Secure Operation of Power System with High Wind Penetration

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Abstract— **With unprecedented growth of wind power stations being connected to the grids all over the world, the running of the power system becomes more and more challenging. In order to operate power system securely, not only its conditions at a given time should be examined, but also its projected conditions with varying amounts of wind generation should be checked.**

This task can be performed using proposed *W*ind generation *S*ecure Level *A*ssessment *T*ool (WSAT) based on stability analysis of transfers between wind power generation and conventional power generation on the power system.

In real-time (RT) application WSAT obtains modified power flow snap-shot file from SCADA/EMS and runs stability assessment of mentioned transfers. When one of the stability criteria thresholds is reached, the corresponding wind generation with agreed margin is considered as wind generation limit according to this criterion. WSAT can also make wind generation limit forecasts (FC) for next 24 hours using generation schedule from Reserve constrained unit commitment program and updates from Trader – most probable dispatch at a given instant of time.

Keywords - wind penetration, stability, security, WSAT

I. INTRODUCTION

Wind power generation share has significantly increased in generation portfolios of many countries and is set to further growth within next 10 years. E.g. the installed capacity of wind power stations (WPS) in Europe was near 70 GW (13% of peak demand) in 2008 and is planned to increase to 140-180 GW in 2015 [1]. Even more ambitious targets for renewable energy sources integration with wind its largest share are set in the island of Ireland aiming for 40% of energy being produced from renewable energy sources in 2020 [2].

The island of Ireland's power system is a separate synchronous system that has limited HVDC inter-connection to Scotland. The combined maximum/minimum demand of the two systems is approx. 6,800/2,500 MW. Tripping of the largest generator (440MW) can result in a frequency fall of more than 0.6 Hz even with primary fast acting operating reserve of 81% of the maximum in-feed. The relatively small size of the system also dictates wider frequency variations under normal conditions (±0.1 Hz 90% of the time). Generation plant (installed capacity) is mostly thermal, with some 6% hydro and hydro pumped storage, and 13% wind that is rapidly increasing as mentioned above.

An additional 500MW HVDC link to the UK grid based on VSC technology (due for commissioning in 2012) is expected to improve the island's ability to accommodate wind generation.

Increasing wind penetration changes the operational characteristics of the power system mainly because

- wind power generation technologies are different from conventional ones
- wind power output varies in time frames from seconds to hours
- it is impossible accurately predict wind generation at any given time

Increased levels of wind generation introduce new risks and challenges for the transmission system operator that they have to deal with [3].

In Ireland the lowest conventional generation possible could occur during low-load summer night valley. If only 50% of 770 MW of wind generation scheduled for connection before August 2010 will be commissioned, we can have instances of wind penetration of 70%. Already instances are recorded in Ireland with wind penetration of up to 50% [4]. Can the system be run safely with such big amount of wind that does not provide essential services like primary reserve, frequency governing, appreciable voltage regulation etc. that conventional generation does?

The maximum wind power penetration level can be estimated by the following equation:

$$P_{wind}^{\max} = P_L - P_{CG}^{\min}, \tag{1}$$

where P_L is total load demand; and $P_{CG}^{\min}$ is minimum conventional generation

$$P_{CG}^{\min} = \sum_{i=1}^{n} P_i^{\min gen} + R . \tag{2}$$

Here $P_i^{\min gen}$ is lower generation limit of conventional unit i and R is total operational reserve including provision for wind

$$R = w\left(\sum_{i=1}^{n}(R_i) + R_{st}\right), \tag{3}$$

where w is factor of operational reserve increase due to wind, R_i is reserve contribution from i-th generator without provision for wind, and R_{st} is a static reserve (HVDC backup, contracted load shedding etc). Factor w is estimated to be in the range 0.015 to 0.02 based on statistical analysis of 5-sec frequency and wind power variations on the Irish System) [5]. Fig. 1 schematically shows the wind curtailment requirements based on described approach.

