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(71) Applicant *(for all designated States except US)*: VESTAS WIND SYSTEMS A/S [DK/DK]; Alsvej 21, DK-8940 Randers SV (DK).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: NIELSEN, Peter [DK/DK]; Ahornvænget 6, DK-7000 Fredericia (DK). ZAMASTIL, Martin Høgdahl [DK/DK]; Gammel Viborgvej 85, DK-8471 Sabro (DK).

(74) Agents: MADSEN, Steen et al.; Inspicos A/S, P.O. Box 45, Kogle Allé 2, DK-2970 Hørsholm (DK).

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(54) Title: SIMULATION MODEL

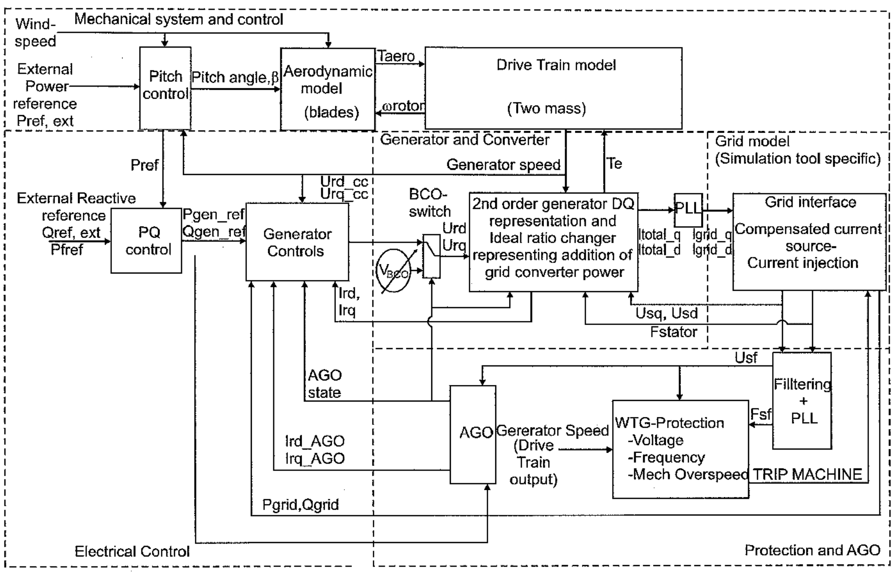

Fig. 1

(57) Abstract: The present invention relates to a method and a model for simulating a blocked rotor converter situation in a power generation system comprising an electrical power generator operatively connected to a rotor converter, the method comprising the step of replacing a first rotor resistance value, R_r, by a second rotor resistance value, R_{BCO}, during said blocked rotor converter situation.

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SIMULATION MODEL

FIELD OF THE INVENTION

The present invention relates to a method for simulating the stability of a power generating unit adapted to feed electrical power into a power supply grid.

BACKGROUND OF THE INVENTION

Simulation methods can be implemented using general purpose electronics simulation tools where each component of the real system is represented by a corresponding component in the simulation model. Simulation method may give a good perception of the real system's behavior, e.g. during transient grid conditions.

However, when simulating e.g. electrical grids with a plurality of power generating units, such simulations may be very time consuming, particularly if different protective measures are provided to protect the converters during transient grid conditions.

It may be seen as an object of embodiments of the present invention to provide a simulation model that facilitates faster simulations of power generating units during transient grid conditions, such as low voltage ride through events.

DESCRIPTION OF THE INVENTION

When simulating electrical power generating systems with a power electronic converter in a large electrical power network, there is a need for fast simulation speeds. Moreover, the simulation must show the real response like it would be the in the real network.

When using power electronic converters having a switch frequency of several kHz it is pointless to show the actual switching. Instead the power electronic converter is simulated by using a variable current or voltage source. This works well for the steady state operation.

For situations where there are disturbances in the grid or faults in the power electronic converter, that causes the converter to go into a blocking mode, the simple representation by using variable current or voltage sources, would not show the right response.

The ideal situation would be to simulate the power electronic converter by using the fast switches during the fault. However, this would slow down the simulation time by several decades. Another way to simulate the power electronic converter would be to model the converter using a simple diode model. This would increase the speed of the simulation. An even faster way to simulate the blocked converter situation would be to insert a resistor between the generator and the voltage/current source.

Often the need for the simulation of the converter blocking happens during a so called Low Voltage Ride Through (LVRT) event where the voltage on the electrical power supply grid drops to a rather low value. Whether it is a LVRT event depends on the grid operator. In some areas a 15% voltage drop would be considered a LVRT event whereas in other areas a higher voltage drop is required.

