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Field experience with Statcom in application to wind farms

***Abstract**. In the paper field experience with Statcom in application to a wind farm is presented. Statcom in such applications is usually used to provide low voltage ride-through and improve stability of the power system. In this case the reactive power compensation capabilities are utilized. Statcom can generate reactive power according to a selected strategy directly in the point of connection of the wind farm to the power system. This provides additional advantages over the direct turbine control: it can stabilize the power system, decrease flicker level and provide reactive power directly in the DSO's connection irrespective of wind farm's turbines operation.*

Streszczenie.** Artykuł prezentuje doświadczenia z wdrażania układu typu Statcom do kompensacji oddziaływania farmy wiatrowej. Kompensatory Statcom w tych zastosowaniach zwykle używane są do zapewnienia poprawnej pracy podczas zaburzeń napięcia oraz do poprawienia stabilności systemu elektroenergetycznego. W prezentowanym przypadku wykorzystano zdolność układu do nadążnej kompensacji mocy biernej. Kompensator wytwarza moc bierną w zależności od wybranej strategii kompensacji bezpośrednio w punkcie przyłączenia farmy do systemu. Taki sposób przyłączenia ma szereg zalet w stosunku do bezpośredniego sterowania mocą bierną turbin wiatrowych: umożliwia m.in. stabilizację systemu, zmniejszenie poziomu wahań napięcia i generację mocy biernej niezależnie od trybu pracy turbin. **Doświadczenia z wdrażania układu typu Statcom do kompensacji oddziaływania farmy wiatrowej

Keywords: wind farm, Statcom, reactive power compensation, system integration, ancillary services.
Słowa kluczowe: farmy wiatrowe, Statcom, kompensacja mocy biernej, przyłączenie do systemu, usługi systemowe

Introduction

Increasing share of wind power in power system causes issues that could affect supply quality and stability of the power system. Integration of wind farms (WF) with the power system requires additional ancillary services. On the other hand a WF can be also utilized as an ancillary service provider. The services could include reactive power compensation, voltage regulation, and flicker control.

Requirements of power system operators for WF can be divided into three general groups:

1. capability to work under a power system fault or voltage dip condition,
2. capability to regulate voltage or reactive power,
3. capability to regulate power frequency and system stability improvement.

The requirements can be fulfilled with control of wind turbines or by means of additional conditioners e.g. Statcom. Wind turbines with double feed induction generators (DFIG) work with variable speed and can provide reactive power control. Application of DFIG turbines is beneficial for the power system despite the cost of extra converter. However DFIG turbines are susceptible to voltage dips caused by faults in the power system. Power electronic solutions can be used it this case to improve low voltage ride-thought (LVRT) of the turbines. The solutions can be additionally used to provide ancillary services like voltage regulation or reactive power compensation. This application involves utilization of Statcom compensators.

State-of-the-art studies of Statcom are mostly focus on enabling WF to work under power system faults and to improve the system stability. In [1] Statcom is applied to stabilize voltage on a wind turbine terminals. The study presents a comprehensive computer simulations of different techniques to fulfill grid requirements. Statcom is found effective however utilization of DFIG converter would be more advantageous in some specific cases. In [2] application of Statcom to compensate reactive power of WF is analyzed. Analysis of three compensation strategies by means of digital simulation is presented. The conclusion is that the Statcom compensator significantly improves voltage stability margin during e.g. a voltage drop caused by large load start-up. Application of Statcom to improve LVRT is analyzed also in [3, 4, 5, 6, 7]. Solving WF integration issues with Statcom is also analyzed in [8].

Reactive power control of WF is proposed in [9, 10]. In the papers three compensation strategies: constant power, constant power factor and constant rms voltage are described and analyzed by means of computer simulations. The articles focus on wind turbines control in order to mitigate flicker severity, but the analysis is also useful for selecting compensation strategies for WF in general. The main conclusion in [9] is that a WF should generate reactive power in fixed lagging power factor mode in order to mitigate voltage variation. The conclusion is based on analysis of WF connected by means of different MV overhead lines i.e. with positive X/R ratio. In [10] wind turbine limitation is also analyzed with the final conclusion that a WF should include extended reactive power capabilities in order to limit the flicker emission.

