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RESEARCH NOTE

Comparative Study of the Performance of Static Synchronous Compensator, Series Compensator and Compensator /Battery Integrated to a Fixed Wind Turbine

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ABSTRACT

This paper studies the interest of the integration of battery energy storage with Static Synchronous Compensator (STATCOM) for improving the low voltage ride through capability (LVRT) of a fixed speed wind turbine connected to the grid. For this reason and by applying a grid fault, a comparison is made between integrating the SSSC, the STATCOM and the STATCOM with battery energy storage. The system with the aforementioned flexible alternating current transmission system (FACTS) systems is simulated using MATLAB/SIMSCAPE and the results show that the STATCOM with a battery is most efficient in terms of improving the LVRT of a fixed speed wind turbine.

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1. INTRODUCTION

The penetration of wind power into the electric power systems is in constant growth, which presents a great challenge to meet the network requirements. Indeed, with the increasing share of energy from the wind power system, wind turbines have to remain connected to the grid in transient voltage conditions in order to be in compliance with the grid codes which vary according to the transmission system operator (TSO) [1, 2]. The grid requires that wind turbines be treated as conventional production units and participate in the regulation of active and reactive power and voltage control, and system frequency [3].

In this paper, we examine the ability of a fixed speed wind turbine to gather under voltage grid requirements and stabilize the grid voltage during faults by applying the FACTS devices. The performance of this system with either the STATCOM system compensating device or the SSSC has been shown in several studies but the objective of this study is to compare the performance of the STATCOM, SSSC and the STATCOM with a battery energy storage.

For this purpose, we model in MATLAB/SIMSCAPE, the system under grid fault with firstly the STATCOM, the SSSC and finally with STATCOM/battery energy storage. These FACTS devices are evaluated for their performances in terms of under voltage requirements and from the simulation results, a comparison of their performances is presented.

2. SYSTEM PRESENTATION

The system consists of a fixed speed wind turbine connected to the grid. The FACTS device (STATCOM, SSSC or STATCOM with battery) is connected between the wind turbine and the grid at the point of common coupling PCC (Figure 1) in order to improve power quality during faults.

2. 1. Wind Turbine Wind turbines are systems that harness the kinetic energy of the wind for useful power. Wind flows over the rotor of a wind turbine cause

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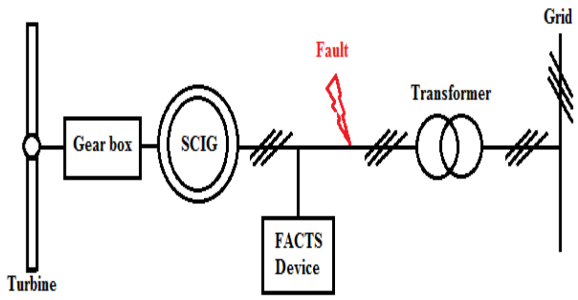

Figure 1. SCIG connected to the grid

it to rotate on a shaft. The resulting shaft power can be used for mechanical work, like pumping water, or to turn a generator to produce electrical power [4].

For converting kinetic energy into electrical energy, two different approaches exist, fixed speed and variable speed [5]. The fixed speed wind turbines using squirrel-cage induction generators (SCIGs) are the traditional ones while the variable speed wind turbines have received increasing attention during the past decades. Although the use of variable speed wind turbines is the trend, fixed speed wind turbines are still used widely especially in offshore wind farms [6, 7].

In this work, the fixed speed wind turbine using squirrel-cage induction generator is used. During a fault, squirrel-cage induction generator will accelerate due to the imbalance between the mechanical power extracted from the wind and the electrical power delivered to the grid. After a fault, the generator consumes reactive power and it slows down voltage restoration. When the voltage does not rise quickly enough, the generator continues to accelerate and consume even larger amount of reactive power. This process may eventually lead to voltage and rotor speed instability, if the wind turbine is connected to a weak grid. To prevent these types of instabilities, the fact devices can be connected to the system.

2. 2. STATCOM The Static Synchronous Compensator (STATCOM) is a switching converter-based, shunt connected device used to regulate voltage and power flow on electric power systems by means of reactive power injection or absorption [8]. This device consists of a voltage-sourced converter (VSC), which generates a controlled AC voltage at its output, with the use of a coupling transformer, DC capacitor and power electronics [9]. The converter is controlled by PWM techniques (Figure 2).

