Verification of a Wind Farm Aggregated Generic Dynamic Model Based on a Real Fault Ride-Through Test in the Grid

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Abstract -- Full power converter wind turbines are believed to have better grid fault responses compared to other types of wind turbines. However, validation of this model with field measurement data is rarely reported in papers. This paper is aimed at validating a dynamic model of a wind farm consisting of full power converter wind turbines against field measurements recorded at Estonian power system.

I. INTRODUCTION

According to new Estonian Electricity Sector Development Plan, 30% share of wind generation in total installed capacity is foreseen by 2018. During the last 5 years there has been a remarkable increase in wind power development. One of the reasons is advantageous soil for wind power integration from government side, i.e. purchasing obligation and subsidies for electricity from renewable energy sources have been written into legislation. The overall amount of wind power capacity, which is applied for connection, is around 4000 MW. Current share of wind power that is in operation is 108 MW. The tendency shows that the capacity of wind generation almost doubles every year. Winter peak of electricity demand in Estonia is around 1 500 MW, which is significantly smaller compared to the amount of wind power connection applications.

The larger the percentage of wind turbines in generation portfolio the bigger effect they have on the system operation and the bigger is their responsibility to maintain stability of entire power system, even after major grid disturbances. One of the important functions in nowadays wind farms that support stable operation of power system is fault ride-through (FRT) capability. The FRT capability is investigated in this paper based on a real on-site test taken place in the Estonian power system.

In autumn 2008, Estonian TSO Elering performed an acceptance test for one of the wind farms connected to 110 kV transmission network. The purpose of the tests was to verify wind farm compliance with the Estonian grid code [1] and company standard [2]. One part of these tests was to validate FRT capability.

This paper is aimed at comparing real measurement data with composed dynamic model simulation results and determining their coincidence and the factors that have effects on their compatibility. The comparison makes it possible to verify and to evaluate the model accuracy and compliance with real operation.

Whilst wind turbine and its control system are complicated and various models are used to describe them, there is still a gap between their real operation and model simulation results. Several validations of wind turbine models against field measurement data have been reported. For example, in [3] and [4], validation of fixed speed wind turbines dynamic models is presented. A similar validation for a doubly fed induction generator wind turbine is reported in [5]. On the other hand, validation of full power converter is still rarely found in literature.

It is most important to minimize the model inaccuracy because in a heavily loaded power system, a small change in machine response can have influence on maintaining equilibrium state of the system operation. That is why in a small power system like the one in Estonia, additional on-site tests are necessary to be carried out.

II. WIND FARM TESTS AND MEASUREMENTS

In order to ensure proper operation of a new wind farm, functionality of its real-time information transmission and to verify the farm correspondence with the grid code, before it is being incorporated into the grid, comprehensive verification and acceptance tests on site are performed. Factory testing and wind tests by accredited laboratories are presumptions to qualify for final on-site tests before concluding grid connection agreement.

After the tests, verification of the models should be performed and the model should be supplied to the power
system operator for power system stability assessment, control and protection system coordination and planning purposes.

The profoundness of the test is induced by the characteristics of Estonian power system, its connection to IPS/UPS system and special regulations for upholding the frequency and voltage.

The purposes of on-site tests are particularly explained in [6]. The main targets of such a test are to identify the depth of voltage dip caused by short-circuit, to identify the power curve on PQ-diagram, to control the irregular change of generator terminal voltage, to determine the circumstances of overload characteristics, power quality parameters, etc. The testing comprises fast reduction and up-regulation of active power (for example, it is required in emergency cases that active power must be reduced from 80% to 20% in 2 seconds), regulation of voltage/reactive power ($V$ is constant, $Q$ is constant at different active power values etc.), a short-term disconnection (10 seconds) and reconnection of the connection between the wind farm and the power grid, wind farm in operation with and without central control system, etc. Additionally, real short circuit is carried out in the network to test wind turbine FRT capability. Intervals of all measurements, measurement configuration and testing and measurement techniques should correspond to IEC standard 61400-21 [7] and IEC Technical Report 61000-4-30 [8].

It is essential that all requirements should be fulfilled before connecting the wind farm into the power system without any restrictions.

A. Wind farm on-site test

The acceptance tests of observed wind farm, including a real fault test were performed in October 2008. The tested wind farm is located at the western part of Estonia, near the sea-coast close to Virtsu village. The wind farm consists of three full power converter wind turbines with nominal power 2.3 MW and it is connected to 110 kV transmission grid. The wind farm grid consists of one 16 MVA transformer with nominal voltages of 110/20 kV and approximately 3 km of 20 kV cable, leading sequentially to each turbine step-up transformer. The total capacity of the installed wind turbines is 6.9 MW though the planned capacity of whole wind farm is 13.8 MW and the rest of the turbines will be installed in the future.