It becomes clear that it is possible to achieve abovementioned requirements by means of a Statcom compensator connected in PCC of WF and MV/HV station. This is the main motivation for the Statcom installation presented here and for study efficiency of its compensation strategies. The main goal is to build an industrial-scale pilot installation which facilitates developing of optimal compensation strategy for Statcom.

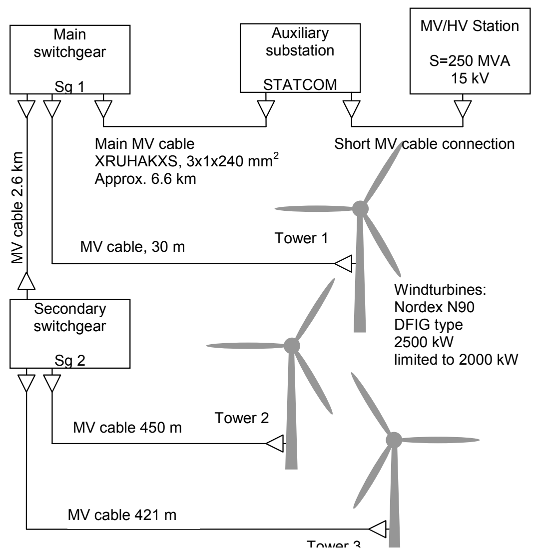

Fig. 1. Schematic diagram of the system

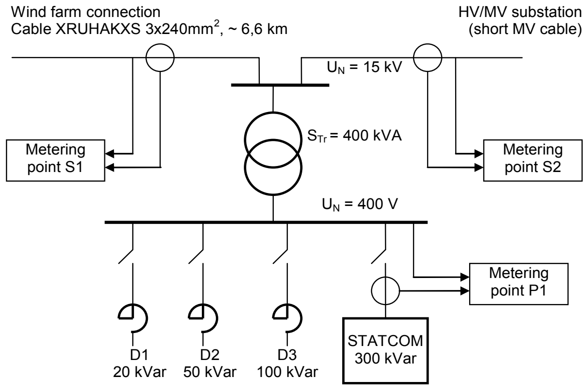

Fig. 2. Schematic diagram of the system – auxiliary substation

The paper describes some field experiences with operation of the Statcom – installation, start-up and initial compensation studies.

System description

The power system with a wind farm is shown in Fig. 1. The WF consists of three DFIG type wind generators of 2.5 MW nominal power. The turbines have their generation limited to 2 MW each, so the total power of the WF is 6 MW. The turbines are connected by means of MV cable to the main switchgear Sg1. Due to local conditions the towers are not in one place but rather distributed in some area, resulting in quite lengthy cable interconnections. The main switchgear Sg1 provides common point of connection to the grid. The switchgear Sg1 and MV/HV station are connected by approx. 6.6 km MV cable. This type of WF integration is quite common in the country.

The main issue in this system is that the total reactive power of the MV cables dominates over the WF resulting in high billings due to excessive capacitive energy. Consequently, the auxiliary substation with compensation chokes has been built in close proximity of the MV/HV substation – see Fig. 2. The main function of the chokes is compensation of the total reactance of the cables. This solution has not been found as effective as expected. The WF is equipped with DFIG type turbines which can work in different reactive power control modes. On the other hand the cable reactive power depends on the voltage which in turn changes during a day. In consequence the total reactive power measured in the point of evaluation (MV/HV Station) varies significantly which makes typical, passive compensation very difficult to adjust. This was the main reason to utilize a power electronic solutions i.e. 300 kVar Statcom – see Table 1.