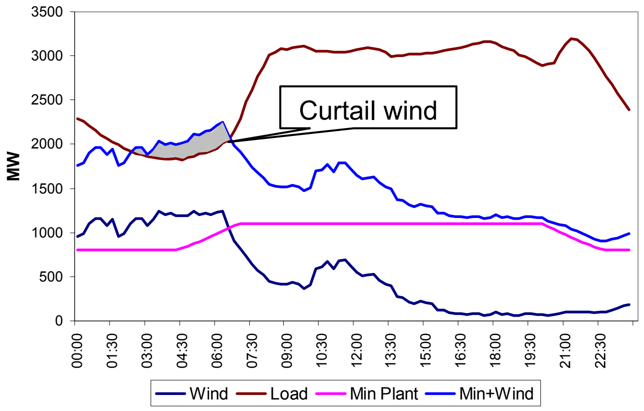

Fig. 1. Wind curtailment requirement

II. STABILITY OF THE POWER SYSTEM

The overall power system stability at given instant of time can be assessed by considering its components as depicted in Fig. 2 below.

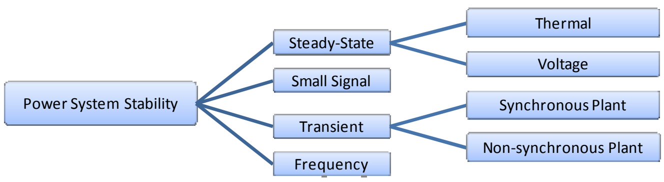

Fig. 2. Components of the overall power system stability

A. Components of Power System Stability

Steady-state stability can be described as ability of the system to arrive and safely operate without disconnecting the customers in conditions when one (N-1) or more (N-k) power system components (transmission lines, transformers, generators, loads) have been disconnected from the system. This includes

- Thermal stability – ability of the system to keep power flows in its elements below their thermal capability limits (thermal ratings) in all N-1 contingencies and credible N-k contingencies. Here under N-1, N-k contingencies we understand outage of 1 or k elements of the power system (transmission lines, transformers).
- Steady-state voltage stability – ability of the system to maintain secure voltage levels and voltage gradients on the system within standard levels in all N-1 contingencies and credible N-k contingencies.

Small-signal stability is an ability of the system to maintain synchronism of its synchronous plant and keep connected its non-synchronous plant if subjected to small disturbances. These can be small variations in loads, in generation including wind, changes of automatic settings etc.

Transient stability is an ability of the system to keep its components connected to the system if subjected to large disturbances. The latter can be faults on transmission system cleared by protection, or/and sudden trips of large generators or loads etc. This includes

- Synchronous plant stability - maintaining its synchronism (rotor angle stability)
- Non-synchronous plant stability – keeping other sources of generation connected to the system.

Frequency stability – ability of the system frequency to stay within safe limits and return to standard level if subjected to large disturbances as described above.

B. Criteria of Power System Stability

Using an appropriate model of the power system, power system stability components can be assessed by simulation of discussed conditions and/or disturbances and comparing the results with set stability criteria. Some of the criteria we use in WSAT are as follows:

- **Thermal stability criterion:** Lines, cables and transformers are loaded less than 100% of their nominal thermal ratings in base case and less than 110% in N-1 contingency cases.
- **Voltage stability criterion:** Steady-state voltage levels at all TSO buses (110 kV and higher) are within limits in per units (e.g. 0.9 – 1.1 in base case and 0.85 – 1.15 in N-1 contingency cases).
- **Synchronous plant transient stability criterion:** Maximum rotor angle of synchronous unit are within its ability to stay in synchronism (e.g. maximum angle separation of any two generators in the island 360^0).
- **Frequency stability criterion:** Frequency deviation on trip of a generation unit or three-phase fault with forced outage of the element (Line or Cable) is less than 1.0 Hz with duration of the frequency deviation bigger than 0.5 s.

