conditions and topology. To date, online DSA technologies have been implemented in many power system control centers.

This article presents an application example of online DSA technology in performing near-real-time security assessment of the power system that covers Ireland and Northern Ireland. It is a single synchronous system that has limited HVdc interconnection to Scotland. The combined maximum and minimum demand of these two systems is approximately 6,800 and 2,500 MW, respectively. Tripping of the largest generator (440 MW) can result in a frequency fall of more

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than 0.6 Hz even with a primary fast-acting operating reserve of 75% of the maximum in-feed. The relatively small size of the system also dictates frequency variations wider than those in continental Europe under normal conditions. Generation plant (installed capacity) is mostly thermal, with some 6% of hydro and hydro pumped storage and a 16% wind share that is increasing rapidly. An additional 500-MW HVdc link to the U.K. grid based on voltage source converter (VSC) technology (due for commissioning in 2012) is expected to improve the power system's ability to accommodate wind generation. Increased wind penetration changes the operational characteristics of the power system, primarily due to the unique nature of the wind generation technology described earlier. Increased levels of wind generation introduce new risks and challenges for the transmission system operator. For example, can system security be maintained with instances of wind penetration (wind generation as a percentage of total generation) of 50% or more? At present, wind generation does not provide certain essential services such as primary reserve, frequency governing, and voltage regulation that are provided by conventional generation. Can wind power generation on a synchronous system be maximized at a given time while maintaining reliable and secure operation?

Answers to these questions can be obtained by using the Wind Security Assessment Tool (WSAT), which has been successfully applied to the EirGrid system. WSAT is an online DSA system, and it is based on stability analysis of system conditions obtained in real time or by forecast.

Power System Stability and Online DSA

Power system stability can be assessed by considering its various forms:

1) **Steady-state stability:** Steady-state stability is the ability of the system to arrive at a safe steady state without disconnecting customers following the outage of one (N−1) or more (N−k) power system components (transmission line, transformer, generator, or load) from the system. This includes:
   - **Thermal constraints:** the requirement to maintain power flows in the elements of a system without exceeding their thermal capability limits (thermal ratings) in all N−1 contingencies and credible N−k contingencies.
   - **Steady-state voltage stability:** the ability of the system to keep secure voltage levels and voltage gradients on the system within standard levels in all N−1 contingencies and credible N−k contingencies.
2) **Transient stability:** Transient stability is the ability of the system to keep its components connected following large disturbances. These can be faults on the transmission system cleared by protection and/or sudden trips of large generators, loads, and so on. This further includes:
   - **Synchronous plant stability:** the ability of the system to maintain its synchronism (rotor angle stability)
   - **Nonsynchronous plant stability:** the ability of the system to keep other sources of generation connected to the system.
3) **Small-signal stability:** Small-signal stability is the ability of the system to maintain synchronism of its synchronous plants and keep its nonsynchronous plants connected following small disturbances including small variations in load, generation (including wind), changes of settings for automatic control devices, and so forth. In particular, any spontaneous oscillations caused by such disturbances must be sufficiently damped.
4) **Frequency stability:** Frequency stability is the ability of the system to control its frequencies within safe limits and to return to the permitted frequency range following any disturbances.

Using an appropriate model for the power system, various forms of stability can be assessed by simulating particular conditions with disturbances (contingencies) and comparing system performance with the set stability criteria. Although many types of criteria exist to measure the degree of stability from different perspectives, the criteria used in WSAT include the following:

1) **A thermal criterion:** Transmission lines, cables, and transformers must be loaded at less than 100% of their nominal thermal ratings in base-case conditions and less than 110% in N−1 contingency conditions.
2) **A voltage stability criterion:** Voltage stability must be maintained in base-case conditions and all studied contingency conditions. Steady-state voltage levels at all buses within the EirGrid system (110-kV and higher) must be within the following limits: 0.95–1.1 p.u. in base case conditions and 0.9–1.12 p.u. in N−1 contingency conditions.
3) **A synchronous plant transient stability criterion:** Maximum rotor angles of synchronous generators must be within limits to stay in synchronism. This is implemented in WSAT as a requirement that maximum angle separation of any

two synchronous generators in one island must be less than 360°.

