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Control of synchronized doubly-fed induction generator under grid conditions

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Abstract

For megawatt-class (MW-class) wind turbines, the alteration of rotor speed considerably affects the optimal performance, according to the energy flow characteristics of generators. A robust approach, based on a hydro-dynamically controlled gearbox, provides accurate speed adjustments for fixed-speed generators, normally at the synchronous speed. The existing topologies, which use the traditional synchronous generator, perform poorly due to lack of control in the rotor electromagnetic circuit during load changes and input energy fluctuations. Therefore, a doubly-fed induction generator (DFIG) is utilized with the rotor winding being fed with direct current in order to control the output power of the machine. At this mode of operation, there is no considerable active power flowing in the rotor and thus the converter rating reduces considerably. However, when working as a synchronous generator, the DFIG behaves in the same manner and causes electromagnetic oscillation, as well as undesired unbalanced thermal load in the rotor winding and power components of the converter.

This research work develops control techniques which combine feedback and feedforward topologies to reduce oscillations in the electromagnetic torque, load angle, as well as the reactive power of a DFIG at the synchronous operating point. According to the critical damping method, the damping torque is controlled to maintain the critical state of the entire system. This method is based on the dynamic analysis of torque components in the machine. As a consequence, an additional damping torque is fed to the control loop to eliminate the vibration of variables during the alteration of operating parameters. The other method, namely coupling approach, is based on the analysis of the vibration components of variables like torque, reactive power, and load angle. Thus, the oscillation parts are provided simultaneously at their set values and the vibration is eliminated.

On the other hand, as the share of wind energy in the power network increases, the generators are required to stay connected in cases of voltage depression, in accordance with the grid code of each nation. This research introduces methods to support the generator to ride through the temporary low voltage (LVRT) to minimize the waste of wind energy. These methods use the support of active crowbar mechanism and a direct rotor voltage control, in order to reduce the oscillations in machine variables and keep them within a safe limit. Furthermore, in case of unbalanced grid voltage dips, a novel approach is proposed to separate the positive and negative components, so that these components can be controlled separately. This control structure can reduce the negative impact on stator current, rotor current, torque as well as active and reactive powers, when the machine works at the synchronous mode. Optimal methods to determine the reference value of negative sequence controller are also proposed in order to simultaneously eliminate the oscillation in variables.

The behaviours of the above mentioned schemes are investigated by the means of Matlab/Simulink simulation and experimental test model to validate the proposed approaches.

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List of symbols

$\underline{a}$	Exponential operator
A	Swept area of rotor blades; gain factor
C	Aerodynamic power coefficient
D	Damping ratio
f	Frequency
G	Transfer function (control object); controller
i	Current
j	Complex operator
J	Moment of inertia
k	Counter point; torque coefficient
K	Voltage sag level; gain of transfer function
L	Inductance
m	Torque
n	Speed (electrical machine)
N	Samples of a window cycle
p	Active power
q	Reactive power
R	Resistance
s	Laplace variable; generator slip; apparent power
t	Time
T	Sampling period; time constant (transfer function)
u	Voltage

V	Proportional gain of a controller; speed (wind)
w	Anti-windup variable
X	Reactance
z	Space vector; number of pole pairs
φ	Power angle
θ	Load angle
ϑ	Electrical angle
ρ	Air density
σ	Leakage factor
τ	Time constant (exponential function)
ω	Angular velocity
ξ	Damping ratio
ψ	Flux linkage
ζ	Damping factor
Δ	Oscillating part

Subscripts

abc	Three phase system; a – acceleration torque
A, B	First and second inductive reactance of voltage sag emulator
C	Constant
CB	Crowbar
D	Damping torque coefficient
DC	DC-link
DT	Delay time
dq	Synchronous *dq*-axis
e	Electromagnetic torque
f	Filter; forced stator flux linkage
F	Field current
g	Closed control loop
G	Grid

i	Current control loop
k	Maximum value of active power, reactive power and torque
kri	Critical damping coefficient
M	Mutual values
m	torque control loop; mechanical speed; limit of control signal
max	Maximum value
n	Grid side converter output values; transient values
nat	Natural frequency
N	Rated value
peak	Peak voltage (sag detection)
P	Internal synchronous induced voltage; pole pairs; aerodynamic power
R	Rotor; controller
sag	Voltage value under sag
syn	Synchronous torque coefficient
sys	Overall closed loop transfer function
S	Stator
SM	Synchronous drive
T	Turbine
V-ASG	Asynchronous generator loss
V-SR	Converter loss
W	Wind
sin, cos	Sine and cosine oscillating component
0	Non-oscillating component; time at the beginning of voltage sag
1, 2	Positive and negative sequence
αβ	Stationary $\alpha\beta$-axis
μ	Magnetisation current

Superscripts

′	Referred to stator
+, −	Time before and after voltage sag
*	Reference value, complex number conjugation

List of acronyms

AC	Alternating Current
ADC	Analog-to-Digital Converter
ARO	Weighted ARithmetic Optimization
BC	Before Christ
CO	COupling damping control
CR	CRitical damping control
DAC	Digital-to-Analog Converter
DC	Direct Current
DFIG	Doubly-Fed Induction Generator
SDFIG	Synchronized Doubly-Fed Induction Generator
DFT	Discrete Fourier Transform method
DSC	Delayed Signal Cancelation
IEA	International Energy Agency
ISV	Integral of Squared Value
LVRT	Low Voltage Ride-Through
MPPT	Maximum Power Point Tracking
MW	MegaWatt
NSC	Negative Sequence Controller
OP	Optimal Torque
PCC	Point of Common Coupling
PI	Proportional-Integral controller
PLL	Phase Locked Loop

P&O	Perturbation and Observation method
PSF	Power Signal Feedback
PV	Peak Voltage method
RSC	Rotor Side Controller
RVC	Rotor Voltage Control method
TSO	Transmission System Operators
TSR	Tip Speed Ration
VSO	Vibration Sum Optimization
VUF	Voltage Unbalance Factor
WT	Wind Turbine
ZOH	Zero-Order Hold (DAC)