Ain Shams University
Faculty of Engineering
Electric Power and Machines Department

Aggregation of equivalent models of large wind farms connected to power grids under normal operation and some disturbances

BY

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A Thesis Submitted to
Department of Electrical Engineering
In Partial Fulfillment of the
Requirements for the Degree of
Doctor of Philosophy

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Abstract

With increasing the penetration rate of wind power, wind farm begins to affect the power systems, so the modeling of wind farms for grid integration studies is now an important issue. Such effect is studied and justifies the need for a dynamic model of a wind farm comprising a large number of generators; however, detailed dynamic models demand much simulation computation time. Aggregation technique of wind farm is required in order to decrease the model order with keeping its accuracy high.

The first part of the thesis studies some of the different types of aggregation techniques of a large wind farm. It operates with the most commonly used wind generators in a wind farm such as doubly fed induction generator (DFIG), permanent magnet synchronous generator (PMSG), and squirrel cage induction generator (SCIG). Firstly, we study the complete model of each wind generator type, and then present some of the different types of aggregation techniques. The chosen five techniques are, full aggregated model utilizing equivalent wind speed (FAM-EWS), full aggregated model utilizing average wind speed (FAM-AWS), multi full aggregated model utilizing equivalent wind speed (MFAM-EWS), mixed semi-full aggregated model (MSFAM) and semi-aggregated model (SAM). The thesis compares the complete wind farm models and the studied types of aggregation techniques; the comparison is based on the proximity of the simulation results of the normal and abnormal response for each complete wind farm model and the aggregated wind farm models. These techniques have been carried out by MATLAB/Simulink program to compare between the complete model by using different effects such as values of wind farm active power, reactive power, the voltage at the point of common coupling (PCC) and system dynamics to show each of aggregation technique effectiveness.

The thesis focuses on some wind turbines trip. It uses a detector to adjust the aggregated wind farm model (AWF) according to the status of the wind turbines (in service or not) without stopping the simulation process.

There are two options for transmitting the generated power of wind farms to AC grid (1) High-voltage alternating current (HVAC) or (2) High-voltage direct current (HVDC). The thesis studies the two options of transmitting the generated power.

The second part of the thesis works with offshore wind farm integrated to weak and passive AC grid systems through multi-terminal high voltage direct current (MT-HVDC) transmission system. Furthermore, the effect of utilizing a superconducting magnetic energy storage unit in a hybrid power system containing offshore wind farm is studied. The behavior of the offshore wind farm integrated to weak and passive AC grid system is tested for transient responses on the network and the offshore wind farm by MATLAB/Simulink program.

KeyWords

Wind farm; doubly fed induction generator (DFIG); permanent magnet synchronous generator (PMSG); squirrel cage induction generator (SCIG); and superconducting magnetic energy storage (SMES).

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List of Symbols

A : The rotor disk area (m2)
c : The number of clusters in a wind farm
C : The capacitor capacitance (F)
C_p : The turbine performance coefficient
C_{p_opt} : An optimum value of performance coefficient
d-q : Direct and quadrature
D : The chopper duty cycle
D_m : The damping of the mechanical coupling
e'_d and e'_q : The internal transient voltage components of the thevenin equivalent of induction generator
E' : The internal transient voltage of the thevenin equivalent of induction generator
E_{SMES} : The energy storage in SMES coil
index j : Refers to each individual wind
index d : Refers to the direct components
index q : Refers to quadrature components
index s : Refers to the stator
index r : Refers to the rotor
index eq : Refers to equivalent
index ph : Refers to each of the phase
i : Denotes the generator current
i_{ds}, i_{qs} : The components of the generator (stator) current
i_{dr}, i_{qr} : The rotor currents
i_{dg}, i_{qg} : The components of wind turbine generation current (the grid current)
i_{DC} : The direct current delivered through the dc side of the converter (A)
i_d, i_q : The components of the current flowing at the ac side of the converter
$i^*_d(i_{d\_ref})$, $i^*_q(i_{q\_ref})$: The references components of the current flowing at the converter
I_c : The capacitor current
I_g : The wind turbine generation current (the grid current)
I_s : The generator (stator) current
I_r : The rotor current (rotor side converter current)
I_{ph} : Three phase current
I_o : The controllable current source into the DC bus
i_L : The direct current flowing through the dc link
i_{dc}, i_{qc} : The components of the capacitor current
I_{SMES} : The DC current flowing through the SMES coil
J_r : The rotor inertia (s)
J_g : The generator inertia (s)
K_m : The stiffness of the mechanical coupling
L : leakage inductance of the phase reactor (H)
$L_{\sigma s}$: The stator leakage inductance
$L_{\sigma r}$: The rotor leakage inductance
L_m : The magnetizing inductance
L_{ds}, L_{qs} : The stator inductances