In order to comply with the above-mentioned object and the above-mentioned needs the present invention relates, in a first aspect, to a model for simulating a power generation system comprising an electrical power generator operatively connected to an electronic power converter, wherein, during a predetermined mode of operation of the power generation system, a first rotor resistance value, R_r, of the model is replaced by a second rotor resistance value, R_{BCO}.

The model according to the first aspect of the present invention may be implemented as a single-phase in a synchronous system or a multi-phase model in a stationary system, i.e. a model for simulating single- or multi-phase systems, such as three-phase system.

The power generator may, in said simulation model, be represented by a set of rotor winding equations and a set of stator winding equations.

Thus, the electronic power converter may be represented by a modified rotor resistor value during the predetermined mode of operation.

In addition, the electronic power converter may be represented by a voltage source during said predetermined mode of operation. Thus, the electronic power converter may be represented by a modified rotor resistor value in combination with a voltage source.

The predetermined mode of operation is typically initiated if some sort of fault is detected. Thus, the predetermined mode of operation may relate to a blocked converter situation, i.e. to a situation where the power converter is defect or not able to supply power due to the low voltage situation.

The voltage source representing the electronic power converter during the predetermined mode of operation may comprise a controllable voltage source. Also, the second rotor resistance value, R_{BCO}, may be variable.

The predetermined mode of operation, such a LVRT event, may be detected by an AGO module of the model. As it will be described in further details below the AGO module goes into a certain mode of operation, said mode of operation launching the predetermined mode of operation.

The simulation model according to the first aspect of the present invention may in principle be implemented in any simulation tools, such as for example in a PSS/E environment.

In a second aspect, the present invention relates to a method for simulating a blocked rotor converter situation in a power generation system comprising an electrical power generator operatively connected to a rotor converter, the method comprising the step of replacing a first rotor resistance value, R_r, by a second rotor resistance value, R_{BCO}, during said blocked rotor converter situation, said second rotor resistance value, R_{BCO}, preferably being variable.

The method may simulate single- or multi-phase systems, such as three-phase system.

The method may further comprise the step of representing the rotor converter by a controllable voltage source during said blocked rotor converter situation.

In a third aspect, the present invention relates to a computer program product for performing the simulation method according to the second aspect when said computer program product is run on, or executed by, a microprocessor.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will now be explained in further details with reference to the accompanying drawings, wherein

Fig. 1 shows the overall block diagram of the simulation model,

Fig. 2 illustrates the converter blocking operation,

Fig. 3 shows equivalent circuits of the 4^{th} and the 2^{th} order QD synchronous models,

Fig. 4a shows the voltage source, the inserted resistor R_{BCO} and the generator equivalent circuit in a QD synchronous domain, and Fig. 4b shows a 3 phase voltage source, the inserted resistors R_{BCO} and the generator rotor and stator windings in a 3 phase representation, and

Fig. 5 illustrates the AGO state control.

While the invention is susceptible to various modifications and alternative forms, specific embodiments have been shown by way of examples in the drawings and will be described in detail herein. It should be understood, however, that the invention is not intended to be limited to the particular forms disclosed. Rather, the invention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined by the appended claims.

DETAILED DESCRIPTION OF THE DRAWINGS

In its broadest aspect the present invention relates to a simulation model for simulating a power generation system with an electrical generator feeding energy to a power electronic converter. During a blocked converter scenario the converter model is changed in that a blocking resistor is inserted, or alternatively or in addition, an existing rotor resistance is changed so that its value also contains a blocking resistor. The power electronic converter is represented by a variable voltage source. For simulation purposes the generator is represented by a set of rotor winding equations and a set of stator winding equation.

The model can be represented a multiphase system or a synchronous DQ system. The model can be represented by a vector having a length and an angle.

According to the present invention it becomes possible to identify if a blocking of a converter has happened between two time steps. This information is important for fast simulations where the time steps are much faster than the actual converter blocking.

Also, detection of converter blocking may be done by voltage level rather than current level. Finally, shaping of the curve for the response due to the blocking can be implemented in the simulation model using pre-calculated results.

In order to implement reliable simulation models of electrical machines in simulation software tools, such as for example PSS/E, a 4^{th} or 2^{nd} order model for the induction machine or doubly fed induction machine (DFIG) is needed.

The induction machine model implemented in the simulation tools is often considering the reference frame moving at the synchronous or stator speed, leading the internal signals to be DC in nature.