Table 1: Nominal parameters of the Statcom

Nominal power	300 kVar
Supply voltage	3 x 400 V
Mains frequency	50 Hz
PWM switching frequency	5 kHz
Rated RMS current	450 A
Peak current	1000 A
Current ripple	< 0.5 A
Response time	63 μs
Ambiend temperature	5°C to 40°C
Cooling	forced air flow

Statcom

Statcom is an power electronics device connected to power system which is able to produce reactive (capacitive or inductive) current in fully controllable manner. It consists of a voltage source inverter (VSI) which produces sinusoidal voltage in phase with the supply voltage. Voltage drop across the coupling inductor forces reactive current flow. Therefore by controlling amplitude of the VSI voltage a full control on reactive current is obtained. Statcom is used in the industry as a fast reactive power compensator.

The reactive power is calculated utilizing only fundamental components:

(1) $$Q_{(I),1} = 3U_{(I),1} I_{(I),1} \sin\varphi_{(I),1}$$

where $Q_{(I),1}$ is reactive power, $U_{(I),1}$ is a positive symmetrical component of fundamental voltage, $I_{(I),1}$ is a positive symmetrical component of fundamental current, $\varphi_{(I),1}$ is phase shift between positive components of current and voltage.

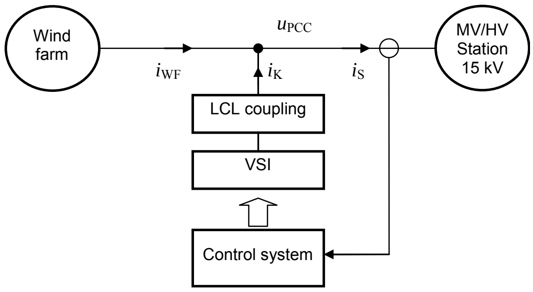

Fig. 3. Control system of the STATCOM

Figure 3 presents schematic diagram of the Statcom. The device contains three main parts

1. voltage source inverter (VSI), which consists of two parallel inverter modules,
2. LCL coupling circuit which produce reactive current based on voltage difference between VSI and the system voltage; the circuit also compensates ripples originating from PWM,
3. a controller unit responsible for computation of reference values.

a)

b)

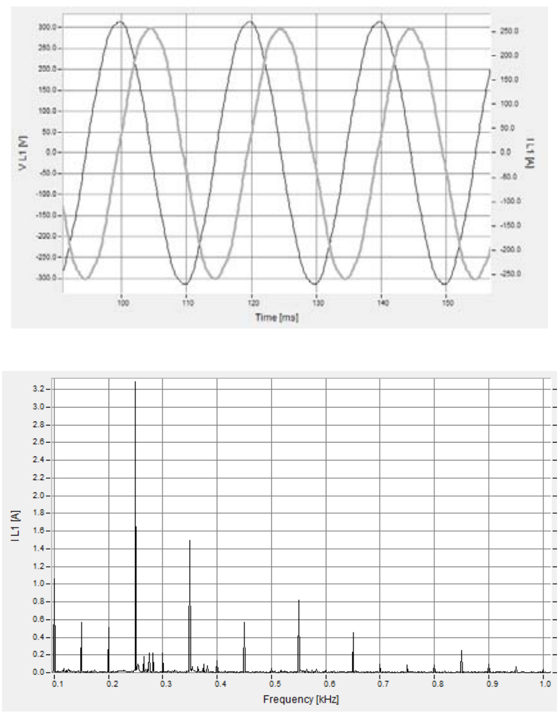

Fig. 4. Waveforms of voltage (thin black) and current (thick gray) of phase L1 (a) and spectrum of the current (b)

The control loop works in feedforward or feedback mode depending on requirements. In the presented installation only feedback control loop is utilized. The main parts of the controller are:

- DC voltage regulator to cover losses,
- current reference calculation based on selected compensation strategy,
- current regulator,
- PLL with prediction of PCC voltage.