III. SECURE LEVEL OF WIND PHYLOSOPHY

The inception of wind power generation and its increasing share in generation portfolio significantly changes generation patterns. The variety of such patters is virtually unlimited due to essentially random combination of load, weather, and Electricity Market conditions at any given instant of time. This in turn leads to unlimited verities in both base case and contingency case scenarios in terms of:

- Power flow patterns

- Voltage profiles
- Dynamic characteristics of the power system etc.

In these conditions power system operator needs to know what maximum amount of wind generation can be kept on the system without compromising its security. This maximum amount of wind generation we call a **S**ecure **W**ind generation **L**evel (SWL). We assess SWL at any given instant by our approach implemented on the base of PowerTech Labs Inc. DSATools [6] that employs on-line stability analysis of *transfers* between wind and conventional generation. Transfer is referred in this paper as an increase/decrease of wind generation in steps with matching decrease/increase of conventional generation according to its Merit Order.

The transfers are arranged as follows. Starting from the initial case (the power flow for the entire power system with initial values for the dynamic studies) the amount of wind generation MW (source) is increased by defined steps (e.g. 50 MW) in proportion to difference between maximum export capacity (MEC) of WPSs and their current production. The conventional generation (sink) in turn is decreased by the same amount based on its merit order down to its minimum generation. When the minimum generation limit of the conventional unit is reached, this unit is disconnected. During *i*-th transfer the source generation is increased/decreased until either one of stability criterion is violated or the source is fully dispatched. In case of stability criterion violation at step *k* the amount of wind generation at step *k-1* is considered as wind generation limit P_i^{tr} satisfying that stability criterion.

The overall SWL $P_{wind}^{on-line\max}$ on the system is estimated as a least of the wind generation limits of individual transfers as follows

$$P_{wind}^{on-line\max} = \min\{P_i^{tr}\} \qquad (4)$$

At present WSAT employs two transfers: VSA Merit ScaleUp transfer and TSA Merit ScaleUp transfer. In VSA transfer all N-1 and credible N-k contingencies are applied at each transfer step. In TSA transfer three-phase short circuits are applied at each transmission line of the transmission system and cleared by zone 2 protection. Also trips of biggest generating units are modeled at each TSA transfer step.

IV. WSAT Impementation

The structure of WSAT is shown in Fig. 2. The input data for WSAT is obtained from SCADA/EMS as power flow snapshot files ftp-ed to WSAT data server. Other data such as Wind power Forecast data [7] and RCUC data [8] is extracted from Corporate LAN.

WSAT operation is controlled by **DSA Service**. **WSAT Manager** is an interface module with full GUI for DSA Service. **VSAT Client** and **TSAT Client** are the Windows service version of VSAT and TSAT Client applications. They run on WSAT Client in real-time mode. **VSAT Server TSAT Servers** are the Windows service version of the VSAT and TSAT Server applications. They run on WSAT Server in real-time mode, but may also run on off-line study server. **WSAT Client** is the computer that runs DSA Service, DSA Manager, VSAT Client, and TSAT Client. **WSAT Monitor** is a Windows application that monitors WSAT operation and visualizes results.

The WSAT flow-chart is shown in Fig. 3. The current network state (snapshot file) is exported from SCADA/EMS to a raw data file (EMS RAW file) every 5 minutes by the real time data preparation tool (RTDPT) on the EMS and copied to the WSAT working directory.