4) **A frequency stability criterion:** Frequency deviation in the event of tripping one generator or three-phase fault with forced outage of an element (transmission line or cable) must be less than 1.0 Hz when the duration of the frequency deviation is longer than 0.5 s.

Criteria 2 and 3 are presently enforced in WSAT. Criteria 1 and 4 will be considered for the next phase of the WSAT deployment.

As described earlier, assessing system stability with respect to the above criteria for the real-time system condition can be done by using online DSA. Online DSA is essentially a technology that takes a snapshot of a power system condition, performs the desired security assessment (including determination of stability limits) in near real time, and provides the operators with warnings of abnormal situations as well as remedial measure recommendations, if applicable.

An online DSA system may consist of up to six main functional modules (see Figure 1), as follows:

1) **Measurements:** This module obtains the real-time system condition. This function is also part of the energy management system (EMS). While measurements from traditional SCADA systems can generally meet online DSA input data requirements, the latest data collection technology—for example, phasor measurement unit (PMU)-based wide-area measurement systems (WAMs)—can provide much better and more accurate system conditions. This can greatly improve the quality of the online DSA application.
2) **Modeling:** This critical module assembles a set of models suitable for DSA. Some functions in this module (such as the state estimator) are also part of the typical EMS; others may be functions specific to online DSA, including
   - creation of modified system conditions if forecast or study mode analysis is required
   - external network equivalencing
   - modeling of important equipment (such as wind turbines) and the associated control and protection systems, including reactive power compensation, in addition to the conventional models required for off-line planning studies
   - contingency definition that considers real-time node and breaker configuration and special protection system arming status
   - corrections and enhancements to the system model from the state estimator, e.g., addition of missing system components (such as station service loads), merging or splitting generator units, correction of inconsistent data (such as generator reactive capabilities), and so on.
3) **Computation:** This module is the computation engine of DSA, which handles two types of problems associated with DSA:
   - steady-state system performance, such as thermal, voltage deviation, and slow-voltage stability
   - electromechanical transient performance (from a few seconds up to 20 s, following a contingency), such as fast-voltage stability, transient stability, small-signal stability, and frequency stability.

Three main analysis options are usually required to investigate these problems:

- ✔ security assessment of the base-case conditions (for real-time, forecast, study, and other purposes)
- ✔ determination of the stability limits
- ✔ identification of applicable remedial actions to handle insecure contingencies and to increase the stability limits, if necessary.

In addition to the above analysis options, advanced computational techniques are often used to meet performance requirements, e.g., contingency screening techniques are used to quickly filter out noncritical contingencies from detailed analysis, and distributed computation techniques perform analysis in multiple available CPUs to improve computation speeds.