Typical Statcom utilizes a choke to produce reactive current. However in order to suppress PWM ripples and provide non-distorted waveform there is advanced passive LCL coupling utilized [11].

Although Statcom can provide LVRT and diminish flicker emission of WF, it is used as a fast reactive power compensator. The Statcom is able to utilize one of three compensation strategies in the point of common coupling (PCC):

- constant reactive power,
- constant power tangent,
- constant rms voltage.

The PCC is the auxiliary substation and current measurement is done in the DSO connection which is equivalent to feedback control of the Statcom.

Table 2. Voltage and current distortion analysis

		Currents			Voltages		
		L1	L2	L3	L1	L2	L3
THD [%]		2.77	2.70	1.31	1.80	1.71	2.11
Fundamental		239.26	241.14	242.32	314.04	315.80	313.37
Harmonic [%]	2	0.61	0.32	0.49	0.06	0.05	0.08
	3	0.33	0.54	0.84	0.21	0.17	0.10
	4	0.21	0.17	0.12	0.04	0.02	0.05
	5	1.90	1.88	1.59	0.45	0.50	0.44
	6	0.10	0.08	0.02	0.05	0.01	0.05
	7	0.91	1.04	0.94	1.22	1.13	1.05
	8	0.07	0.07	0.08	0.04	0.02	0.06
	9	0.32	0.15	0.26	0.04	0.03	0.08
	10	0.06	0.09	0.06	0.03	0.04	0.08

Installation and start-up

The installation is under field tests from Dec. 2014. The most important aspect of the power electronics based compensator is the ability to generate non-distorted current so the supply quality in the PCC is not deteriorated. Disturbance emission from the WF is quite small due to relative high short-circuit capability and lack of nonlinear loads in the PCC. Due to the presence of the MV cables (distributed capacitance) there is always a risk of a resonance so keeping small emission of harmonics form the Statcom is crucial. Figure 4 shows Statcom current and supply voltage waveforms with current spectrum analysis. Table 2 shows analysis of voltage and current distortion of a selected phase. There is no significant distortion or ripples originating form PWM. Fifth and seventh harmonics are also present in the grid current but the values are relatively small. Theirs direction varies during a day and are probably connected with supply distortion caused by upstream loads.

Operation of Statcom can be affected by short-term variation of the WF power e.g. due to power oscillations. Figure 5 shows an example of power oscillations obtained by measurement with 20 ms interval. Two oscillation frequencies can be identified in the active power waveform, with the shortest period of approx. 66 ms. The oscillations are approx. 40 kW of amplitude which is approx. 5% of generated power. The amplitude is highly variable and there are also time periods without any oscillations. Power variations can have impact on Statcom output power which in turn can amplify the oscillations. Controller parameters of the Statcom has been adjusted in the manner that Statcom do not generate oscillating power. In the analyzed system the oscillations do not have big influence on voltage variation in PCC due to short-circuit capability of the grid.

a)

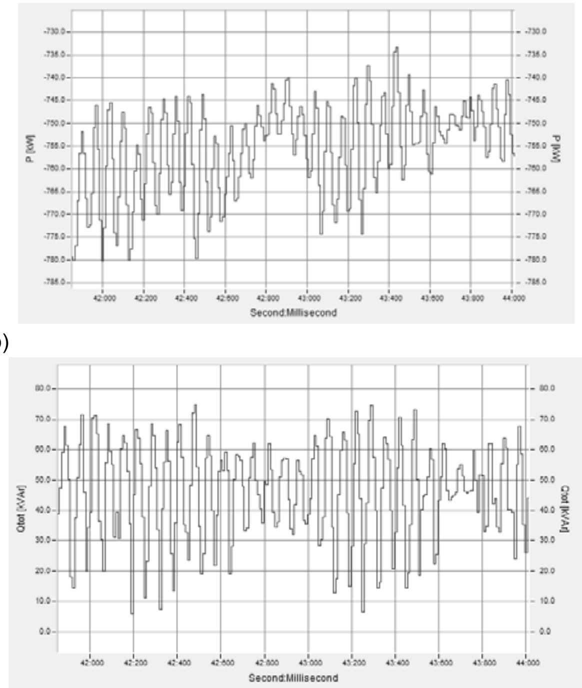

Fig. 5. Active (a) and reactive (b) power oscillations of the wind farm. Negative active power means energy generation, reactive power is presented as absolute value of capacitive power

a)