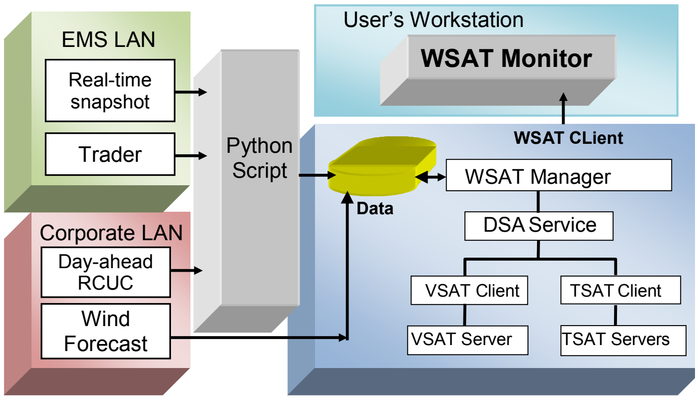

Fig. 2. WSAT software structure

Using Windows Scheduled Tasks WSAT runs a Python script which finds the most recent snapshot, modifies it according to the WSAT input data requirements and places it in a special directory which WSAT continually scans. WSAT uses equipment names instead of bus names because in the EMS RAW file bus names could change depending on the circuit breakers positions of multi-sectional substation bus-bars. Therefore the Python script adds unique names to the buses, loads, generators, branches, transformers, and switched shunts. The equipment names are based on data which is contained in the EMS RAW file. These names are used in all WSAT files that are maintained at WSAT client (contingency files, transfer files, dynamic files etc.). Further transformation in the EMS RAW file is to account for the fact that some of the WPS's appear in the snapshot file as negative loads, or embedded within a normal distribution transformer load. These WPS's need to be extracted from the loads and modeled as generators. Python script searches through the original RAW file and makes appropriate modifications to represent all WPS as generator models.

At present real-time EMS snapshot raw data file only covers the RoI's network. To obtain the RAW file for the whole island of Ireland a merging tool developed by PowerTech Labs is used to attach an equivalent model of Northern Ireland's power system. This merging tool will be discarded as SCADA data for the combined island's transmission network is available.

When WSAT finds a new modified file is ready, it starts calculation of SWLs for real-time (RT) case.

Wind Generation Forecast data is updated hourly and sent to the WSAT Server.

Forecast cases (FC) are proposed to be run as follows. Twenty-four hour ahead SWLs forecast (24FC) is calculated via separate task. It calculates one time point 24 hours in the future using network topology from the most recent EMS snapshot file while the conventional generation schedule, and load schedule are extracted from the data produced by market scheduling Reserve Constrained Unit Commitment (RCUC) tool sent to the WSAT server every 4 hours.

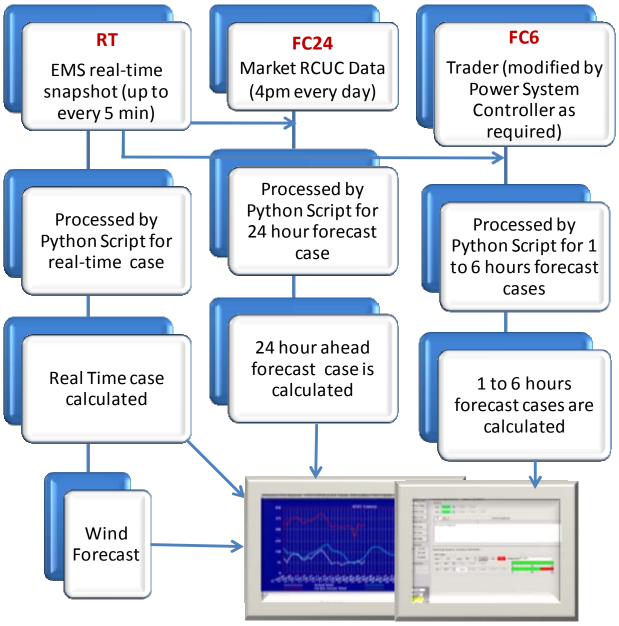

Fig. 3. WSAT flow-chart

The most up-to-date dispatch plan is contained in the Trader – the electronic table based on RCUC that includes operational modifications made in the National Control centre (NCC) by the power system operator. This dispatch is fed into first six hour forecasts (6FC) that are being re-calculated every hour based on the most recent network topology and Trader data.