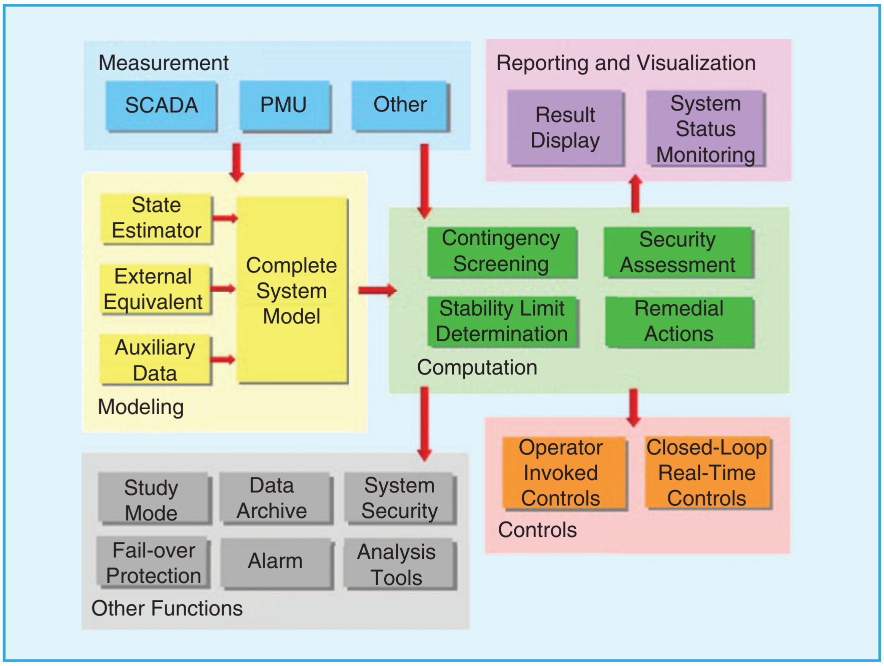


figure 1. The main functional modules of an online DSA system.

> Special modeling considerations may also be necessary in WSAT, in addition to the conventional models to be included in the analysis.

4) **Reporting and visualization:** This module includes display and visualization of DSA results as well as reporting of the operational status of the DSA system. Considerable attention has been paid to the visualization of DSA results. This not only focuses on the information to be presented but also on how it is presented. Web-based and geographical display methods are becoming more and more popular.
5) **Control:** In this module, various controls (such as generator rejection) are used as remedial actions to ensure system security. Online DSA can be integrated with such controls to provide settings calculated in real time and even to send the arming signals when the system condition requires such controls to react. This area is considered one of the main attractions of online DSA.
6) **Other functions:** This module collects functions to improve the reliability, usability, and applicability of the online DSA system. Some of these play important roles in the deployment of online DSA, including:
   - system security, to be compliant with a specified set of cybersecurity standards
   - data archiving, to provide history cases ready for use in study mode
   - integration with other analysis functions (such as oscillation monitoring based on PMU measurements) to extend online DSA functionality.

The WSAT system installed at EirGrid is a special deployment of online DSA. Some of its unique features, such as modeling, security assessment, and system operations, are described below.

Modeling Requirements

As in any technical analysis, modeling is always an important part of the analysis. Special modeling considerations may also be necessary in WSAT, in addition to the conventional models to be included in the analysis. In the case of EirGrid, these included the following:

1) **Merging the Northern Ireland–equivalent model:** At present, the full Ireland network model is not available in EirGrid's EMS. But in order to get credible results for large system disturbances, it is very important to consider the generation in Northern Ireland. A custom tool was developed to merge a dynamic equivalent model of the Northern Ireland system with the real-time snapshot of EirGrid. The dynamic equivalent was obtained with the DYNRED software of the Electric Power Research Institute (EPRI), using a planning case for the full Ireland system. The custom tool takes this equivalent and scales the load and generation in Northern Ireland, based on the Irish system load, interconnector flows, and rules for generator dispatch provided by EirGrid. This merging process will be discontinued when additional SCADA data for the Northern Ireland system becomes available.
2) **Generic wind turbine model with full converter interface:** A generic model for wind turbines with a full converter interface (back-to-back VSC) was developed, which was required for WSAT to model the dynamics of the numerous wind turbines in the Irish system with this type of converter technology. Some key aspects of the model are listed below:
   - The details of the VSCs and the mechanical conversion of wind to electric power are not included. The fast response of the VSCs effectively isolates the grid from these dynamics when studying electromechanical dynamics of the grid.
   - A constant active power order during normal operation is assumed. The model includes options for blocking and unblocking (with user-defined ramping) for low-voltage operation and recovery, however.
   - The reactive power control is a straightforward P-I controller for the terminal voltage, with optional droop on the reactive power output of the unit.
3) **Customization of the generic DFIG model for acceptable MW response:** A generic DFIG model developed by Western Electricity Coordinating Council (WECC) was initially used during the testing of WSAT. It showed unacceptable active power response for large conventional unit trips, however. In particular, it appeared that the wind units were showing either active power increase or decrease in response to the frequency dip. Based on EirGrid's experience, however, the units do not show any such behavior—just some inertial response during the first few seconds of the event. Two modifications to the generic model were made, as follows:
   - **Droop reset of the pitch angle control:** Since the pitch angle control is based on comparing the speed with a speed reference, a large frequency dip causes the steady-state output of the controller to increase, which results in MW decrease of the unit. This was

addressed by adding a droop feedback around the P-I controller for the pitch angle, so that the pitch angle would be restored to 0° once the system frequency recovered (see Figure 2).