For the SI model written in space vector form, it should be noted that the space vector representation is valid in both **D+jQ** or **Q+jD** frame conventions.

$$\underline{U_s} = -R_s \cdot \underline{I_s} - \frac{d\underline{\Phi_s}}{dt} - j \cdot \Omega_s \cdot \underline{\Phi_s} \qquad \underline{\Phi_s} = (L_{ls} + L_m) \cdot \underline{I_s} + L_m \cdot \underline{I_r} = L_s \cdot \underline{I_s} + L_m \cdot \underline{I_r}$$

$$\underline{U_r} = -R_r \cdot \underline{I_r} - \frac{d\underline{\Phi_r}}{dt} - j \cdot s \cdot \Omega_s \cdot \underline{\Phi_r} \qquad \underline{\Phi_r} = (L_{lr} + L_m) \cdot \underline{I_r} + L_m \cdot \underline{I_s} = L_r \cdot \underline{I_r} + L_m \cdot \underline{I_s}$$

[Eq 1]

The parameters and the space vectors involved in the model [Eq 1] are as follows:

$\underline{U_s}$ is the stator voltage.

$\underline{I_s}$ is the stator current.

$\underline{U_r}$ is the rotor voltage transformed to stator side.

$\underline{I_r}$ is the rotor current transformed to stator side.

$\underline{\Phi_s}$ is the stator flux.

$\underline{\Phi_r}$ is the rotor flux transformed to stator side.

$\underline{\Omega_s}$ is the stator or synchronous angular speed.

R_s is the stator resistance.

R_r is the rotor resistance.

L_{ls} is the stator leakage inductance.

L_{lr} is the rotor leakage inductance transformed to the stator side.

L_m is the magnetising inductance.

s is the slip of the machine, a-dimensional by definition.

The definition of the slip is given below. Similar to the synchronous speed, the rotor speed in electrical radians will be denominated with Ω_r.

$$s = \frac{\Omega_s - \Omega_r}{\Omega_s} \qquad \text{[Eq 2]}$$

The total stator L_s and rotor L_r inductances are also exemplified in [Eq 1] as the final variables composing the stator and rotor fluxes.

<u>The QD 4th Order Model</u>

In this case, the space vector system leads to the next 4th order model in SI units - it is basically what [Eq 1] is stated but only decomposed on Q-D axes.

$$U_{sq} = -R_s \cdot I_{sq} - \frac{d\Phi_{sq}}{dt} + \Omega_s \cdot \Phi_{sd}$$
$$U_{sd} = -R_s \cdot I_{sd} - \frac{d\Phi_{sd}}{dt} - \Omega_s \cdot \Phi_{sq}$$
$$U_{rq} = -R_r \cdot I_{rq} - \frac{d\Phi_{rq}}{dt} + s \cdot \Omega_s \cdot \Phi_{rd}$$
$$U_{rd} = -R_r \cdot I_{rd} - \frac{d\Phi_{rd}}{dt} - s \cdot \Omega_s \cdot \Phi_{rq}$$

The QD 2nd Order Model

The 2nd order version of the per-unit model will follows the 4th order closely; the only difference will come from the derivatives of the stator flux components that will equal zero in the 2nd order model – meaning the stator flux is considered constant.

$$u_{sq} = -r_s \cdot i_{sq} + \omega_s \cdot \phi_{sd}$$
$$u_{sd} = -r_s \cdot i_{sd} - \omega_s \cdot \phi_{sq}$$
$$u_{rq} = -r_r \cdot i_{rq} - \frac{1}{\Omega_b} \cdot \frac{d\phi_{rq}}{dt} + s \cdot \omega_s \cdot \phi_{rd}$$
$$u_{rd} = -r_r \cdot i_{rd} - \frac{1}{\Omega_b} \cdot \frac{d\phi_{rd}}{dt} - s \cdot \omega_s \cdot \phi_{rq}$$

The models shown are all represented in a so called synchronous reference frame system. It would be general knowledge to the person skilled in the art to use the same model in a stationary reference frame with a multi phase representation. Other more simple or complex generator model could be used as well. The associated simulation results would most like vary but the spirit of the invention would not be any different.

The equivalent circuits of the 4th and the 2nd order QD models are shown in Fig. 3a and Fig. 3b, respectively.

Referring now to Fig. 1 an embodiment of the present invention is depicted. As seen in Fig. 1 the system comprises wind turbine generator in a DFIG configuration together with a rotor connected to a power electronic converter. The power electronic converter can be split into two parts, namely a grid side converter and a generator side converter.