To maintain the security of supply for other customers in the area during FRT test, the wind farm was connected to the system through radial scheme (Fig. 1). As seen in the figure, the wind farm is located at substation E (SS E). A three-phase short-circuit was applied on the line departing from substation A (SS A). During the fault test, the farm was connected to the main grid through 110 kV overhead lines, 35 kV submarine cables and six step-up transformers connected to both sides of the cables. In order to successfully perform the test, relay and other automation functions were disabled/adjusted.

Through preliminary calculations and simulations, it was determined that as a result of rearranged scheme, the voltage in the region would correspond to normal operation and during short-circuit the voltage at substation E, which is the closest one to consumers, will remain at sufficiently high level to minimize the disturbance on consumers side.

The measurements were performed using a power quality analyser operated by Tallinn University of Technology (TUT). The equipment enables to record voltages, currents, active, reactive and apparent power with the sampling rate of 9.6 kHz. During the normal operation, the parameters are stored after every 0.2 second. During transient events, the parameters are stored with sampling rate of 9.6 kHz for 6 seconds, which include 2.2 seconds of pre-fault measurement data. These features allow detailed investigation of electromechanical dynamic response of the wind farm.

The fault was applied on the 110 kV overhead line outsets close to substation A (see Fig. 1). Before the fault, the line was disconnected by feeder disconnector at substation A. At substation E near the point of common coupling (PCC) of the wind farm, the line was disconnected by a circuit breaker. At the fault point, portable conductors were connected on the line phases and the conductors were brought together, leaving air gap of 5 cm between the phases. Before the fault, relay protection settings and time delays were changed so the requested fault duration could be achieved. Switching on the short-circuited line circuit breaker at substation E resulted in electrical arc discharge between the electrodes. This discharge sustained until the relay protection switched the faulty line off.

![Fig. 1. Principal diagram of the network during FRT test in observed wind farm.](image)

The input data for measurement analysis and dynamic model tuning were instantaneous voltage (Fig. 2) and current (Fig. 3) in each phase, which were recorded with equipment described previously. A MATLAB routine was used to process the data and represent the desired quantities, e.g. RMS values of voltages, currents, active and reactive power.

B. Fault response of the wind farm

Duration of the symmetrical 3-phase short-circuit at substation A was 560 ms and remaining voltage at substation E was 0.03 pu (voltage dip 97%). Instantaneous voltage and current response before, during and after the short-circuit test are shown in Fig. 2 and Fig. 3, respectively. The pre-fault line voltage at the 110 kV measurement point was 1.1 pu. During
5 ms after the fault is applied, voltage at measured point was going down to nearly zero and remained at that level for 555 ms. Following the fault, the wind farm current increases by approximately 22%. A closer investigation shows that the current is in phase with the voltage. This fact indicates that the converter intentionally increase the active current injection in order to reduce the dc-link voltage build up due to power imbalance between the grid-side converter and the generator-side converter during the fault. 60 ms after the fault was initiated, the current goes to nearly zero, which suggests that the converters may be deactivated.

After the fault clearing, the voltage instantly increased up to 0.98 pu and then within 250 ms it smoothly increased to the pre-fault level at 1.11 pu.

The filtered active and reactive power measurement results of the FRT test are shown in Fig. 4. Before the fault, the wind farm power output was 6.73 MW, which is close to the rated value (6.9 MW). During the fault, the power output of the wind farm went down to zero. Power generation was restored close to the pre-fault level 1 second after the fault clearing. The continuous power output after the fault was 6.26 MW i.e. 7% lower than the pre-fault level. One plausible explanation of this power reduction is that the mechanical power of the wind turbine was reduced due to acting of pitch controller during the fault. Nevertheless, this power level still meets the criteria stated in the grid code that requests the wind farm power output to restore at least 90% active power production of pre-fault level.

After the fault clearing, the wind farm did not immediately generate active power. It took 200 ms until the wind farm active power output was gradually increased. The ramp up of active power generation from 0 to 6.26 MW was managed in 0.8 seconds.

During normal operation, the wind farm maintained zero reactive power exchange with the grid. Even during the fault, the wind farm was able to maintain the reactive power flow at zero level. Instantly after the fault clearing, wind farm consumed 3 MVAr of reactive power and after 500 ms the reactive power exchange between the grid and wind farm was balanced again.

The reactive power consumption phenomenon was investigated in frame of current paper. There were two preliminary guesses for reasons that might cause such kind of reactive power response, i.e:

- Inrush currents of wind farm power transformers after voltage restoration
- Reactive power flow from the grid is compensating the differences in voltages at wind turbine converter terminal and at grid side instantly after fault was cleared.

During the fault the voltage at converter terminals was reduced close to zero and the current contribution by the wind turbines during the fault was inappreciable.