2. 3. SSSC The Static Synchronous Series Compensator (SSSC) is one of important FACTS devices.

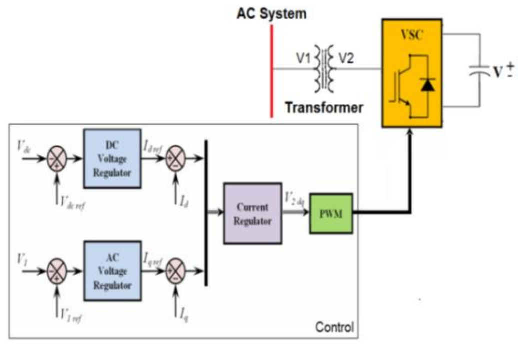

Figure 2. STATCOM control scheme [9]

It is a voltage source converter which injects, from a DC voltage source (capacitor), an almost sinusoidal voltage of variable and controllable amplitude and phase angle, in series with a transmission line [10].

The injected voltage is almost in quadrature with the line current in order to increase or decrease the overall reactive voltage drop across the line and thus control the reactive power flows.

The control system (Figure 3) implements a PWM that generates the switching signals for the VSC from the calculated *d* and *q* components of the converter voltage [9].

2. 4. STATCOM/Battery Without an energy storage system, FACTS devices can support the grid with only reactive energy. By integrating an energy storage system (ESS) with FACTS devices, an independent real and reactive power absorption or injection into and from the grid is possible.

Since the STATCOM is the most important FACTS device, the combination of STATCOM with ESS enables significant performance improvements over traditional STATCOM. In fact, with this combination, it is possible to control also the active power flow between the STATCOM and the grid unlike the STATCOM without ESS which allows an exchange of reactive energy only.

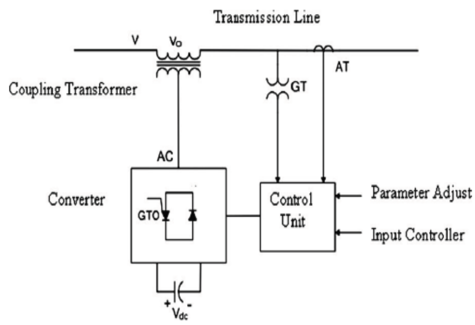

Figure 3. Systematic diagram of SSSC

The ability to control the active power and reactive power is highly effective especially for damping rapidly the oscillations and responding to sudden load transients.

The combination STATCOM with ESS is realized by integrating an ESS to the DC bus of the STATCOM. The ESS used are: Superconducting Magnetic Energy Storage (SMES), Flywheel Energy Storage (FES), Advanced Capacitors and Battery Energy Storage. The Battery Energy Storage is the best suited in STATCOM since it rapidly injects or absorbed reactive power to stabilize the grid system. It also controls the distribution and transmission system in a very fast rate.

3. SYSTEM MODELING IN MATLAB/SIMSCAPE

The wind energy generating system is connected to the grid through a transmission line of 25 km. We apply a fault to the system in order to measure the performance of the different FACTS devices: STATCOM, SSSC and STATCOM/battery. So, we have three topologies to model in MATLAB/SIMSCAPE.

The model of the system with the STATCOM is illustrated in Figure 4. The detailed model of the subsystem ‘wind turbine’ is illustrated in Figure 5.

