Study of Two MPPT Methods for High Inertia Wind Turbine with Direct Driven PMSG

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***Abstract* — The aim of this work is to study and compare two methods for maximum power point tracking (MPPT) for megawatt wind energy conversion systems. The performance of the optimal tip speed ratio control (TSR) and the optimal torque control (OTC) is analyzed using Matlab/Simulink model of a wind turbine with direct driven permanent magnet synchronous generator (PMSG) connected to the grid via full scale back-to-back converter. The simulation results show that the OTC has positive effect to the studied system's stability, minimizing the power fluctuations. The response to wind speed variations of the TSR method is faster but it leads to mechanical stress in the system.**

Keywords— MPPT, PMSG, power control, WECS

I. INTRODUCTION

The MPPT algorithm has a high importance in variable speed wind energy conversion systems (WECS) because it can rise the efficiency of the whole system and to reduce the power fluctuations. The two of the most commonly used MPPT methods are the TSR and the OTC [1]. These methods have been investigated before, and they showed similar performance in small wind turbines with low rotor inertia [2]. However, the contemporary trend is the power of a WECS to increase constantly. The megawatt turbines have high inertia, which needs to be considered when choosing a control method because it affects the performance and the robustness of the system [3], [4]. The main goal of this work is to develop complete model of WECS, which involves the mentioned MPPT methods. With the developed Matlab/Simulink model are studied: the effect of the wind speed variation on the system's stability, the combination of MPPT and maximum torque per ampere control strategy (MTPA) on the generator's power, the mechanical stress, the DC-link voltage and the overall performance of the system.

II. SYSTEM DESCRIPTION

For the analyses in this work a model of 2MW WECS is used [5]. It is shown in Fig. 1 and includes a wind turbine, directly coupled to the generator's shaft. The generator is salient pole permanent magnet synchronous machine with inset magnets. It is connected to the electrical grid via a combination of two 3-phase voltage source converters, with a "back-to-back" structure.

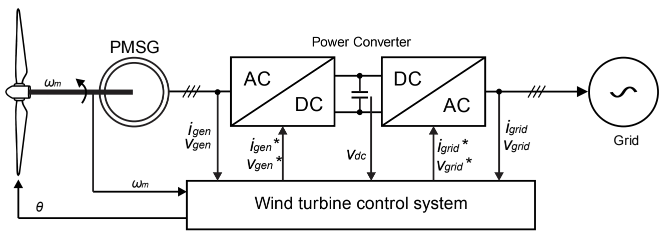

Fig. 1. Diagram of the studied WECS with PM synchronous generator and a grid connected "back-to-back" converter.

A. Modeling of the Wind trurbine

The maximum power which can be extracted by the wind turbine can be expressed by:

$$P = \frac{1}{2}\rho A v^3 C_p(\lambda, \theta) \tag{1}$$

where the air density is ρ, v is the wind speed, A is the area, swept by the turbine blades, C_p is the turbine's power coefficient which depends on the tip speed ratio λ and the pitch angle of the turbine blades θ.

The tip speed ratio is described as:

$$\lambda = \frac{\omega_m r}{v} \tag{2}$$

where ω_m is the angular velocity of the wind turbine and r is the radius of the turbine.

B. Maximum Power Point Tracking Method

The TSR method for MPPT is based on calculating the reference speed of the generator for a measured wind speed where the turbine's TSR is at its optimum and the wind turbine has maximum power coefficient. This method proposes to have fast response because the location of the maximum power point is immediately known. A diagram of a wind turbine with TSR control is shown in Fig. 2.

Main drawback here is the need of anemometer for the wind speed measuring and the high importance of the sensor

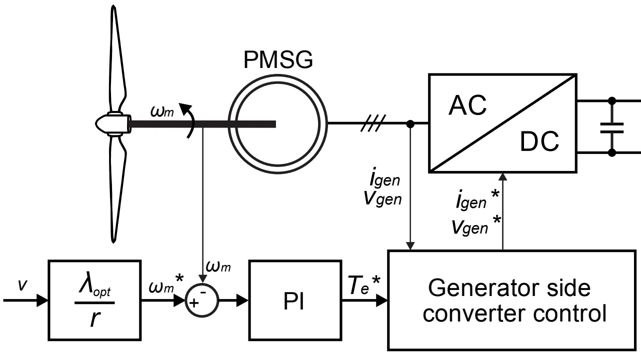

Fig. 2. Block diagram of a WECS with TSR method for MPPT.

accuracy. In most cases, this sensor is placed on top of the nacelle which results in inaccurate measurements. Also, the power of the turbine increases with the rotor's swept area. For megawatt turbines the wind speed variations across that area cannot be taken into account by one point measuring. Another difficulty is the noise injected in the control system. A low pass filter can be used, but it affects the system's response time. On the other hand, this method can be easily implemented.