- **Variable phase-locked loop (PLL) gain:** A low value of the gain for the PLL allows a droop to appear on the active power output because of the lag between the angle of the current injection and the angle of the bus. In normal operation, the gain needs to be high to prevent this; during faults, however, a lower value is necessary to improve numerical behavior at low voltages. The DFIG model therefore detects low voltages and automatically switches to a low value of PLL gain when they occur (see Figure 3).

"Secure Wind Level" Concept

The theoretical maximum wind power penetration level can be estimated as the difference between load (including losses) and minimum conventional generation. The latter is defined by a combination of requirements for minimum ramping rates, operational reserve, and reactive power reserves. In order to be able to operate the system as close as possible to its theoretical maximum of wind generation, the concept of a *secure wind generation level* (SWL) can be defined. SWL is simply the maximum amount of wind generation minus the assumed safety margin. The question then becomes how to determine SWL. The increased amount of wind power generation in the power system generation portfolio significantly changes generation patterns. The variation of such patterns is limitless due to the random combination of load, weather, and electricity market conditions at any given time. This leads to unlimited variations in base-case scenarios in terms of:

- power flow patterns
- voltage profiles
- operating points of generating units
- operating points of controllers (governors, automatic voltage regulators, under-load tap changers, static var compensators, and so on).

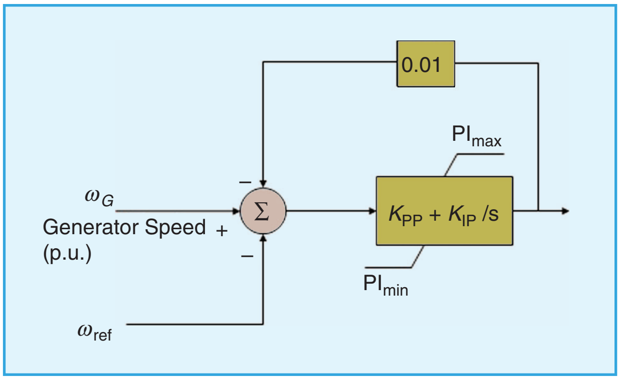


figure 2. Feedback for pitch angle reset in the generic DFIG model.

All these factors add complexities in the determination of SWL. In WSAT, the maximum amount of wind on the system while retaining system security is assessed through analysis of the voltage and transient stability of the system with increased wind generation and, subsequently, decreased conventional generation. This procedure starts from the base case and proceeds until any of the stability criteria described earlier is violated. This assessment is known as analysis of a *transfer* between wind and conventional generation (see Figure 4). Transfers are arranged starting from the base case; the amount of wind generation megawatts (source) is then increased by defined steps in proportion to the difference between the maximum export capacity (MEC) and the current production of wind generation. The number of conventional generation megawatts (sink) in turn is decreased by the same amount based on a prespecified merit order, down to the minimum generation. When the minimum output limit of a conventional generation unit is reached, this unit is disconnected from the system. During the transfer, the source generation is adjusted until either a stability criterion is violated or the source is fully dispatched. In case of a stability criterion violation at step k of this adjustment, the amount of wind generation at step $k-1$ is considered as the wind generation limit satisfying that stability criterion. Once the wind generation limit is established, SWL can be easily determined.

WSAT Structure

The structure of WSAT is shown in Figure 5. SCADA/EMS and other sources provide WSAT with the following three sets of input data:

1) a real-time system snapshot from the state estimator solution

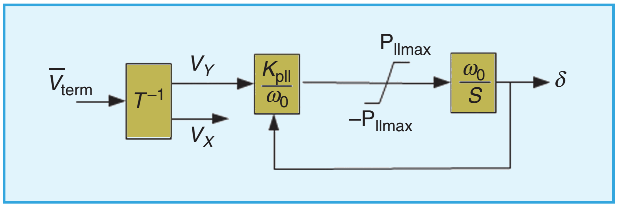


figure 3. PLL phase angle tracking loop (K_{pll} gain is varied based on voltage level).