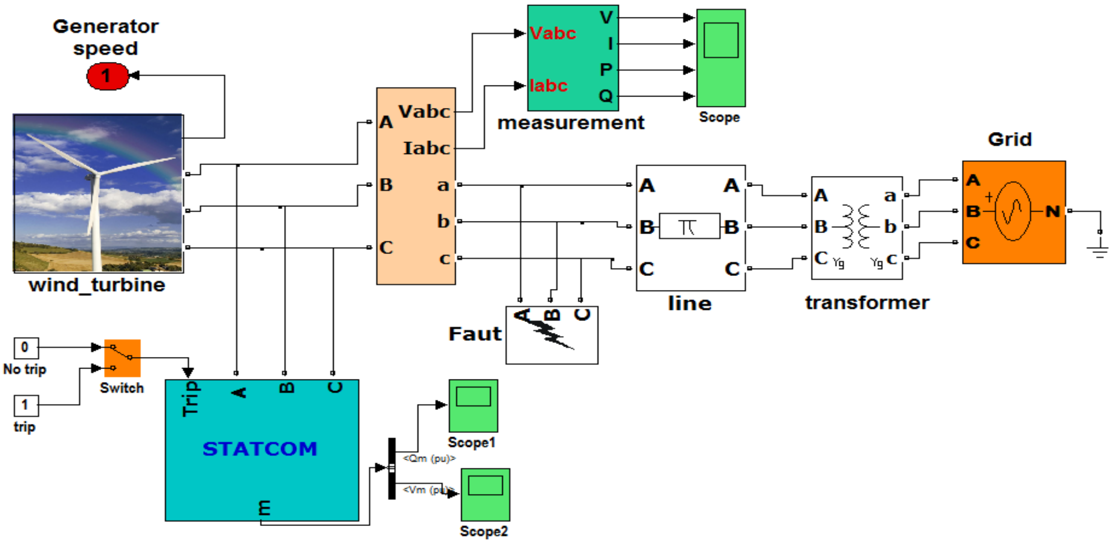

Figure 4. Model in SIMSCAPE of the wind turbine with STATCOM during fault

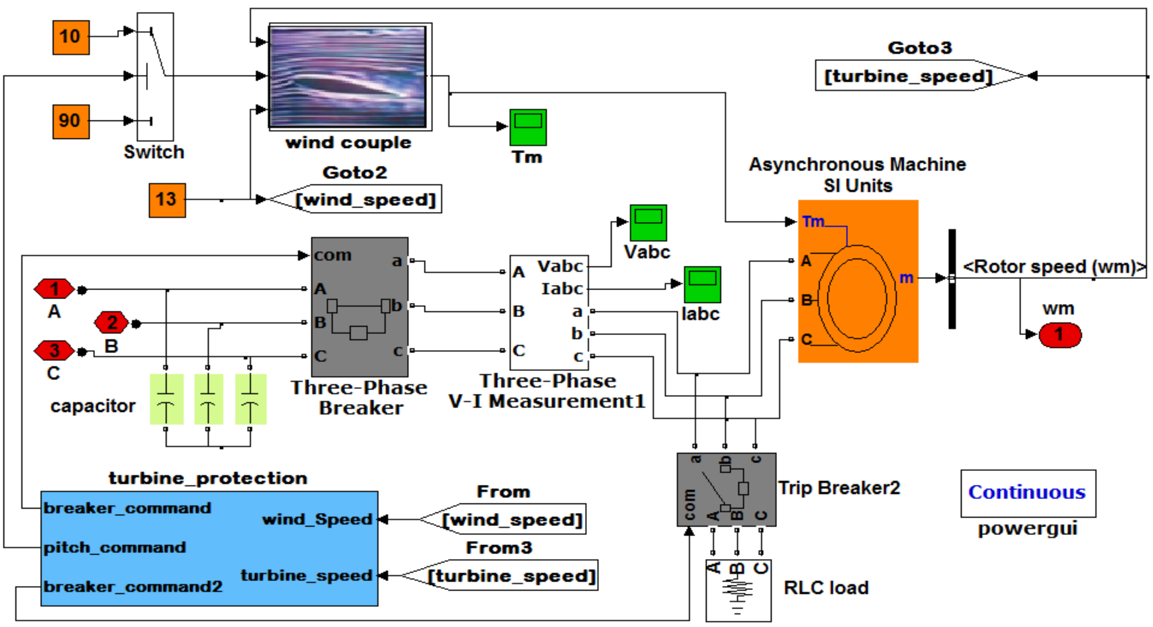

Figure 5. Model in SIMASCAPE of the wind turbine system

3. 1. Model of the System with STATCOM The block ' wind couple' shown in Figure 8, calculates the aerodynamic torque applied to the blades. This torque depends on the wind speed, the speed of the generator and the pitch angle [4] as shown in Equation (1):

$$Pm=1/2.\rho.pi.R^2.v^3.Cp(\lambda,\beta) \tag{1}$$

Cp is the power coefficient or performance coefficient which indicates the efficiency with which the turbine converts the mechanical energy of the wind into electricity. The theoretical maximum coefficient of performance, 16/27, is never achieved by practical wind turbines due to the irregularities in the wind speed and other environmental factors. A more realistic value for the *Cp* for existing wind turbines ranges from 30-50% [11].