The other method under study is the OTC. Its working scheme is shown in Fig. 3. Here, the generator's torque is maintained at its optimum value T_{opt} where the maximum power coefficient C_{pmax} occurs [6]. This method directly defines the generator torque based on a predefined curve $T_{opt}(\omega_m)$

$$T_{opt} = k_{opt}\omega_m^2 \tag{3}$$

The difference between the electromagnetic torque of the synchronous generator and the wind turbine's mechanical torque will slow down or speed up the rotor to the maximum power point. The OTC is supposed to be slower than TSR control, because the difference between the two torques remains quite limited. The method needs pre-known turbine characteristics for extraction of the optimum torque coefficient k_{opt}. Also it requires a speed sensor, which may be replaced by sensorless rotor position and speed estimation system. The sensorless control uses state observer for the estimation, by measuring the machine's currents.

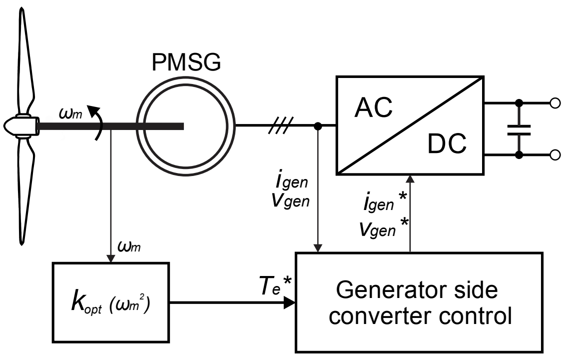

Fig. 3. Block diagram of a WECS with OTC method for MPPT.

C. Generator Model

The generator model is created in *dq* synchronous rotating reference frame. The iron saturation, eddy currents, and hysteresis losses are neglected.

The generator's voltages are expressed as:

$$\begin{cases} v_d = -Ri_d + \omega_r L_q i_q - L_d \dfrac{di_d}{dt} \\ v_q = -Ri_q - \omega_r L_d i_d + \omega_r \lambda_r - L_q \dfrac{di_q}{dt} \end{cases} \tag{4}$$

where R is the resistance of the stator winding, L_d and L_q are the direct (d) and quadrature (q) axis inductances, λ_r is the flux linkage, created by the permanent magnets, ω_r is the electrical angular speed of the machine's rotor and v_d, v_q, i_d , and i_q are respectively the generator voltages and currents in the dq-frame.

The electromagnetic torque T_e is described by:

$$T_e = \frac{3}{2} p_p \left[\lambda_r i_q - \left(L_d - L_q\right) i_d i_q\right] \tag{5}$$

where p_p represents the pole pairs.

The mechanical equation describing the drive train is:

$$J\frac{d\omega_m}{dt} = T_m - T_e \tag{6}$$

where J is the system's moment of inertia, ω_m is the mechanical speed of the generator's rotor and T_m is the mechanical torque of the generator.

D. Converter Model

In the studied WECS, a full scale back-to-back voltage-source converter is used. This topology uses two, 3-phase converters, coupled by a DC-link with a filter capacitor. Each of them can operate in rectifier or in inverter mode. In the studied configuration, the generator side converter operates as a rectifier, while the grid side converter operates as an inverter. The converters are represented using switching function concept [7]. Actually they are replaced by controlled voltage sources. The voltages are functions of the DC-link voltage and the transistors' control signals. The DC-link current is presented as a function of the three line currents (of the generator or filter) and the control signals. A block diagram is shown in Fig. 4. A Space Vector Pulse Width Modulation (SVPWM) strategy is employed, to control the converters.

E. Converter Cotrol Strategy

The machine is controlled by Field Oriented Vector Control (FOC) and MTPA control strategy. The MTPA's main goal is to find the maximum possible torque for a given stator current.

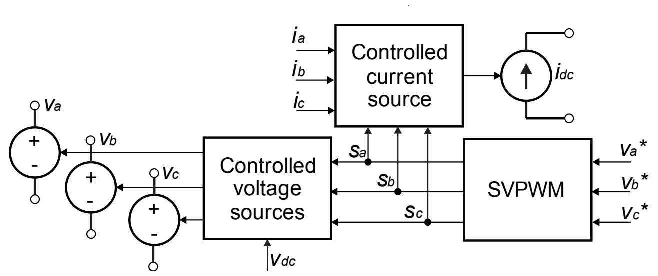

Fig. 4. Switching function model of the converter.