As the grid-side converter is consequently controlled with unity power factor, there is no reactive current flowing through the grid side converter. The DC-link controller feeds the rotor power to the grid in order to preserve the energy balance across the DC-link. The contribution of the rotor power to the total current out of the wind turbine is modelled by an ideal ratio changer with a built-in slip dependency.

$$P_{total} = (1 + slip) \times P_{stator} \qquad Q_{total} = Q_{stator}$$

Still referring to Fig. 1 the controllable switch just in front of the generator (BCO switch) allows to switch the rotor voltages of the machine away from the current controller outputs and onto a controlled voltage source. This switching action is activated by an AGO state machine, cf. Fig. 5. At the same time the rotor resistance value used in the machine equations is changed from its nominal value (R_R) to a value called R_{BCO}.

Fig. 2 shows the converter blocking operation emulated by external controlled voltage source and a variable rotor resistance, R_{BCO}, in the DFIG model. The signal from the current controller state to the V_{BCO} state in controlled by the AGO state machine.

Both V_{BCO} and R_{BCO} are determined 'empirically' by running numerous simulations with a very detailed model. The same simulations have been used to define the criteria for switching the AGO state machine into State 2. This means that even though the simulation runs with a much higher time steps than the actual response shows, the performance can show the proper response since the ‘empirically’ simulations are stored in the model and can be used during the converter blocking operation.

A LVRT logics block must generate three outputs for the rest of the system to use during a low voltage ride through event. These outputs are:

1. AGO state
2. Ird_AGO current
3. Irq_AGO current

During LVRT, the turbine is running in current control mode and hence the power loop is disabled in this mode.

The outputs of the LVRT block are thus reference currents in the d and q axis and a logic signal indicating whether the system is in normal mode (0=power control) or LVRT mode (1=current control).

Besides the generator controls, the AGO state signal affects the PQ-limit block and it is also used to control the BCO-switch at the rotor terminals of the generator, cf. Fig. 1.

Fig. 4a shows the voltage source, the inserted resistor R_{BCO} and the generator equivalent circuit in a QD synchronous domain. Fig. 4b shows a 3 phase voltage source, the inserted resistors R_{BCO} and the generator rotor and stator windings in a 3 phase representation,

The main function of the AGO state machine is to switch the electrical control block between power control and current control mode. In order to assure a bump-less transfer when the power control is regained, the AGO state signal is also used to reset reference filters and the integrator of the power loop PI controller. The AGO state machine is shown in Fig. 5.

<u>AGO state 0</u>

In this state the AGO is inactive, but it continuously monitors the stator voltage in order to detect if a ride-through sequence should be initiated. The stator voltage amplitude and its rate of change determine whether the state changes to State 1 or State 2. The electrical control remains in normal operation (power control) as long as the AGO state machine is in State 0.

<u>AGO state 1</u>

In this state the power control loop is disabled and AGO current references are fed directly to the rotor current controllers. When the voltage is restored ($|U_s|$ >

U_{LVRT}), preparations to finish the AGO sequence and return to State = (Normal Operation) is initiated. Upon the change from State 1 back to State 0, the AGO-switch in the control loop switches back in the power controller with a reset of the integrator state.

AGO state 2

State 2 is a transition phase between State 0 and State 1. Entry is exclusively from State 0 and exit is always to State 1. This State is introduced in order to represent the generator response to a blocked rotor converter. The BCO-switch (Blocked Converter Operation) switched to the voltage source V_{BCO} all the time the AGO state machine is in State 2. Furthermore, the rotor resistance of the generator model is altered throughout the activation period of State 2. Upon entry into this State a timer is activated. When this timer expires, the state machine shifts to mode 1. During the AGO state 2, the integrator as well as the output of the current controllers are reset to the value of zero. When leaving State 2 (and entering State 1= current control), the currents are ramped towards the values calculated by the State 1 controllers.

CLAIMS

1. A model for simulating a power generation system comprising an electrical power generator operatively connected to an electronic power converter, wherein, during in a predetermined mode of operation of the power generation system, a first rotor resistance value, R_r , of the model is replaced by a second rotor resistance value, R_{BCO}.

2. A simulation model according to claim 1, wherein the predetermined mode of operation is associated with a blocked converter situation.

3. A simulation model according to claim 2, wherein the electronic power converter is furthermore represented by a voltage source during said predetermined mode of operation.

4. A simulation model according to claim 3, wherein the voltage source representing the electronic power converter during the predetermined mode of operation comprises a controllable voltage source.

5. A simulation model according to any of claims 1-4, wherein the second rotor resistance value, R_{BCO}, is variable.

6. A simulation model according to any of the preceding claims, wherein the electronic power converter represented in the model comprises a rotor power converter.

