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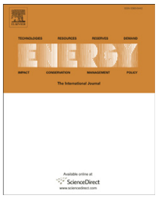

Performance prediction of a multi-MW wind turbine adopting an advanced hydrostatic transmission

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ABSTRACT

This paper analyzes the performance of multi-MW wind turbines by means of a specific numerical model, with the aim of evaluating the application of an advanced hydrostatic transmission in a conventional state-of-the-art machine. The interest for such a solution is mainly related to the potential increase of reliability and reduction of maintenance costs in spite of an expected reduction of performance. The implemented numerical algorithm considers the energy model of single components of the whole turbine drive-train, from the blades to the electric grid. The model is firstly applied to a conventional turbine and validated according to available yearly data from a wind farm. Then, it is used to calculate the annual energy production for different drive-train configurations applied to the same rotor, including the widespread solution with induction generator and inverter connected to the rotor, permanent magnet generator with direct drive connection or the proposed advanced hydrostatic transmission. The differences in yearly electricity output among the investigated configurations are within few percentage points.

1. Introduction

The worldwide request for alternatives to fossil fuels has been growing considerably during the last decades, driving a rapid improvement of technologies exploiting renewable energies. Among them, there are wind energy conversion systems, mainly based on large-scale wind turbines using either a mechanical gearbox or a low-speed generator [1,2]. Both DFIG (doubly fed induction generator) wind turbines and direct-drive PMG (permanent magnet generator) wind turbines are widely used, nowadays. Low-speed PMG machines have higher reliability, compared to DFIG ones, owing to the elimination of the high-speed rotating components. As a matter of fact, the frequency converters for rotor speed variation and, in most cases, the mechanical gearbox are components that allow to obtain high overall efficiency in state-of-the-art multi-MW wind turbines, but are the main responsible for faults and out-of-service [3], causing high maintenance costs, especially in off-shore applications [4].

High-pressure fluid power systems, actually present in various applications such as fuel injection equipment [5], construction machinery [6], hybrid propulsion [7] and lubrication systems [8], could be used to replace some critical components of a wind energy conversion system. In particular, a hydrostatic transmission can link the rotor to the electric generator, combining good efficiency and grid stability with high reliability and relatively low costs. Recently, attention has been paid to solutions of hydrostatic transmissions integrated in wind turbine drive-trains, ranging from 100 kW [9] up to 1 MW [10] machines. Techno-economic feasibility studies for a proposed 1.5 MW wind turbine utilizing a continuously variable ratio hydrostatic drive-train were presented as well [11]. However, no matter how compact and robust they may be, state-of-the-art positive-displacement units currently present in hydrostatic transmissions really suffer from reduced efficiency at partial load and displacement volume different from the maximum, so energy transfer from the rotor to the electric generator could be seriously penalized. Digital fluid power is a recent branch that offers high potential for innovative solutions. A successful application requires new components, a sound understanding of the system and new control principles. Specific details about the state of the art can be found elsewhere [12], but in all cases, control is effected by switching valves. Digital fluid power offers several advantages compared with analog technologies, i.e. higher efficiency, precision, redundancy, robustness, as well as higher component

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Acronyms

DD	digital-displacement
DFIG	doubly fed induction generator
FSC	full scale converter
HT	hydrostatic transmission
IGBT	insulated-gate bipolar transistor
PMG	permanent magnet generator
RMS	root mean square
SCIG	squirrel cage induction generator
SG	synchronous generator
VCE	collector–emitter voltage

Nomenclature

Cp	power coefficient
Δp	pressure difference (MPa)
α	factor determining the current displacement volume
β	pitch angle (deg)
η	efficiency
λ	tip speed ratio
μ	fluid dynamic viscosity (cP)
ξ	dead volume ratio
φ	phase of voltage relative to current
Ψ	dimensionless loss coefficient
B	fluid bulk modulus (MPa)
i	number of gearing stages
n	rotational speed (rpm)
Q	volumetric flow rate (dm^3/s)
V	maximum displacement volume (dm^3/rev)
z	number of cylinders or pumping elements