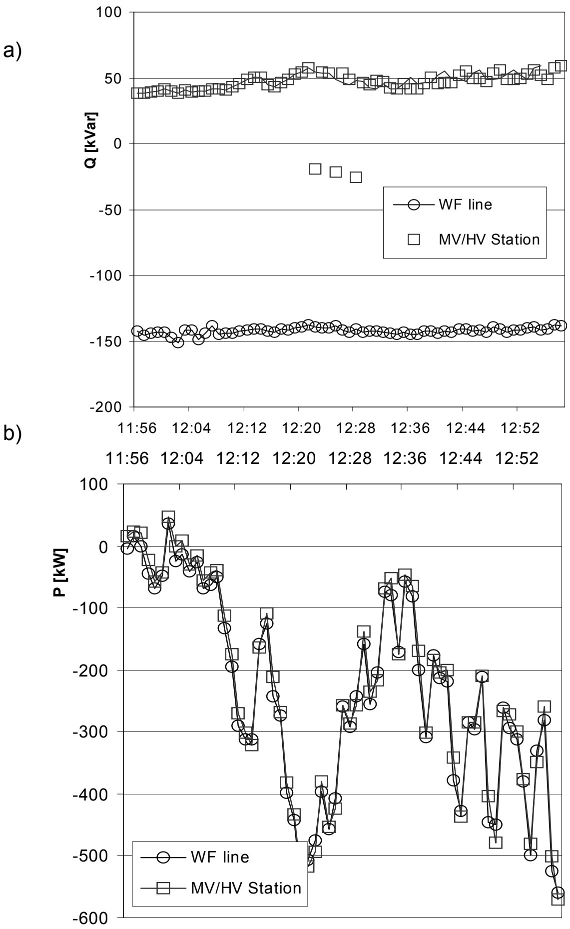

Fig. 6. WF line and DSO's line power in fixed reactive power mode of compensation: reactive power (a) and active power (b). Negative reactive power values indicates capacitive power, negative active power indicates energy generation

Fixed reactive power mode

This mode of control stabilize reactive power of MV/HV station line despite changes in the active or reactive power of WF. The mode could be useful to decrease variation of reactive power and decrease voltage variation in consequence. Some reports e.g. [9] concludes that this mode is equivalent to fixed power factor control according to diminishing flicker and losses. When the strategy is applied to wind turbines control it is equivalent to have fixed compensation unit and can enforce stiff voltage profile for weak grids [10]. Therefore the strategy has been implemented in order to test whether it would be beneficial for WF.

Some preliminary measurements are presented in Fig.6. The figure shows active and reactive power of WF and DSO line (metering point S2). Reactive power of the DSO's line is kept constant at approx. 47.1 kVar (lagging) regardless the active power change. Reference value for the power is 40 kVar (lagging), average reactive power of the WF line is approx. 142kVar (leading). The difference between reference and actual value is the measure of static controller bias and metering uncertainty. During the test Statcom went three times into emergency operation which rendered negative reactive power measurement in the DSO line. Samples related to this state are marked as outfits and removed from further analysis.

Due to short metering duration (approx. 1 hour) it is not possible to fully evaluate efficiency of the mode – during the metering the WF reactive power is quite constant..