Inrush currents of transformers have characteristics similar to the measured ones, especially considering the profile of the current waveform [9]. Consequently the second mentioned assumption was found out as most probable reason for such reaction in reactive power flow. However, for a more accurate investigation, a detailed model of converter with all its function logics and detailed model of transformer should be available.

Despite the transient explained above, these reactive power changes during and after the fault are acceptable at the observed case. However, it may be necessary to improve the reactive power response performance, especially in respect of large scale wind farms where large reactive power injections...
towards wind farms after faults could result in an unacceptable voltage change in the rest of the grid.

From the measurement data it can be seen that there are no significant power oscillation and it affirms the fact that full power converter wind turbine is able to respond quickly to the changes in grid voltage and to achieve desirable active and reactive power output within a short period of time.

III. MODEL OF FULL POWER CONVERTER WIND TURBINE

During a grid fault, the capability of the grid-side converter of wind turbine to inject active power is limited, while the power flow from the generator remains large. As consequence, the power from the generator is accumulated in the dc-link, which causes an increase in the dc-link voltage. If the accumulated power is not dissipated, it may lead to dc-link over-voltage which may harm the power converters.

One solution to maintain the dc-link voltage level within the allowable limits is to dissipate the excess of power by means of a dc-link chopper. In this way, the generator terminal does not sense any disturbance since the dc-link voltage is virtually maintained constant [10].

If the excess of power in the dc-link during fault cannot be fully diverted into the dc-link chopper, the generator power must be reduced. This reduction leads to wind turbine overspeed, thus the aerodynamic power must also be reduced by adjusting the pitch angle [10].

In this paper, however, the generator power is assumed to be constant and therefore there is no need to model the generator and the generator-side converter when investigating short-term voltage stability. In other words, the full power converter wind turbine can be sufficiently modelled by a power controlled grid-side converter taking into account the current and voltage measurement time responses.

As shown in Fig. 5, the injected active and reactive current components are controlled by means of PI controllers. The delays in the current and voltage measurements are represented by time constants $T_i$ and $T_v$ respectively. The wind turbine model is then integrated into PSS/E network model as a voltage source behind transient reactance.

The fault response of grid-side converter, while PSS/E is used to implement the full converter wind turbine model for a system study, whereas the power system network is modelled in PSS/E format. Moreover PSS/E enables to assess the functionality of the model in different operational regimes and in case of different faults. The preliminary result confirms that the model is in compliance with the system model and gives similar results with the measurement data (Fig. 6, Fig. 7 and Fig. 8). System simulations were not performed in this paper since they are beyond the scope of this study, however it is planned to elaborate the model and perform system studies in the future.

IV. SIMULATION AND VALIDATION OF THE MODELS

In the simulation, PCC bus voltage is used as an input for the wind turbine model. Response comparison between the measurement and the simulation data is presented in Fig. 6 to Fig. 8.

![Fig. 6. Measured and simulated voltage at the PCC](image)

![Fig. 7. Measured and simulated active power response of the wind farm at the PCC](image)

![Fig. 8. Measured and simulated reactive power response of the wind farm at the PCC](image)

As discussed earlier, the power level after the fault is slightly lower than the level before the fault due to reduced aerodynamic power. In contrast, the mechanical power is assumed to be constant in the model/simulation and hence the electric power output return to the nominal level once the
voltage level is recovered. Nevertheless, the maximum power level discrepancy between the measurement and the simulation result is less than 0.1 pu.

As shown in the measurement data, during the fault the reactive power is kept zero. At the moment of fault clearing, the wind farm absorbs reactive power. However, a relatively quick response of the converter is able to maintain the reactive power level close to the initial value within 500 ms. The simulation result shows that the reactive power response of the wind farm can be well reproduced by the model. In this simulation, the total reactive power response of all components behind the PCC is emulated in the wind turbine model.

V. CONCLUSIONS

In this paper field measurement data, containing fault response of a wind farm consisting of full converter wind turbines was presented. The observed wind farm successfully fulfilled the requirements of the grid code and remained connected to the grid after severe fault close to the wind farm.

In frame of this paper, an aggregated model of observed full converter wind turbines was developed. Grid model of the corresponding network was rearranged according to operational regime during measurements and the developed model was implemented in the network model. The response accuracy of the wind farm aggregated model is verified against the measurement data and it was found that despite simplifications the model enables to simulate the important characteristics of the wind farm response when subjected to a grid fault.

To achieve better compliance of the model with real operation, more measurement data should be available, especially for different operation regimes and different output power.

As in near future there will be more on-site tests and measurements while new wind farms are integrated to the grid, there will be additional information with increased quantity and details. New measurements allow us to elaborate the existing models and to design new models for different types of full converter wind turbines. In the next step, system simulations can be performed to analyse large-scale integration of wind farms and the dynamic stability of power system.

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