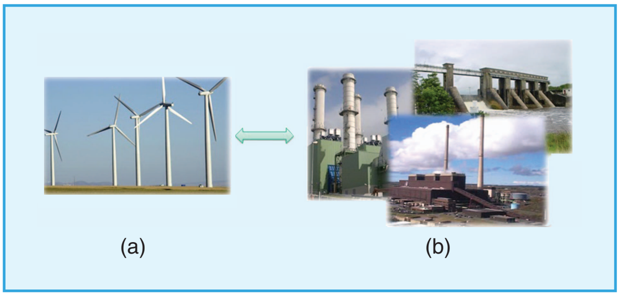


figure 4. Transfer between wind and conventional generation.

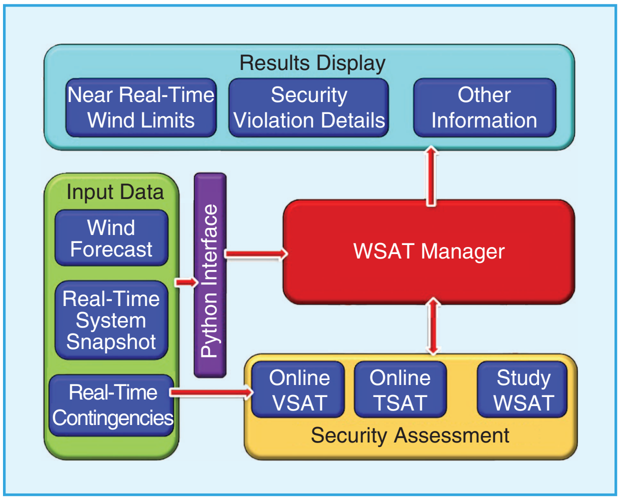


figure 5. WSAT structure.

2) a set of real-time contingencies associated with the network topology corresponding to the state estimator solution
3) wind forecast data extracted from the corporate LAN, which is used to create the short-term forecast system models (these data are updated hourly).

These data sets are exported every 5 min, which means that WSAT can potentially run as often as every 5 min. The actual assessment cycle in WSAT can be configured and currently runs every 15 min.

WSAT operation is controlled by the WSAT Manager application, which runs online voltage security assessment, or VSA (the online VSAT module), and online transient security assessment, or TSA (the online TSAT module), in both real-time and forecast modes. There is also an off-line study mode (Study WSAT) that can be used to study special VSA and TSA scenarios. Using Windows Scheduled Tasks, WSAT runs a Python script that finds the most recent real-time snapshot data, modifies them according to the WSAT input data requirements, and passes them to WSAT Manager for processing. The modifications performed in the above procedure include:

- ✔ adding equipment names to avoid ambiguity in case of bus reconfiguration
- ✔ constructing wind turbine models from those modeled in EMS as negative loads and those embedded within normal loads.

Once a real-time system snapshot and/or a forecast system model is passed to WSAT, WSAT starts the security assessment for the base case and all predefined transfers.

WSAT offers extensive output results that can be retrieved, starting from high-level data (WSAT summary) and proceeding to more detailed information, including:

- ✔ secure wind generation levels (SWL)
- ✔ detailed stability violations reports
- ✔ preventative control measures.

The grid controller can view results using the WSAT Monitor tool installed on workstations connected to the corporate LAN. The grid controller has access to all levels of output data on request, but only high-level summary results are automatically presented on the WSAT Monitor interface. This lets the grid controller not only observe how the SWL evolves in time but also obtain quick answers as to which criteria have been violated, where they are violated, and how this affects SWL. Further analysis can be performed, if necessary, for any archived history cases by study engineers using the study mode.