This coefficient differs according to the turbines. In our case, the coefficient is given by the relation in Equation (2). It is the most used formula.

$$Cp=0.22(116/\lambda'-0.4a-5)*exp(-12.5/\lambda') \tag{2}$$

where a is the angle of attack of wind turbine and λ' depends on λ and a as shown in Equation (3):

$$1/\lambda'=1/(\lambda+0.08a)-0.035/(a^3+1)\rho \tag{3}$$

and λ is the specific speed witch is calculated by Equation (4):

$$\lambda=U/v=\omega.R/v \tag{4}$$

where U is the tip speed of the blades, v is wind speed, R is the radius or length of the blades and ω is the rotational frequency of the rotor (in rad/s). β is the pitch angle of the blades

The blocks 'STATCOM' and 'FAULT' are ready to use blocks in MATLAB/SIMPOWERSYSTEMS. The block 'FAULT' applies a three phase short circuit where the opening and closing times can be controlled either from an external Simulink signal (external control mode), or from an internal control timer (internal control mode)[2].

3. 1. 1. Model of Wind Couple Subsystem The calculation of the wind couple is based on Equation (1) which is linearized to form a transfer function.

3. 1. 2. Model of Rotor Subsystem in SIMMECHANICS In Figure 7, the blocks bodies model the blades and the rotor bodies (specified by their masses, inertia tensors, and attached body coordinate systems (CSs)) and the blocks joints represent possible motions of bodies relative to one another. The rotor and blades can rotate relative to ground. Also, the blades can make a rotational movement relative to the hub to vary thereby the pitch angle [4].

[2] www.mathworks.com

3. 1. 3. Model of Gear Train In the model below (shown in Figure 8), simple and planetary gears are used to transfer torque up and down the driveline axes. The inertia block represents a rotating body specified by its moment of inertia. The choice of planetary gear and simple gear is made to have a greater gear ratio [4].