The MTPA control strategy is defined by:

$$\begin{cases} i_q^* = \dfrac{2T_e^*}{3p_p\left[\lambda_r + \left(L_q - L_d\right)i_d\right]} \\ i_d^* = -\dfrac{\lambda_r}{2(L_q - L_d)} + \sqrt{\dfrac{\lambda_r^{\ 2}}{4\left(L_q - L_d\right)^2} + \left(i_q^{\ *}\right)^2} \end{cases} \tag{7}$$

where i_q*and i_d*are the *q*-axis and *d*-axis currents that will produce the required toque T_e*.

The control strategy for the grid side converter is based on Voltage Oriented Control (VOC). The control of the power flow between both converters is achieved by maintaining the DC-link voltage at constant level.

III. Simulations and Results

The performance of the two MPPT methods is investigated using the developed MATLAB/Simulink model of a 2MW WECS. Pre-defined wind speed profile is used for the simulation. In the simulation, the DC-link voltage is maintained at 1450V. The grid-side converter injects only active power into the grid. In both cases the MTPA strategy for control of the PMSG torque is implemented via the generator-side converter.

In the first case the wind speed changes by steps. This way is presented accelerating and deaccelerating performance of the two control methods. White noise is also added to the wind speed. A comparison of the waveforms obtained with the two methods is shown on Fig. 5. In this figure the power coefficient, the electrical power, electromagnetic torque, the rotor speed and the DC-link voltage are presented. The power coefficient and the electromagnetic torque from this figure are also magnified between 150 and 240 second, and are shown in Fig. 6.

It can be clearly seen that the TSR method has faster response and the system returns to its maximum power coefficient faster. Considering this, the method has greater amount of extracted power from the source but it leads to big torque fluctuations. During the wind speed changes, the TSR puts the generator in motor mode for a short time in order to accelerate the turbine and reach in a fast way the desired speed for maximum power coefficient. This can be seen in Fig. 6 when the electromagnetic torque becomes negative. Besides,

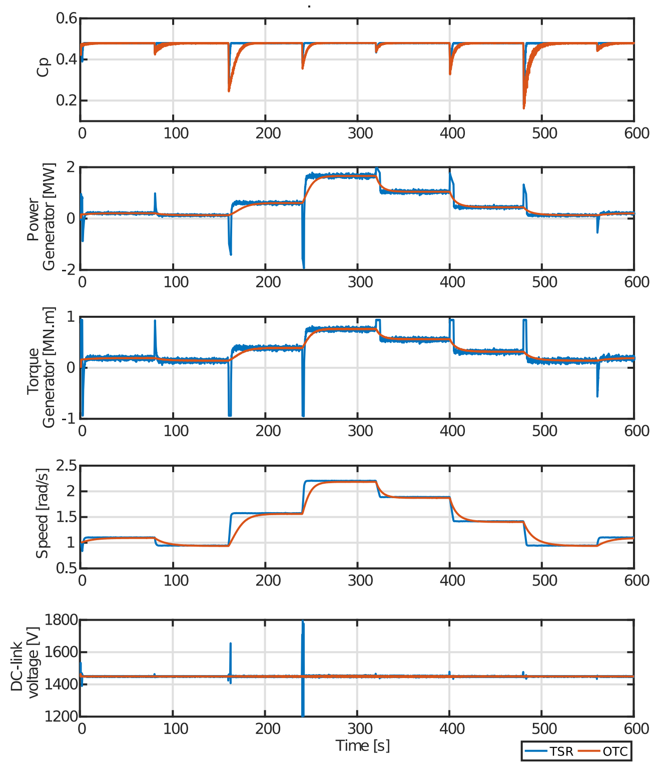

Fig.5. Simulation of the system's behavior under severe wind speed changes

the TSR algorithm pushes the electromagnetic torque to the maximum, which leads to overload protection reaction.

In the second simulation realistic wind profile with rapid speed variations and turbulence is used. The same waveforms as in the previous case are compared in Fig. 7.

On the basis of the performed simulations the qualities of both methods for controlling megawatt WECS are compared.