L_g : The grid inductances
L_{dg}, L_{qg} : The components of the grid inductances (H)
L_{SMES} : The inductance of the coil
m_{ph} : The modulation index
n : The number of wind turbines in a wind farm
p : The number of pole pairs
P_w : The aerodynamic power (W)
$P_{g,eq}$: The equivalent (aggregated) generated active power
P_{ac} : The active power exchanged at the common bus
P_{DC} : The active power of the DC-link
P_g : The active power generated at PCC of a wind farm
P_s : The output active power of the stator winding (generator)
P_r : The output active power of the rotor winding
P_{loss} : Power losses
P_{SMES} : The power absorbed or delivered by SMES coil
Q_g : The reactive power generated at PCC of a wind farm (var)
Q_s : The output reactive power of the stator winding (generator)
Q_r : The output reactive power of the rotor winding
Q_{ac} : The reactive power exchanged at the common bus
$Q_{g,eq}$: The equivalent (aggregated) generated reactive power
R_w : The turbine rotor radius (length of the blade) (m)
R_s : The stator resistance (Ω)
R_r : The rotor resistance
R : The resistance of the phase reactor
R_g : The grid resistance
R_t : Represents equivalent resistance of both switching and resistive losses of the converter
R_{BR} : The braking resistor
s : The generator slip
$S_{j,k}$: The apparent power of each cluster (V.A)
S_j : The rated apparent power of each wind turbines
S_{eq} : The rated apparent power of the equivalent wind turbine
$S_{M,eg}$: The apparent power of the all wind farm.
$T_{m,eq}$: The equivalent (aggregated) mechanical torque (N.m)
T_j : The mechanical torque of each wind turbines
T_w : The mechanical torque of the wind turbine rotor shaft (The aerodynamic torque)
T_m : The mechanical torque of the generator shaft
T_g : The generator electrical torque
T_{g_cmd} : The electromagnetic torque must be generated by the generator
T'_o : The transient open circuit time constant
u : Denotes the voltage (V)
U_g : The wind turbine generation voltage (grid voltage)
U_c : The capacitor voltage (grid side converter voltage)
U_r : The rotor voltage (rotor side converter voltage)
u_{dg}, u_{qg} : The components of wind turbine generation voltage (grid voltage)
u_{dr}, u_{qr} : The components of the rotor voltage

u_{dc}, u_{qc}	: The components of the capacitor voltage (the components of the grid side converter voltage)
u_{ds}, u_{qs}	: The components of the generator (stator) voltages
u_{conv}	: The converter input voltage
u_{dconv}, u_{qconv}	: The component of the converter input voltage
u_d, u_q	: The components of the common bus voltage
$u^*_d(u_{d\_ref})$, $u^*_q(u_{q\_ref})$	: The references components of the common bus voltage
v	: Denotes the wind speed (m/s)
v_{eq}	: The wind incident on the equivalent wind turbine (m/s)
v_j	: The wind incident on an individual wind turbine
v_{avr}	: The average wind incident on the equivalent wind turbine
V_{ph}	: Three phase voltage at the common bus
V_{ph_ref}	: The reference voltage generated from the inner current controller
V_{SMES}	: Voltage across the SMES coil
V_{DC}	: The capacitor terminal voltage
ω	: The system frequency
ω_s	: The synchronous speed (rad/s)
ω_r	: The wind turbine rotor speed (rad/s)
ω_g	: The generator (stator) rotor speed (rad/s) (grid frequency)
$\omega_{g,eq}$	: The equivalent rotational speed (rad/s)
X'_s	: The transient stator reactance (Ω)
X_r	: The rotor reactance (Ω)
X_m	: The magnetizing reactance (Ω)
$X_{\sigma s}$	: The stator leakage reactance (Ω)
$X_{\sigma r}$	: The rotor leakage reactance (Ω)
X_c	: The reactance of the compensating capacitors (Ω)
X_s	: The stator reactance (Ω)
ρ	: The air density (kg/m3)
λ	: Tip speed ratio (ratio between blade tip speed and wind speed)
λ_{opt}	:An optimum value of the tip speed ratio
θ	: Pitch angle of rotor blades (deg)
Ψ_m	: Permanent magnetic flux (Wb)
Ψ_{ds}, Ψ_{qs}	: The components of the flux linkage of the stator (Wb)
Ψ_{dr}, Ψ_{qr}	: The components of the flux linkage of the rotor (Wb)
τ	: The time constant of dc capacitors (ms)

List of Abbreviations

AWF	: Aggregated wind farm
ANN	: Artificial neural network
AVM	: An average value model
B2B	: Back to back
BESS	: Battery energy storage system
CAES	: Compressed air energy storage
CWF	: Complete wind farm
DFIG	: Doubly fed induction generator
EWEA	: European wind energy association
EWS	: Equivalent wind speed
FCM	: Fuzzy C means
FAM_EWS	: Full aggregated model using equivalent wind speed
FAM_AWS	: Full aggregated model using average wind speed
GSC	: Grid side converter
GWEC	: Global wind energy council
GW	: Giga watt
HVAC	: High voltage alternating current
HVDC	: High voltage direct current
IGBT	: Insulated gate bipolar transistors
IG	: Induction generator
LCC	: Line commutated converter
LVRT	: Low voltage ride through
MT-HVDC	: Multi-terminal high voltage direct current
MFAM_EWS	: Multi Full aggregated model using equivalent wind speed
MSFAM	: Mixed semi full aggregated model
MPPT	: Maximum power point tracking
OWF	: Offshore wind farm
PMSG	: Permanent magnet synchronous generator
PC	: Power curve
RSG	: Rotor side converter
PCC	: Point of common coupling
SMES	: Superconducting magnetic energy storage
SFCL-MES	: Superconducting fault current limiter-magnetic energy storage system
SCIG	: Squirrel cage induction generator
SVC	: Support vector clustering
SAM	: Semi aggregated model
TWh	: Tera watt hour
VSC	: Voltage source converter
VSC-HVDC	: Voltage source converter high voltage direct current
WF	: Wind farm
WT	: Wind turbine

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