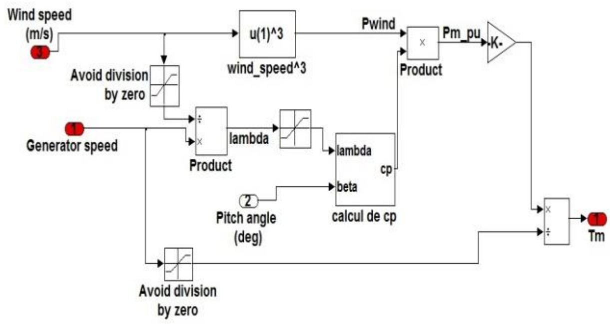

Figure 6. Wind couple model

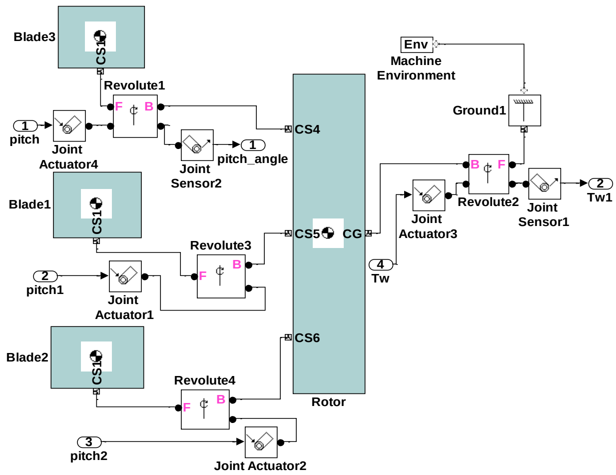

Figure 7. Rotor model

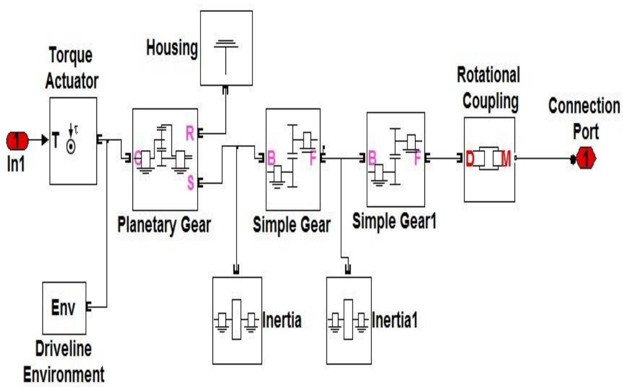

Figure 8. Model of gear train

3. 1. 4. Model of the Asynchronous Machine The model illustrated in Figure 9 consists of an asynchronous machine block ready to use and the loop speed command of the generator based on Equation (5):

$$J\, d\Omega m/dt = re - f\Omega m\text{-}rr \qquad (5)$$

3. 1. 5. Model of Turbine Protectio Protection system (modeled in Figure 10 below) permits immobilizing the wind turbine when the wind reaches a certain strength or when the wind speed is below a certain value by changing the pitch angle of the blades for zero engine torque (beta=0) (shown in Figure 9). Also, in case of over speed generator, it allows triggering the breaker in order to disconnect the wind turbine from grid (shown in Figure 11) and varying the pitch angle to 0 [4].

For the blade protection, if the wind speed is less than 4 m/s or above 25 m/s for a time of 0.05 seconds, the pitch angle value switches from 10 to 0. In order to protect the generator, we switch the pitch angle to 90 and trigger the circuit breaker if the generator's speed exceeds the rated speed by 20% for a period of 0.05 seconds [4].

3. 1. 6. Model of Pitch Angle Command Block In the block depicted in Figure 12, the pitch command output of the blade protection block switches on or off the DC motor in order to vary the pitch angle by rotating the blade.

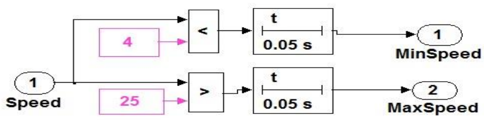

Figure 9. Models of blade protection

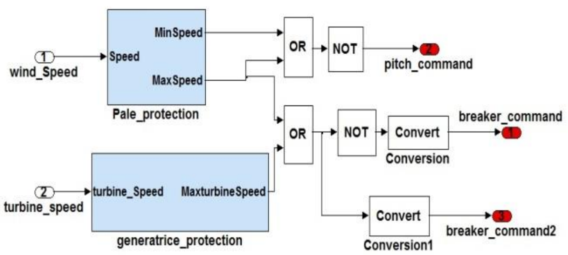

Figure 10. Turbine protection model

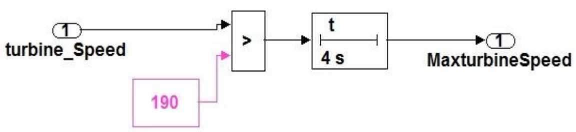

Figure 11. Models of generator protection

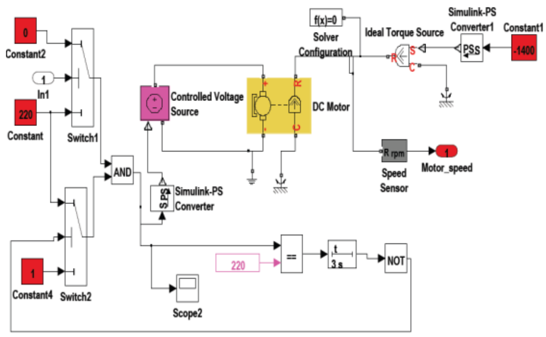

Figure 12. Pitch angle command block

In our case, to pass from beta=10 to beta=0, we need 0.945s and then we stop again the motor. 0.945s is needed because the rotational speed is equal to 30 tr/min. 1400 N.m/s is the value of the load torque represented by the weight of the blade. For our wind turbine, the weight of the nacelle and the rotor is equal to 123 tons.

3. 1. 7. Model of Braking System Block The block depicted in Figure 13, models the hydromechanical command applied to the disc brake.

When we want to stop the wind turbine if the wind speed reaches maximum speed, the hydraulic command provides some pressure sliding thereby a cylinder which in turn pushes the plates of the disc. The other end of the disc brake is mounted on the rotor shaft.