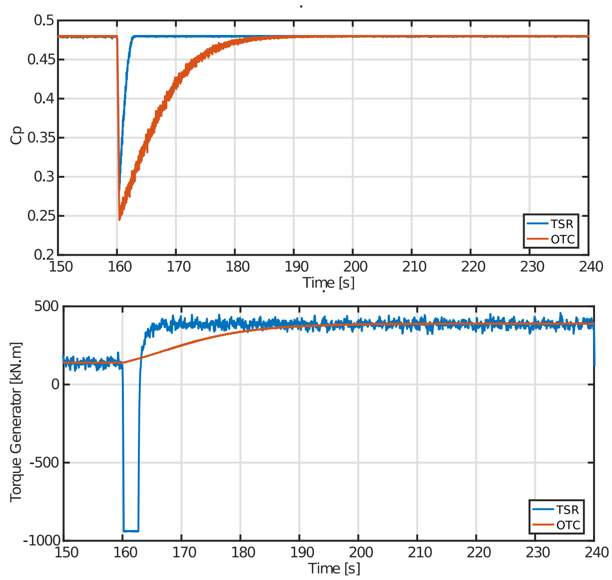

Fig. 6. Power coefficient and electromagnetic torque after third step of the wind speed.

During the simulated period shown in Fig. 7 the total amount of the extracted energy for the TSR is 97.87 kWh versus 96.70 kWh for the OTC. The TSR method has extracted greater amount of energy. The simulations show that under the OTC control the system is running smoother as it can be seen from the generator power curves. There are no DC voltage spikes and the mechanical stress is lower (which is evident from the torque curves).

The main difference between the studied MPPT methods is the transient response of the system. A slower reaction from the OTC is observed. It can be explained with the system's high inertia, particularly, because the difference between the two torques - of the turbine and the generator, remains quite limited. The OTC method proposes smoother system reaction. On the other hand, the TSR method offers faster response but it is accompanied by more severe fluctuations in torque, which affects the whole system's reliability.

IV. Conclusion

In this paper two different MPPT methods for large scale wind turbines are studied and compared. Both methods give good results but the OTC shows its benefits in controlling high inertia wind generators. The OTC method has slower response but the speed variation is smooth and robust, which leads to lower mechanical stress to the shaft and to the generator

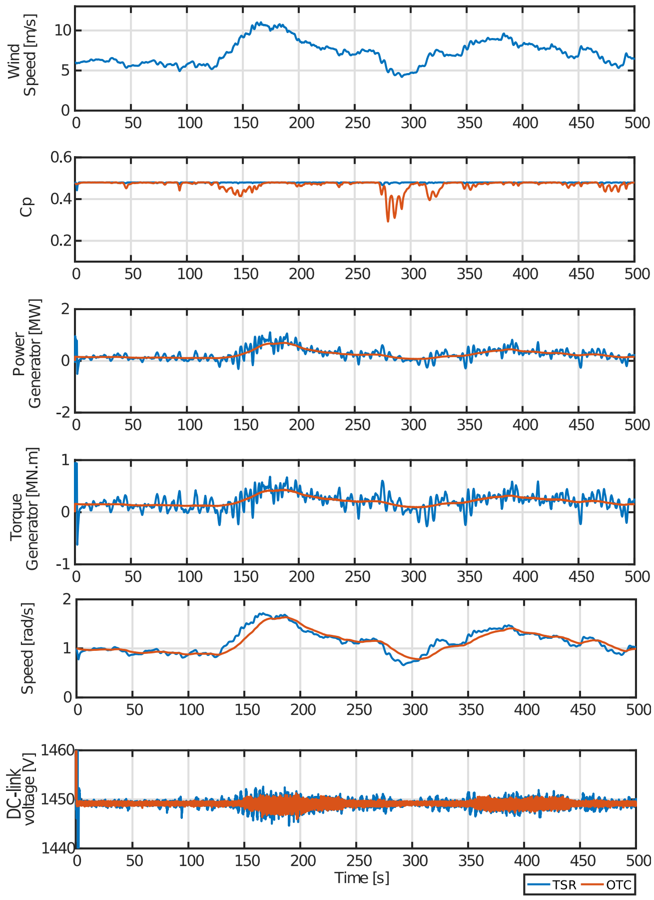

Fig. 7. Simulation of the system's behavior under real wind speed profile.

compared to TSR. The maximum power tracking is very stable and it doesn't cause power spikes. Although the TSR seems to be better in extracting more power and it has very fast transient response it causes fluctuations in the generator's power and in the DC-link capacitor's voltage.

TABLE I. PARAMETERS OF THE WECS'S COMPONENTS

Rated Parameters	**Value**
Genrator phase voltage	562 V
Generator stator current	2634 A
Generator power	2 MW
Generator mechanical torque	852.77 kN.m
Generator rotor speed	22.5 rpm
Stator frequency	11.25 Hz
Generator pole pairs	30
Permanent magnet flux linkage	6.62 Wb
Stator winding resistance	0.73 mΩ
d-axis inductance L_d	1.21 mH
q-axis inductance L_q	2.31 mH
Total moment of inertia	6.15×10^6 kg.m^2
Capacitance of the DC-link	0.01 F
Rated voltage of the DC-link	1450 V

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