WSAT offers an extensive output results that can be retrieved starting from higher level data (WSAT summary) to more detailed information. The operator can review results using the WSAT Monitor tool installed on Workstations connected to the Corporate LAN.

The power system operator will have access to all levels of output data that can be invoked on request, but only high level data will be presented on the GUI on a permanent basis. This allows the Operator not only to observe how the SWL evolves in time both for RT and FC, but also have quick answer on what criteria are violated, where they are violated and how this affects SWL.

Operator will be able to monitor overall WSL calculated by WSAT through GUI that offers both graphic and table form representation. In a customizable timeframe he can see the SWL results as shown by following example. In Fig. 4 a WSAT Summary in graphic form is shown. A the current instant of time the operator can see two results – the final point of RT calculation shown with a red curve, and initial point of FC calculation shown with golden curve. Past RT and future FC results give an insight into the dynamics of the SWL changes. These two curves can also be compared with actual wind power generation (white curve) and forecasted wind power generation (blue curve).

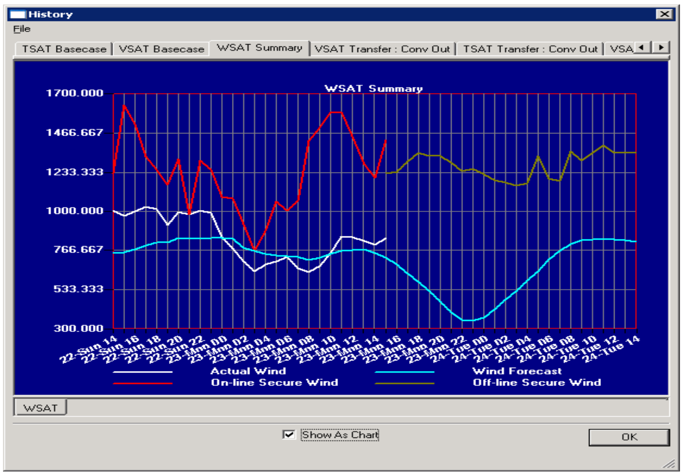

Fig. 4. WSAT summary: Red curve is a RT secure wind limit based on the lowest security limit; Golden curve is FC wind limit for next 24 hours; White curve is actual wind generation; and Blue curve is wind generation forecast. All data is in MW.

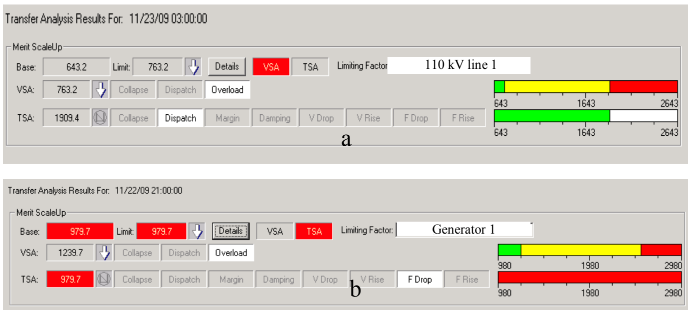

Fig. 5 Visualizations of transfer limits; green area – safe transfer; yellow area – the security criteria is violated; read – collapse: a) Overload due to "110 kV line 1" N-1 contingency in VSA Merit ScaleUp transfer; b) Frequency criterion (F Drop) violation due to Unit 1 trip in TSA Merit ScaleUp transfer

If the operator wishes to know what security criterion violation causes the SW limit at a particular point of time, they may consult graphs of employed transfers showing individual wind limits for thermal, voltage and frequency criteria explained in paragraph II. For example, the SW limiting factor for 3 hours on 23rd November (see Fig. 4) was VSA Merit ScaleUp transfer of Fig. 5a with thermal limit violation in N-1 contingency (outage of 110 kV line 1) that lead to 111.6% overload of other 110 kV line in this area "17010-23210" as can be viewed by operator in VSAT Viewer (extract from this Viewer is shown in Fig. 6). In other case (21 hours on 22nd November) limiting factor was TSA Merit ScaleUp transfer of Fig. 5b was violation of frequency drop limit due to Generator

1 trip. The frequency dip in this case can be viewed by TSAT Viewer as shown in Fig. 7.