7. A simulation model according to any of the preceding claims, wherein the predetermined mode of operation is triggered by an AGO module of the model.

8. A simulation model according to any of the preceding claims, wherein the model is implemented in a PSS/E environment.

9. A method for simulating a blocked rotor converter situation in a power generation system comprising an electrical power generator operatively

connected to a rotor converter, the method comprising the step of replacing a first rotor resistance value, R_r, by a second rotor resistance value, R_{BCO}, during said blocked rotor converter situation.

10. A method according to claim 9, further comprising the step of representing the electronic power converter with a controllable voltage source during said blocked rotor converter situation.

11. A method according to claim 9 or 10, wherein the second rotor resistance value, R_{BCO}, is variable.

12. A computer program product for performing the simulation method according to any of claims 9-11 when said computer program product is run on, or executed by, a microprocessor.

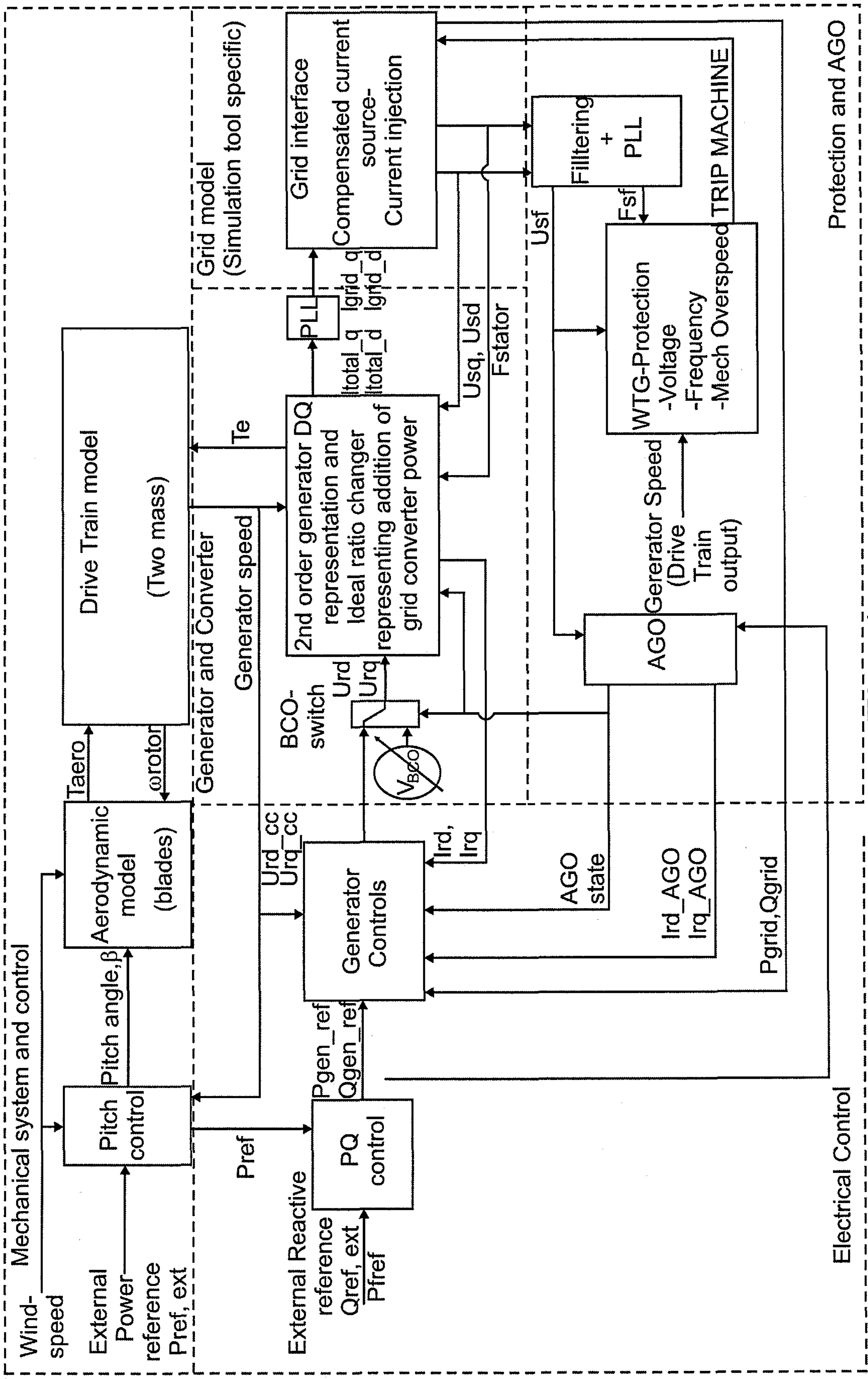

Mechanical system and control
Wind-speed
External Power reference Pref, ext
Pitch control
Pitch angle,β
Aerodynamic model (blades)
Taero
ωrotor
Drive Train model (Two mass)
Generator and Converter
Generator speed
Te
2nd order generator DQ representation and Ideal ratio changer representing addition of grid converter power
Itotal_q
Itotal_d
PLL
Igrid_q
Igrid_d
Grid model (Simulation tool specific)
Grid interface Compensated current source- Current injection
Usq, Usd
Fstator
Filltering + PLL
Fsf
Usf
TRIP MACHINE
Protection and AGO
WTG-Protection -Voltage -Frequency -Mech Overspeed
Generator Speed (Drive Train output)
AGO
BCO-switch
Urd
Urq
VBCO
Urd_cc
Urq_cc
Ird, Irq
Generator Controls
AGO state
Ird_AGO
Irq_AGO
Pgrid,Qgrid
Pgen_ref
Qgen_ref
Pref
PQ control
External Reactive reference Qref, ext
Pfref
Electrical Control

Fig. 1

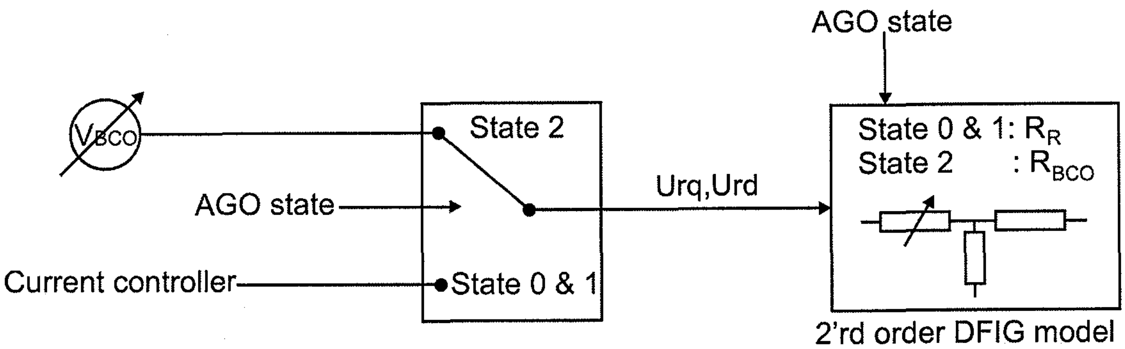
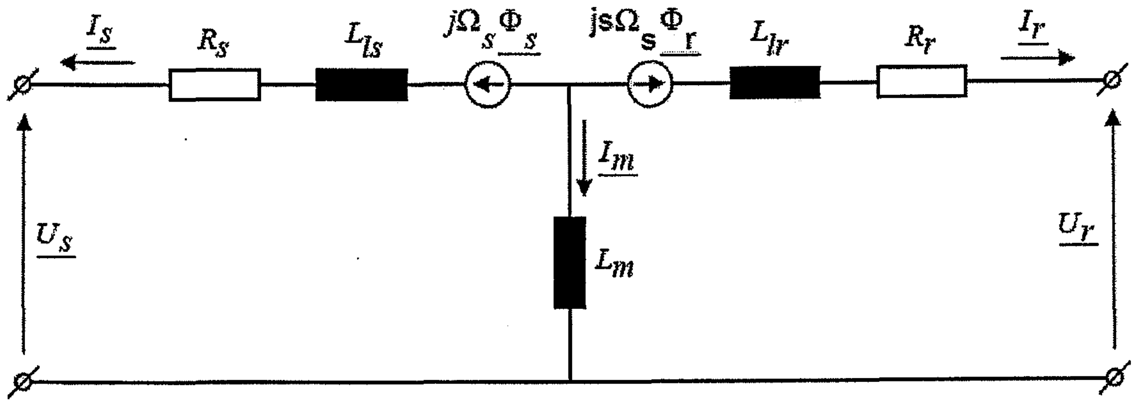
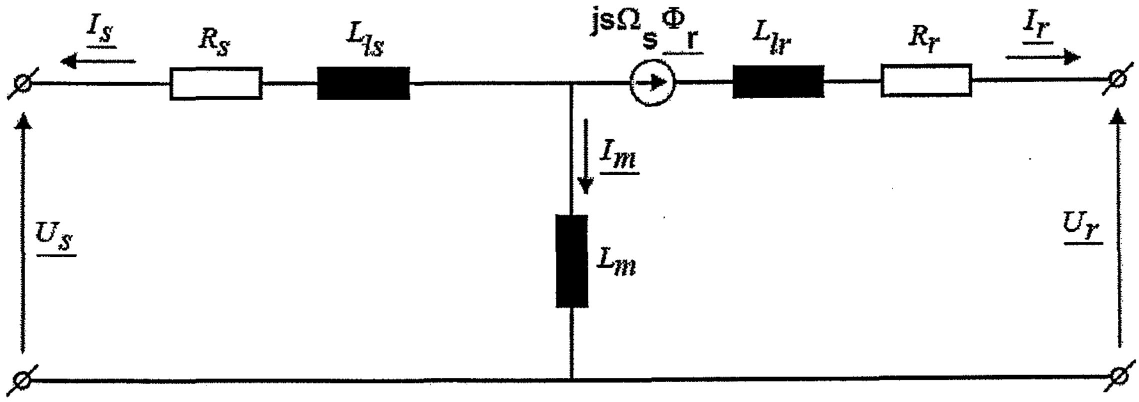

