Reduced Order Model of Wind Turbines based on Doubly-Fed Induction Generators during Voltage Imbalances

S.Engelhardt, C.Feltes, J.Fortmann, J.Kretschmann, I.Erlich

***Abstract*-- This paper deals with modeling of the doubly-fed induction generator (DFIG) and the corresponding converter during voltage asymmetry for stability studies. To enable efficient computation reduced order DFIG models for the investigation of system stability at symmetrical faults were developed in the past and calculation reduced to the fundamental frequency component. These models are extended here to calculate unsymmetrical voltage conditions. Suitable models are presented for the rotor and grid side converter as well as the DC-link. Simulation results are presented for model verification purposes and also for demonstrating the dynamic behavior of a typical wind turbine connected to the mid voltage grid at unsymmetrical faults.**

***Index Terms*-- control system, doubly-fed induction machine, power system stability, wind power**

I. Nomenclature

$\underline{i}$, $\underline{u}$	complex current and voltage
l, x, r	inductance, reactance, resistance
$\underline{\psi}$	complex flux-linkages
ω, s	angular speed, slip
t, T	torque, time constant
Θ_m	inertia of complete rotor shaft
<u>subscripts</u>	
$1,2$	positive, negative sequence
S, R	stator, rotor
d, q	direct, quadrature axis component
h, σ	main field, leakage
<u>superscripts</u>	
$*$	conjugate complex vector

II. Introduction

With the increasing share of wind in power generation the dynamic behavior of the power system will change considerably due to different technologies used for wind generators. On the other hand the development of wind turbine (WT) models suitable for large scale stability studies are still in progress. Models used by manufacturers are, as a rule, too complex containing too many details not necessarily relevant to the desired dynamic simulations. Stability type WT models are urgently needed also for grid code verification purposes. It has been shown already that due to higher penetration level of wind energy, the control of WT may need some modifications to meet the grid requirements of the future. The corresponding proofs have to be provided by the planners and manufacturers before utilities approve grid connection.

In this paper a stability type dynamic model for WT equipped with the most common doubly fed induction generators (DFIG) and the corresponding converters is presented. Conventional synchronous generators are described for stability analysis by reduced order models [1]. The same approximation applied to the DFIG results in a similar model [2]. To enable efficient computation by restricting the calculation to the fundamental frequency component reduced order DFIG models for power system stability studies were presented in the past. With the existing positive sequence models the system behavior at symmetrical grid faults can be simulated [3]. They include models for the rotor and grid side converter with the corresponding dc-link as well as models for speed and pitch angle control.

This paper enhances the existing models for studies regarding active and reactive power capability during periods of voltage imbalance. This topic is presently discussed intensively in Germany and new grid code requirements regarding voltage support of wind energy systems during unbalanced grid faults are upcoming. The models consist of a reduced order machine representation as well as additional control algorithms which take into account voltage and current limitations of a typical DFIG system.

Simulations of a WT for the most common unsymmetrical faults will show the control behavior with special emphasis on the grid code requirement voltage support as well as voltage symmetrization.

A. *Doubly Fed Induction Generator*

The DFIG is the most commonly used device for wind power generation. As is generally known, the rotor terminals are fed with a symmetrical three-phase voltage of variable frequency and amplitude. This voltage is supplied by a

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voltage source converter usually equipped with IGBT based power electronics circuitry. The basic structure is shown in Fig. 1.

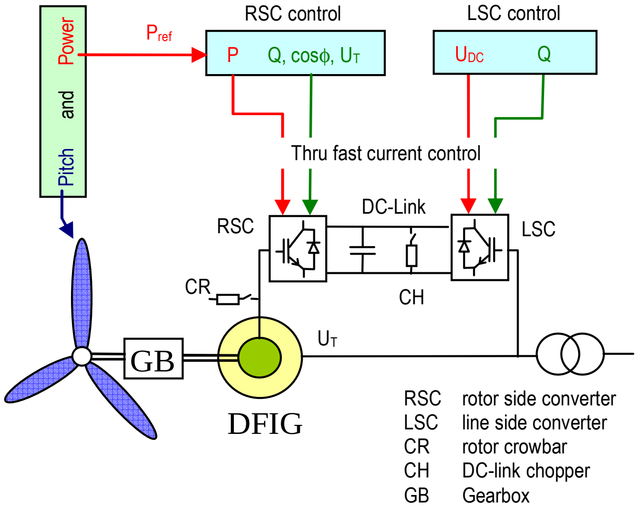

Fig. 1 Main system components of DFIG-based wind turbine

The variable frequency rotor voltage permits the adjustment of the rotor speed to match the optimum operating point at any practical wind speeds. Protection against undesirably high DC voltage is provided by the DC-link chopper (CH). When the rotor current rises and the DC voltage exceeds the upper threshold allowed, the chopper dissipates superfluous energy and balances the dc-link voltage [5-7]. With an adequate rating of the DC-chopper and the rotor side converter (RSC) the power output of the DFIG system can always be controlled up to the current limits during typical grid faults. Thus operation of the system as a conventional slip-ring induction machine by firing the crowbar CB thyristor switches and short-circuiting the rotor terminals has been overcome by modern systems and only is necessary to handle internal faults.

Typically a Dy5 transformer connects the wind energy system to the grid, therefore the zero sequence system (e.g. during earth faults) has no effect on transient electrical and mechanical characteristics of the wind turbine.