From Bus		To Bus		Circuit ID	Area	Zone	Current (A)	Rating (A)	Load (%)
Number	Name	Number	Name						
17010		23210		1	16	4	679.44	608.84	111.6

Fig. 6 Information on overloaded element from VSAT viewer

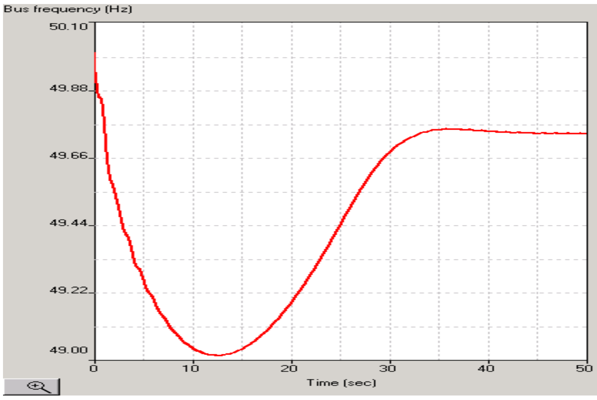

Fig. 7. Frequency change information in TSAT viewer

V. Challenges and Further Work

WSAT has been running on-line in EirGrid in test mode for a year. All three flows (RT, 24FC, and 6FC) of WSAT flow-chart at Fig. 3 have been partially tested, however at present only RT flow is fully implemented.

During this run a number of challenges have been identified and some of them addressed:

1) Thermal overloads of transmission circuits could be related both to wind and conventional generation dispatches. In last case overall SWL could be artificially low, as local generation re-dispatch (both wind and/or conventional) can eliminate overloads and thus increase the overall level of wind based on that criterion.
2) Relation between the amount of wind on the system and transient stability is nonlinear due to fact that different combinations of wind and conventional plant can be on-line in different cases. For example, conditions may occur that transient stability criterion is violated in base case, but in transfer case it is not because initially with wind increase the load of conventional units on-line decreases releasing additional rotating reserve. However, further increase of wind will force conventional units to hit their minimum and they will be disconnected from the system together with rotating reserve they carried before.
3) Network topology changes as a result of scheduled and forced circuit outages. This is more pronounced during summer period when most planned outages are being carried out.

The first and second challenges can be is resolved at present by producing a separate graph in the GUI for the operator to be able to estimate what causes overloads – local wind, system-wide wind or conventional generation. Also an option not to include base case insecurity that is not related to wind can be used in WSAT summary plot.

The third challenge is tackled by using the latest topology of the system for both RT and FC cases with FC cases being recalculated every selected time step (one hour at present) for every point in forecast time frame (at present 24 hours). This approach has its drawbacks as it does not catch the planned outages. We are currently investigating the feasibility of developing a program taking account of planned outages.

Future work will also be focused on the development of regional transfer philosophy as opposed all-island transfer philosophy used at present. This will allow more precise estimating the secure level of wind generation on the system with ability to establish regional limits and indicate possible preventive measures.

VI. Conclusions

Increasing wind generation penetration imposes significant challenges on the transmission system operator that has to maximize use of renewable sources of power generation on the system while maintaining high levels of reliability and security of the power system. In order to assist power system operator in secure running the power system an on-line tool assessing a secure level of wind penetration on the system at any given time is currently being developed and tested by EirGrid Plc and PowerTech Labs. The tool is based on the concept of finding the transfer limit between wind and conventional generation that satisfies selected security criteria.

Once implemented in EirGrid's EMS, the WSAT tool will be used to assess the maximum secure amount of wind power that can be accepted for a variety of system conditions.

VII. References

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