WSAT as Implemented in EirGrid's Control Center

The version of WSAT currently installed at EirGird's control center is able to assess system security by carrying out:

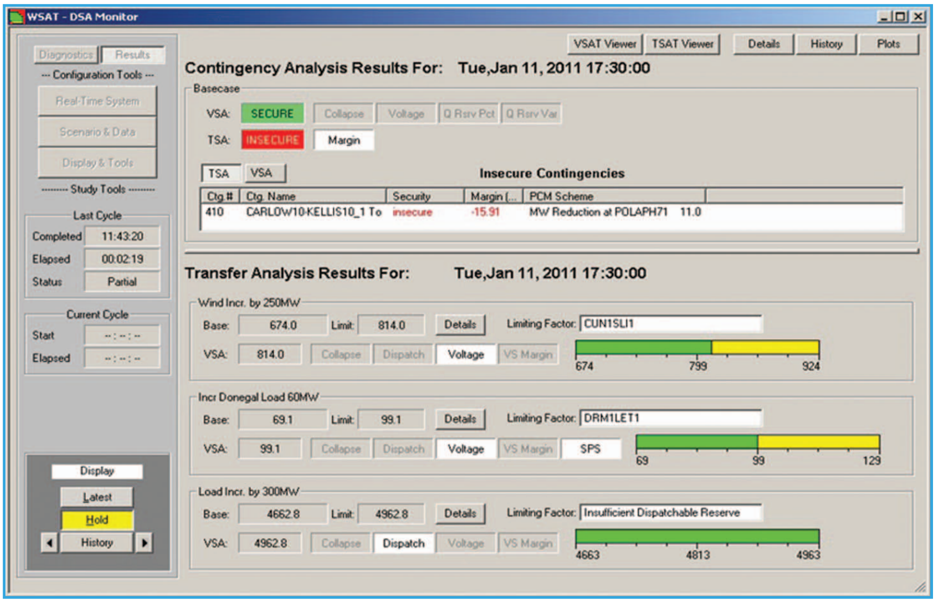
- ✔ voltage and transient stability studies for the latest system configuration (wind generation level, network topology, generation profile, and so on) for N and N−1 conditions
- ✔ voltage stability transfer studies based on the latest system configuration where the total system load is increased by 300 MW from its current level with a matching increase in conventional generation for N and N−1 conditions
- ✔ voltage stability transfer studies based on the latest system configuration where the load in an remote area of the system, susceptible to voltage instability, is increased by 60 MW from its current level with a matching increase in conventional generation for N and N−1 conditions
- ✔ voltage stability transfer studies based on the latest system configuration where the wind generation is increased by 250 MW from its current level with a matching decrease in conventional generation for N and N−1 conditions.

The base case or any other operating point within the appropriate transfer is deemed voltage-secure if it meets the following specified voltage criteria for both N and N−1 conditions:

- ✔ The system remains voltage stable in the pre- and postcontingency conditions.
- ✔ Pre- and postcontingency voltages are within specified limits as described before. A special check can also be made to identify voltage step changes greater than 10% at postcontingency conditions at all voltage levels from 110 kV to 400 kV. Such large voltage step changes can be flagged as criterion violations.
- ✔ Pre- and postcontingency Mvar reserves of selected sources are larger than specified limits. A special check can also be made to monitor the Mvar leading reserves of a group of generators in the Dublin region. This assists grid controllers in securely operating an area of the system with a high concentration of cables

that can be subject to high voltages during night valley periods.

The base case is deemed transiently stable if, for any of the defined contingencies, the transient stability criterion is not violated. These contingencies are defined based on the voltage level of the fault location, the type of protection implemented, and the corresponding protection relay settings. Any reported transient stability violation is accompanied by a preventative control measure which recommends how the instability can be prevented.