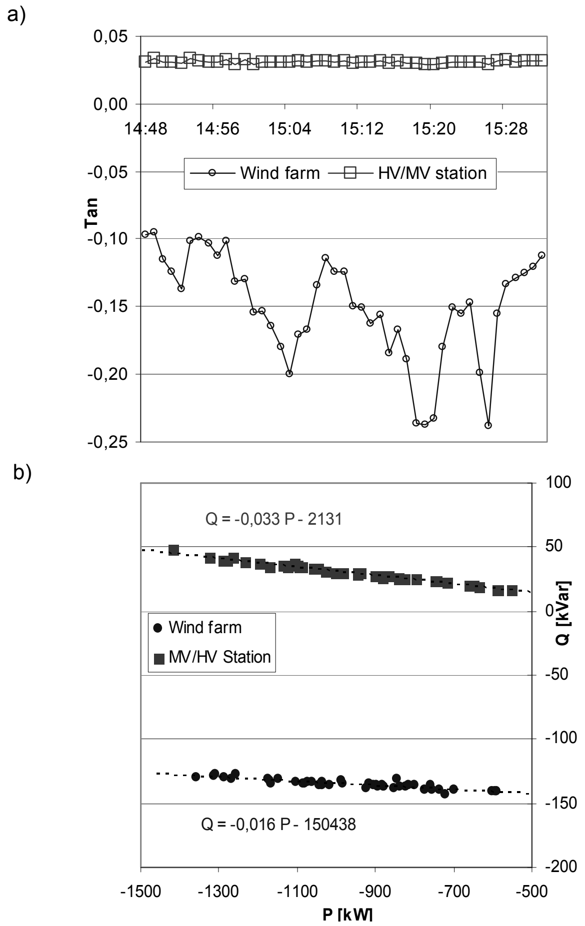

Fig. 7. Power tangent (a) and P-Q correlation (b) of a FW and DSO connection obtained during tangent stabilization strategy. Negative reactive power values indicates capacitive power, negative active power indicates energy generation

Fixed power factor mode

In this mode Statcom generates reactive power so the ratio of active to reactive power in DSO's connection is constant. The strategy is recommended in [9] for WF control in order to mitigate the flicker emission from the WF. The mode could also be beneficial in some cases e.g. due to tariff constraints, when the billings are evaluated based on power tangent.

In this test Statcom keeps the tangent at constant level of 0.03 (lagging). Figure 7a presents power tangent of WF and DSO. The tangent is kept constant and variability of the WF tangent is also decreased. Statcom produces approx. 165 kVar in average. Operation of the Statcom is visible also in P-Q correlation diagram – Fig. 7b. In this diagram each point represent a specific value of active and reactive power. In the figure there are also linear trends with identified equations. The slope of the DSO's trend line resembles the reference tangent, however the slope of FW trend line could be related with the wind turbine operation. The distance between the trend lines is related to Statcom operation. It can be concluded that Statcom not only compensates the capacitive power but also effectively changes power profile i.e. active to reactive power ratio.

Conclusions

In the paper some field experiences with Statcom application to a wind farm are presented. The main reason for the installation is to build a test facility for developing and testing compensation strategies. Statcom capabilities can be used to improve integration of wind farms with the power system. The paper presents measurement results done during installation, start-up and initial operation of the Statcom.

The main issue to solve in this particular wind farm is dynamical compensation of reactive power. The owner of the wind farm bears high costs due to exceeding capacitive power created by underground cable connection. It could be compensated by adjusting operation of wind farm turbines. Preliminary results presented here shows that Statcom can be an efficient solution, however the final conclusion can be drawn after long-term tests.

The secondary goal is to provide a pilot installation for studies to what extent WF can operate as an ancillary service provider. Installation of power electronics compensation devices enable WF to e.g. change voltage profile in the PCC which in turn can be beneficial for DSO.

Currently the Statcom is under service and will be soon operational. Therefore long-term measurement will be possible to carry in order to proof economical efficiency of the compensation.

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