For restarting, the input ON commands the flow of the fluid in the opposite direction. So, the double acting cylinder returns to its initial position.

The value of the applied pressure is calculated based on the following dynamic equation:

$$\omega(t) = -P * \pi * S / J * t + \omega 0 \qquad (6)$$

$\omega 0$ is the rotational speed of rotor and S is the surface of brake pad which is equal to 1.8 m in our case.

The duration of braking is equal to 3s, then ω (t = 3) = 0, J is the moment of inertia of the rotor. It is calculated by equating the rotor to a hollow cylinder and considering the weight equal to 56 tons.

3. 2. Model of the System with Sssc In this case, we consider the same previous model but instead of the STATCOM, we use the block 'SSSC'. This block located in SimPowerSystems library, is connected in series between the wind turbine and the grid unlike the STATCOM (Figure 14).

3. 3. Model of The System with STATCOM/Battery The model in SIMACAPE of the system with the SSSC device is illustrated in Figure 15.

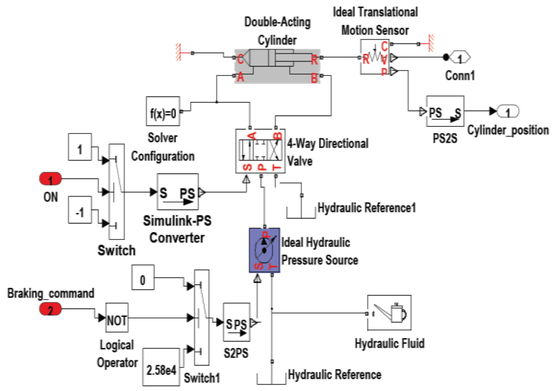

Figure 13. Braking system block

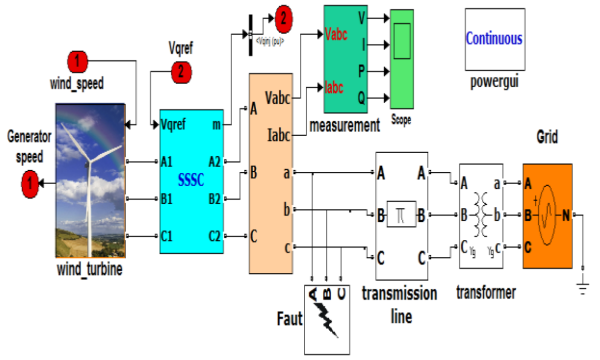

Figure 14. Model in SIMSCAPE of the wind turbine system with SSSC during fault

The block diagram of the main 'STATCOM / Battery' is shown in Figure 16. Unlike a STATCOM block, a battery is used for energy storage. Thus, this block has the advantage of storing and injecting active power and reactive power into the grid. The control of this FACTS device is modeled by the block 'control' shown in Figure 17 and Figure 18 which represents the block 'Régulation_tension', provides control of the voltage to ensure the desired response from the system during transient periods.