Last Cycle
Completed 11:43:20
Elapsed 00:02:19
Status Partial

Current Cycle
Start --:--:--
Elapsed --:--:--

Contingency Analysis Results For: Tue,Jan 11, 2011 17:30:00

Basecase
VSA: SECURE
TSA: INSECURE

Insecure Contingencies

Ctg #	Ctg. Name	Security	Margin (...	PCM Scheme
410	CARLOW10-KELLIS10_1 To	insecure	-15.91	MW Reduction at POLAPH71 11.0

Transfer Analysis Results For: Tue,Jan 11, 2011 17:30:00

Wind Incr. by 250MW
Base: 674.0 Limit: 814.0 Limiting Factor: CUN1SLI1
VSA: 814.0 Voltage

Incr Donegal Load 60MW
Base: 69.1 Limit: 99.1 Limiting Factor: DRM1LET1
VSA: 99.1 Voltage SPS

Load Incr. by 300MW
Base: 4662.8 Limit: 4962.8 Limiting Factor: Insufficient Dispatchable Reserve
VSA: 4962.8 Dispatch

figure 6. The main WSAT screen for grid controllers.

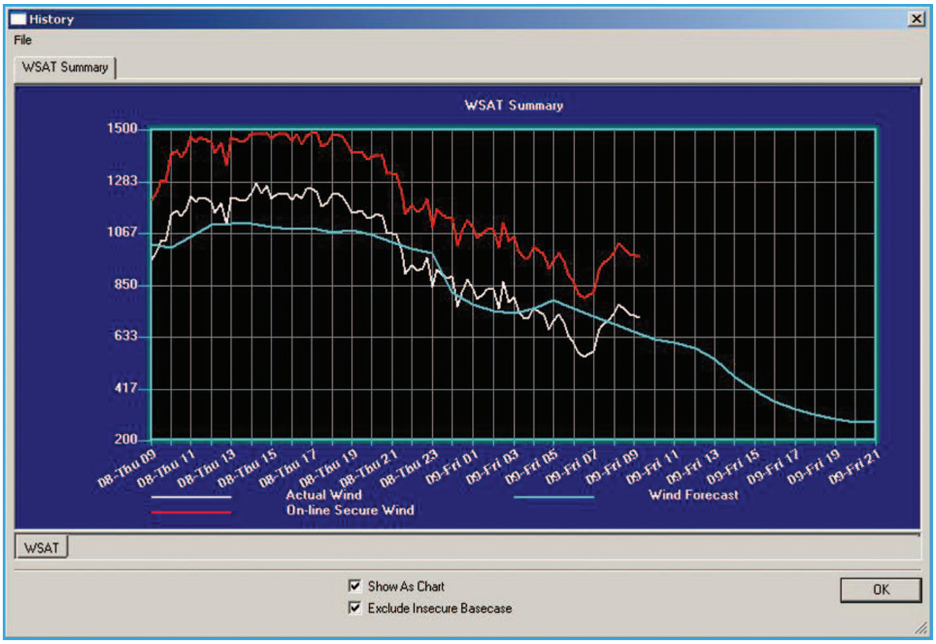
WSAT provides guidance to the grid controller on how to operate the system on a near-real-time basis, as the security assessment runs every 15 min based on the most recent power system snapshot. This translates to more than 400,000 voltage and transient stability studies carried out each day. The WSAT results are presented to the grid controller in a clear, obvious, and unambiguous manner—this is critical to the successful use of the tool in the control center. Essentially, the grid controller must be able to quickly recognize and then interpret reported problems. For example, WSAT Monitor filters the analysis results to show only the voltage and transient stability violations.

A screenshot of the main WSAT screen that grid controllers consult is shown in Figure 6. Grid controllers can also view the trend of SWLs on the system over a specified period of time, as shown in Figure 7.

In Figure 6, the security status for one real-time system condition is summarized. It can be seen that the base system condition would be transiently unstable if contingency 410 occurs. It also shows that a preventive control measure (PCM) has been found for this contingency (the details are available in the next level of display). Below the base-case security display, the results of three transfers are shown. All were performed for voltage stability criteria; transient stability criteria were not applied for this case. The three transfers were:

1) a wind generation increase of 250 MW
2) a load increase in a remote area of 60 MW
3) a total system load increase of 300 MW.

The green bar shows the secure transfer level (i.e., within the green bar, the system can meet all stability criteria for any transfer increase). Once the transfer goes into the yellow region, at least one stability criterion will be violated.