Subscripts

1	single-cylinder
AC	alternating current
b	bearings
DC	direct current
f	friction
fl	flank (of the teeth)
hm	hydraulic-mechanical
k	constant
L	fluid leakage
l	loss
m	motor
nom	nominal
o	oil
p	pump
pa	parallel
pl	planetary
REF	reference
s	seals
th	theoretical
tr	transformer
v	volumetric
vf	viscous friction

standardization potential [13]. As far as this study is concerned, digital-displacement pumps and motors [14] are selected as components of a high-efficiency hydrostatic transmission to be used in a wind energy conversion system in order to enhance its overall efficiency [15,16].

In the next sections, after presenting the basic principle of a hydrostatic transmission and its integration in a wind energy conversion system, details of wind turbine drive-train modeling and drive-train schemes are reported. Eventually, the results of the study are presented and discussed.

2. Hydrostatic transmission in a wind turbine drive-train

Hydrostatic transmissions are widely recognized as excellent systems for power transmission when variable output velocity is required in engineering applications, such as the fields of manufacturing, automation and heavy-duty vehicles. A hydrostatic transmission offers fast response, maintains precise velocity under varying loads and allows to control speed, torque, power or, in some cases, direction of rotation when required [17,18].

The operating principle of a hydrostatic transmission is simple: a positive-displacement pump, connected to the prime mover, generates a flow rate to drive a positive-displacement motor, which is connected to the load. If the displacement volumes of pump and motor are fixed, the hydrostatic transmission simply acts as a mechanical gearbox with fixed gear ratio that transmits power from the prime mover to the load. When using a variable-displacement pump or motor, or both, a continuous control of speed, torque and power is possible. Paying here attention to speed control, it is possible to formulate the theoretical flow rate generated by the pump, along with the theoretical rotational speed of the motor, by neglecting, for the sake of simplicity, leakage flows inside the machines [19]:

$$Q_{\mathrm{p,th}} = \alpha_{\mathrm{p}} \cdot V_{\mathrm{p}} \cdot n_{\mathrm{p}} \tag{1}$$

$$n_{\mathrm{m,th}} = \frac{Q_{\mathrm{m}}}{\alpha_{\mathrm{m}} \cdot V_{\mathrm{m}}} \tag{2}$$

If no fluid loss occurs in the hydraulic circuit, the whole flow rate generated by the pump enters the motor, so the rotational speeds of both pump and motor can be related:

$$n_{\mathrm{m,th}} = \frac{\alpha_{\mathrm{p}} \cdot V_{\mathrm{p}}}{\alpha_{\mathrm{m}} \cdot V_{\mathrm{m}}} \cdot n_{\mathrm{p}} \tag{3}$$

According to the last formula, a proper setting of pump and motor displacement volumes (by means of the factors α_{p} and α_{m}, variable from a minimum close to 0 up to 1) allows to control the rotational speed of the motor. This feature is interesting if a hydrostatic transmission has to be integrated in a wind turbine drive-train. Moreover, if advanced hydrostatic units based on the digital-displacement concept [14–16] are used, thanks to their high efficiency at both full- and partial-load conditions, it is possible to improve the overall energy conversion efficiency of the wind turbine drive-train.

As schematically shown in Fig. 1, the rotor transmits mechanical power to the pump that generates a high-pressure flow rate necessary to drive the motor, connected to the electric generator. Both pump and motor are digital-displacement machines. Other components of the hydrostatic transmission are valves, a hydraulic accumulator, filters, oil coolers, a small system necessary to set the minimum pressure in the hydraulic circuit, along with a control unit of the complex system.

Fig. 2 shows a schematic cross-section of a radial piston unit, whose displacement volume can be increased just by adopting more banks in parallel [15]. Two digital solenoid-driven poppet valves, the first arranged along the piston axis and the second

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