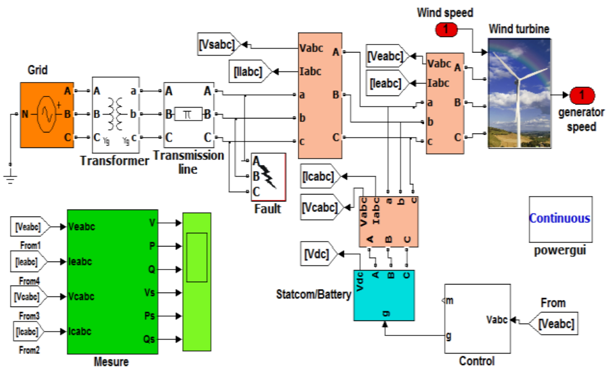

Figure 15. Model of the wind turbine system with STATCOM/battery during fault

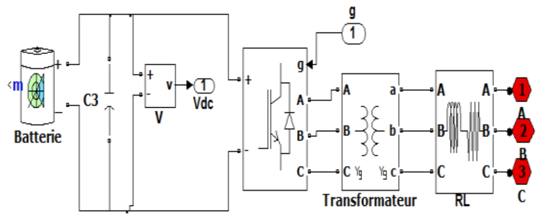

Figure 16. Model in SIMSCAPE of the block STATCOM/battery

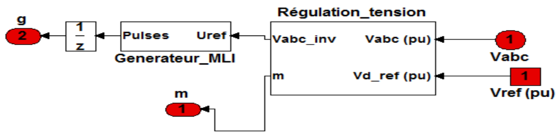

Figure 17. Block diagram of STATCOM/battery control

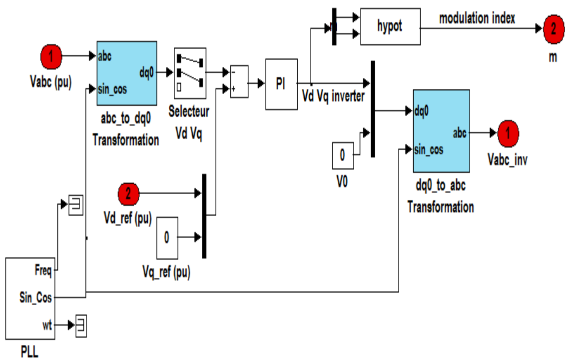

Figure 18. Model in SIMSCAPE of the block STATCOM/battery

Also, it converts this command PWM switching signals to the STATCOM / battery.

4. SIMULATION RESULTS

In order to compare the performance of adding the STATCOM, the SSSC and the STATCOM/battery in terms of improving LVRT capability of the wind turbine, a simulation of the above models is made.

The technical data of the wind turbine, induction generator, the STATCOM, the SSSC and the STATCOM with battery are illustrated in Tables 1 to 3. A three-phase fault is applied between times t = 0.5 s and t = 1.1 s.

Figure 19 shows the voltages at the output of the turbine for different cases. It is clear that the addition of a battery STATCOM improves the voltage during the fault and quickly eliminates voltage fluctuations at times of activation and deactivation of fault compared with only STATCOM and SSSC (Figure 20 and Figure 21), and because of the exchange capacity of active power flow. But the three FACTS components allow to satisfy requirements under voltage.

As depicted in Figure 20, we compare between the performance of the STATCOM and the SSSC. The latter is more effective. It enables stabilizing the voltage to 0.75 p.u during the fault and provides less voltage fluctuations in the moments of fault activation and deactivation.

During the fault occurrence, the active power is set to zero and the generator consumes a large amount of reactive power. But with FACTS systems, reactive power consumption is reduced as depicted in Figure 22. We observe that the SSSC is more efficient for reactive power compensation.

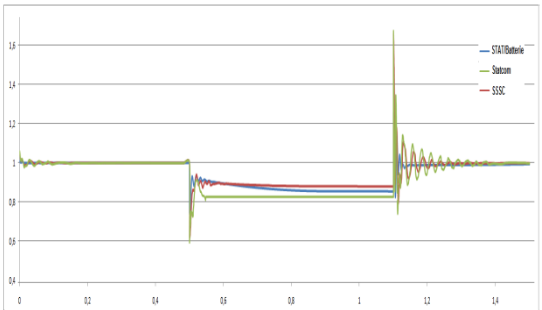

Figure 19. Voltage variation of wind turbine system during a three-phase fault and with STATCOM, SSSC and STATCOM /battery

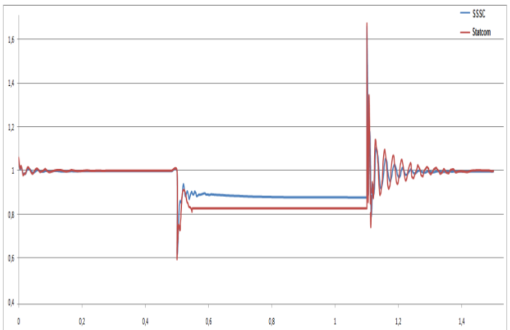

Figure 20. Voltage variation of wind turbine system during a three-phase fault with STATCOM and SSSC

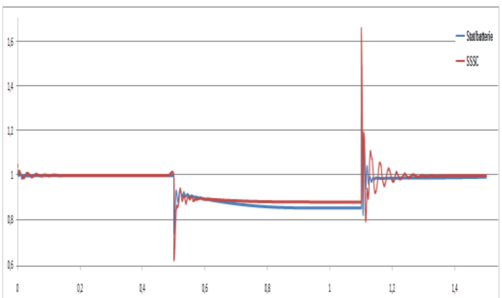

Figure 21. Comparing voltage variation of wind turbine system during a three-phase fault with STATCOM/battery and SSSC

As depicted in Figure 23, the STATCOM with a battery is the only FACTS device which injects an active power into the gird during the fault occurrence.