☑ Show As Chart
☑ Exclude Insecure Basecase

figure 7. Secure wind level trend.

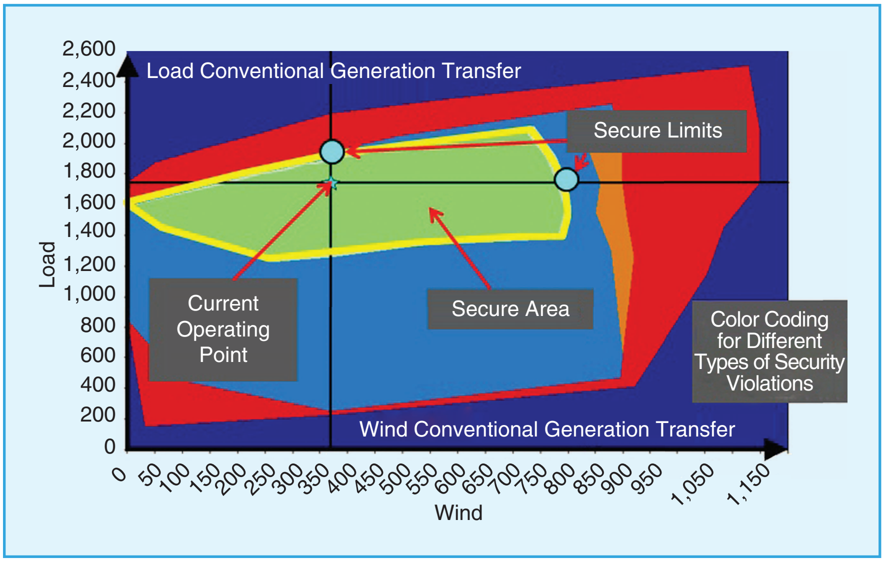


figure 8. Nomogram showing the secure wind level trend for the EirGrid system.

For example, for transfer 1, if wind generation is increased by more than 140 MW to reach a total of 814 MW, a post-contingency voltage deviation criterion will be violated for the contingency shown in the "limiting factor" field. In this case, the SWL will be 814 MW. Note that for transfer 3, the transfer limit bar is all green, indicating that the system is secure if the total system load is increased by 300 MW.

In Figure 7, a histogram is displayed for SWL for a period of 36 hours. The figure shows the forecast wind (blue), actual wind (white), and SWL (red) computed by WSAT. This diagram clearly shows the controller the pattern of SWL (with a cap at 250 MW over the actual wind generation) at different loading and wind generation levels. The plan is to add the forecast SWL to this diagram for the controller to prepare for future system security changes. The computation of the forecast SWL is already implemented in the EirGrid testing system and will be moved to the production system once the testing is complete.

Real-Time Implementation

WSAT was launched in EirGrid's control center in September 2010. The key results from this tool thus far are:

- ✓ Results have indicated that, at current levels of wind penetration, the voltage and transient stability of the system is largely unaffected by the level of wind generation. This is likely to change, however, as the power system evolves and wind generation penetration levels increase.
- ✓ Grid controllers have modified the output of generators per the preventative control measures recommended by WSAT. In one example, this resulted in reducing the output of a generator by 20 MW to avoid possible transient instability for a critical contingency.
- ✓ WSAT has led directly to changes of transmission line protection settings in areas of the system subject to severe transient instability problems.
- ✓ WSAT has been used to closely monitor an isolated area of the system susceptible to voltage collapse. This was not part of WSAT's original design scope but was implemented based on increased real-time operational knowledge of voltage stability.

WSAT has significant potential for further development in many areas, ranging from improving the models to the introduction of a comprehensive two-dimensional transfer analysis for both voltage and transient security assessment. WSAT is also being considered for prediction of power system security six to 24 hours ahead. Some of these features have already been implemented in the WSAT testing system at EirGrid. Figure 8, for example, shows a secure operation region nomogram obtained from a two-dimensional transfer analysis. The green area in this figure is the area of secure operation, while other colors represent areas where security criteria are violated.

For Further Reading

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