AGO state
State 2
AGO state
Current controller
State 0 & 1
Urq,Urd
State 0 & 1: R_R
State 2 : R_{BCO}
2'rd order DFIG model

Fig. 2


$\underline{I_s}$
R_s
L_{ls}
$j\Omega_s\underline{\Phi_s}$
$js\Omega_s\underline{\Phi_r}$
L_{lr}
R_r
$\underline{I_r}$
$\underline{I_m}$
$\underline{U_s}$
L_m
$\underline{U_r}$

a)


$\underline{I_s}$
R_s
L_{ls}
$js\Omega_s\underline{\Phi_r}$
L_{lr}
R_r
$\underline{I_r}$
$\underline{I_m}$
$\underline{U_s}$
L_m
$\underline{U_r}$

b)

Fig. 3

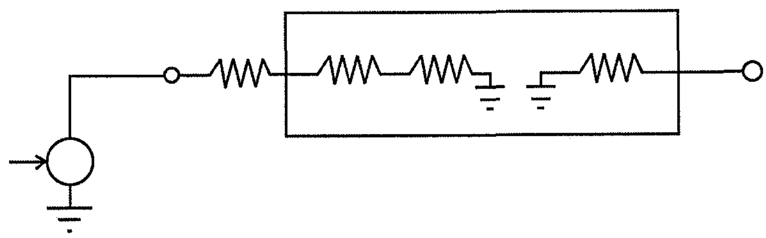


Fig. 4a

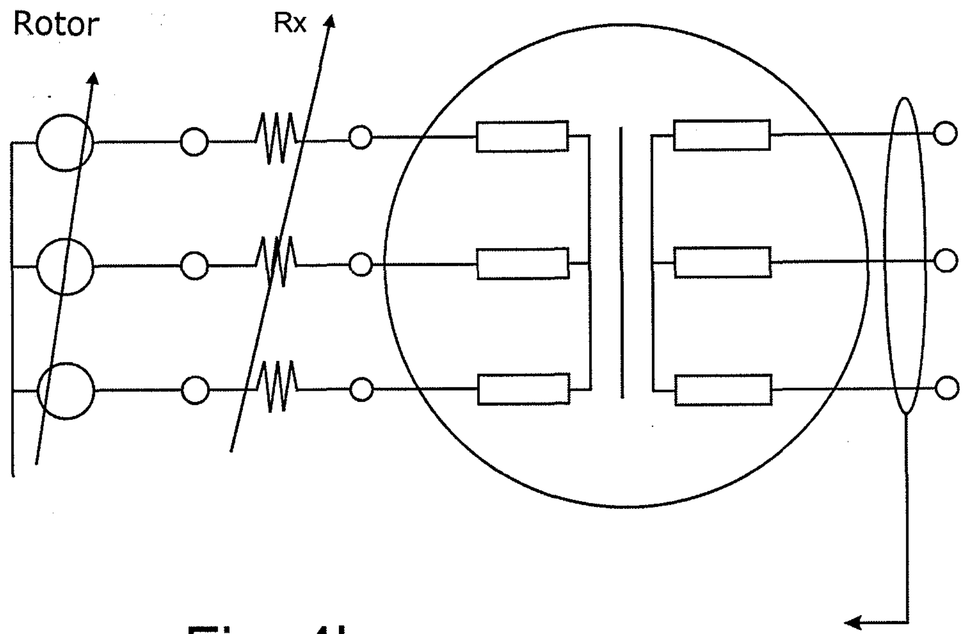


Fig. 4b

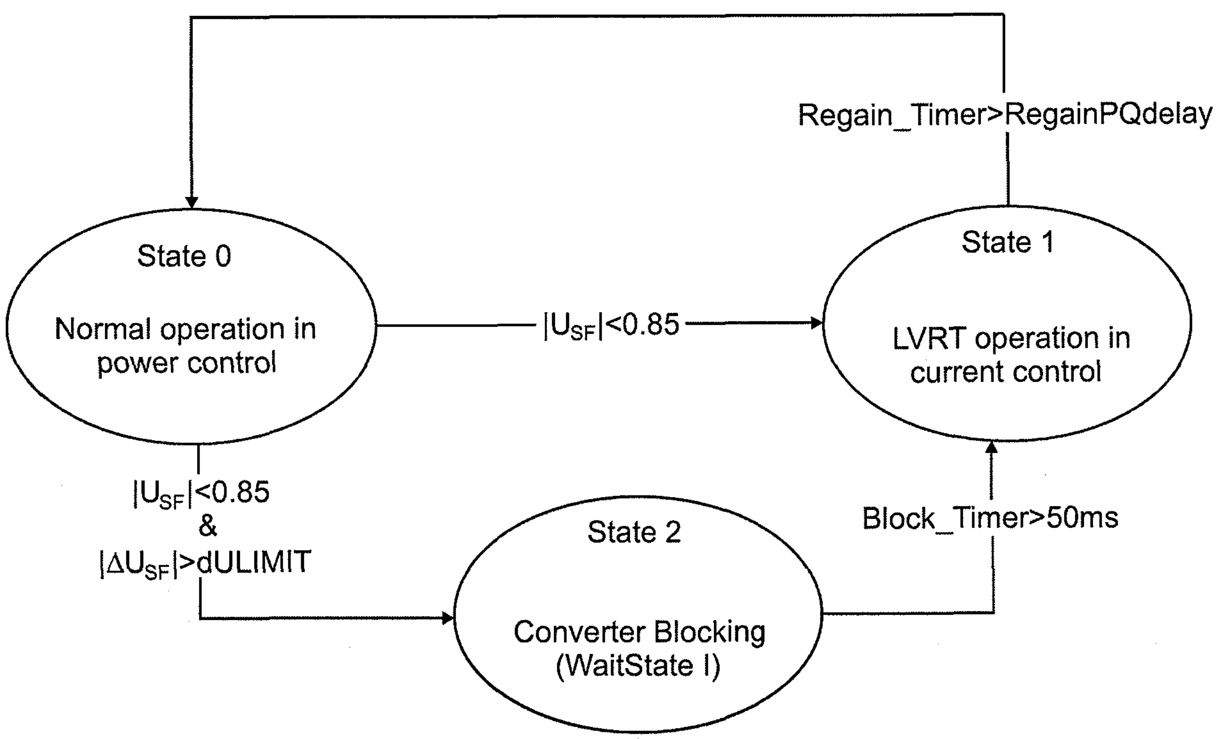

State 0
Normal operation in power control
|U_SF|<0.85
State 1
LVRT operation in current control
Regain_Timer>RegainPQdelay
|U_SF|<0.85
&
|ΔU_SF|>dULIMIT
State 2
Converter Blocking (WaitState I)
Block_Timer>50ms

Fig. 5

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2010/052618

A. CLASSIFICATION OF SUBJECT MATTER
INV. G06F17/50
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G06F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	FERNANDEZ ET AL: "Aggregated dynamic model for wind farms with doubly fed induction generator wind turbines" RENEWABLE ENERGY, PERGAMON PRESS, OXFORD, GB LNKD- DOI:10.1016/J.RENENE.2007.01.010, vol. 33, no. 1, 30 October 2007 (2007-10-30), pages 129-140, XP022321595 ISSN: 0960-1481 the whole document ----- -/--	1-12

[X] Further documents are listed in the continuation of Box C.

[ ] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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"P" document published prior to the international filing date but later than the priority date claimed

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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
13 August 2010	19/08/2010

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Radev, Boyan

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	SANCHEZ ET AL: "Dynamic model of wind energy conversion systems with variable speed synchronous generator and full-size power converter for large-scale power system stability studies" RENEWABLE ENERGY, PERGAMON PRESS, OXFORD, GB LNKD- DOI:10.1016/J.RENENE.2007.06.019, vol. 33, no. 6, 19 February 2008 (2008-02-19), pages 1186-1198, XP022489721 ISSN: 0960-1481 the whole document -----	1-12