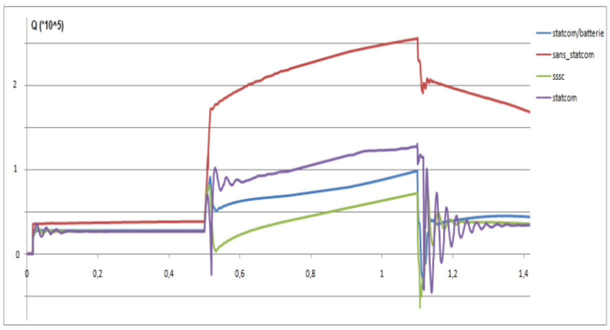

Figure 22. Reactive power consumption of the wind for a three-phase fault without a FACTS system and with STATCOM systems STATCOM and SSSC / battery

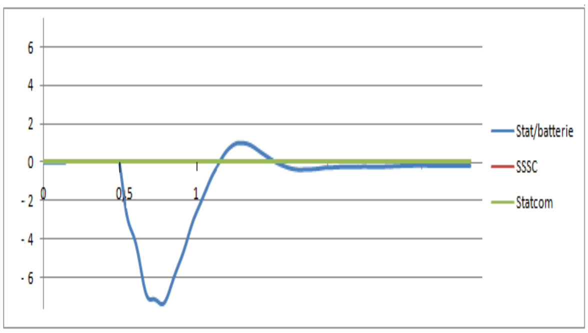

Figure 23. Model in SIMSCAPE of the block STATCOM/battery

TABLE 1. Technical data of the wind turbine system

	Tower hight	55m
	Diameter	32m
Rotor	Cut-in wind speed	4 m/s
	Cut-out wind speed	27 m/s
	Rated wind speed	13
	Rated power	275 kW
	Rated voltage	600 V
	Rated frequency	50 Hz
Genarator	Stator resistance (Rs)	0.016 Ω
	Stator inductance (Ls)	0.06 H
	Rotor resistance (Rr)	0.015 Ω
	Rotor inductance (Lr)	0.06 H
	Pair of pole number	2

TABLE 2. STATCOM technical data

Power	200 kVA
Line series inductance	0.05 mH
Inverter	Tension DC=800V / capacitance DC=1875µF
Battery	1500 Ah

TABLE 3. SSSC technical data

Power	200 kVA
Line series inductance	0.06 mH
Inverter	Tension DC=800V / capacitance DC=1875μF

5. CONCLUSION

In this paper, we studied the interest of integrating a battery energy storage to the STATCOM device for improving the low votage ride through capability (LVRT) of a fixed speed wind turbine. For this reason, a comparison is made between the SSSC, the STATCOM and the STATCOM with battery.

We modeled in MATLAB/SIMSCAPE the system consisting of the wind turbine connected to the grid and with various FACTS devices. By applying a three-phase fault, the simulation results show that the STATCOM with a battery energy storage is most efficient in terms of improving the LVRT capablity of the wind turbine.

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Static Synchronous Compensator /Battery

چکیده

در این مقاله مطالعه‌ای بر روی ادغام ذخیره سازی انرژی باتری با STATCOM برای بهبود قابلیت عبور از ولتاژ پایین (LVRT) یک توربین بادی سرعت ثابت متصل به شبکه انجام گرفته است. به همین دلیل و با استفاده از یک گسل شبکه، یک مقایسه بین یکپارچه سازی SSSC، STATCOM و STATCOM با ذخیره انرژی باتری انجام شده است. این سیستم با سیستم های FACTS مذکور با استفاده از نرم افزار MATLAB/ SIMSCAPE شبیه سازی شده و نتایج نشان می دهد که STATCOM با یک باتری، از نظر بهبود LVRT یک توربین بادی سرعت ثابت، کارآمد ترین می باشد.

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