III. MODEL OF THE DFIG

Decomposition of the DFIG voltage equations into positive and negative sequence yields

Positive sequence components in positive synchronous reference frame:

$$\underline{u}_{S1} = r_S \underline{i}_{S1} + \frac{d\underline{\psi}_{S1}}{dt} + j\omega_0 \underline{\psi}_{S1} \tag{1}$$

$$\underline{u}_{R1} = r_R \underline{i}_{R1} + \frac{d\underline{\psi}_{R1}}{dt} + j(\omega_0 - \omega_R)\underline{\psi}_{R1} \tag{2}$$

$$\underline{\psi}_{S1} = l_S \underline{i}_{S1} + l_h \underline{i}_{R1} \tag{3}$$

$$\underline{\psi}_{R1} = l_h \underline{i}_{S1} + l_R \underline{i}_{R1} \tag{4}$$

Negative sequence components in negative synchronous reference frame:

$$\underline{u}_{S2} = r_S \underline{i}_{S2} + \frac{d\underline{\psi}_{S2}}{dt} + j\omega_0 \underline{\psi}_{S2} \tag{5}$$

$$\underline{u}_{R2} = r_R \underline{i}_{R2} + \frac{d\underline{\psi}_{R2}}{dt} + j(\omega_0 + \omega_R)\underline{\psi}_{R2} \tag{6}$$

$$\underline{\psi}_{S2} = l_S \underline{i}_{S2} + l_h \underline{i}_{R2} \tag{7}$$

$$\underline{\psi}_{R2} = l_h \underline{i}_{S2} + l_R \underline{i}_{R2} \tag{8}$$

with $l_S = l_h + l_{\sigma S}$ and $l_R = l_h + l_{\sigma R}$

Equation of motion:

$$\frac{d\omega_R}{dt} = \frac{1}{\theta_m}\left(\mathrm{Im}\left[\left(\underline{\psi}_{S1} + \underline{\psi}^*_{S2,1}\right) \times \left(\underline{i}_{S1} + \underline{i}^*_{S2,1}\right)\right] + t_m\right) \tag{9}$$

with

$$\underline{\psi}^*_{S2,1} = \underline{\psi}^*_{S2} \exp(-j2\omega t) \tag{10}$$

$$\underline{i}^*_{S2,1} = \underline{i}^*_{S2} \exp(-j2\omega t) \tag{11}$$

A. DFIG positive sequence reduced order model

The reduced order model (ROM) described in [3] for the positive sequence system is derived by setting the stator flux derivate to zero

$$\frac{d\underline{\psi}_{S1}}{dt} = 0 \tag{12}$$

(1) can then be transformed with (3) and (4) to

$$\underline{u}_{S1} = \underline{z}_1{}' \, \underline{i}_{S1} + \underline{u}_1{}' \tag{13}$$

with

$$\underline{z}_1{}' = r_S + j\omega_0\left(l_S - \frac{l_h^2}{l_R}\right) \tag{14}$$

as the internal transient impedance and

$$\underline{u}_1{}' = j\omega_0 \frac{l_h}{l_R}\underline{\psi}_{R1} = j\omega_0 k_R \underline{\psi}_{R1} \tag{15}$$

as the corresponding transient driving Thévenin voltage source.

Replacing $\underline{i}_R$ in (2) with (4) yields the differential equation for the rotor flux in (15)

$$\frac{d\underline{\psi}_{R1}}{dt} = -\frac{r_R}{l_R}\underline{\psi}_{R1} - j(\omega_0 - \omega_R)\underline{\psi}_{R1} + k_R r_R \underline{i}_{S1} + \underline{u}_{R1} \tag{16}$$

Fig. 2 illustrates the positive sequence ROM of the DFIG

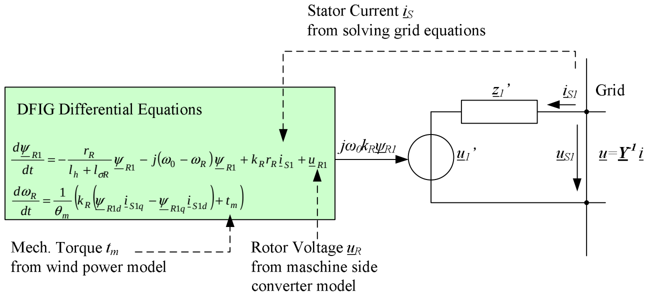

Fig. 2 Reduced order DFIG model for the positive sequence system

B. DFIG negative sequence reduced order model

The negative sequence ROM is also derived by setting the stator flux derivate to zero. After some modifications of eq. (5), (7) and (8) the internal transient impedance can be derived to

$$\underline{z}_2' = r_S + j\omega_0\left(l_S - \frac{l_h^{\,2}}{l_R}\right) \qquad (17)$$

and the corresponding transient driving Thévenin voltage source to

$$\underline{u}_2' = j\omega_0 k_R \underline{\psi}_{R2} \qquad (18)$$

(6) and (8) determine the differential equation for the rotor flux in the negative sequence

$$\frac{d\underline{\psi}_{R2}}{dt} = -\frac{r_R}{l_R}\underline{\psi}_{R2} - j(\omega_0 + \omega_R)\underline{\psi}_{R2} + k_R r_R \underline{i}_{S2} + \underline{u}_{R2} \qquad (19)$$

Fig. 3 shows the expanded ROM of the DFIG for calculation of unsymmetrical faults.

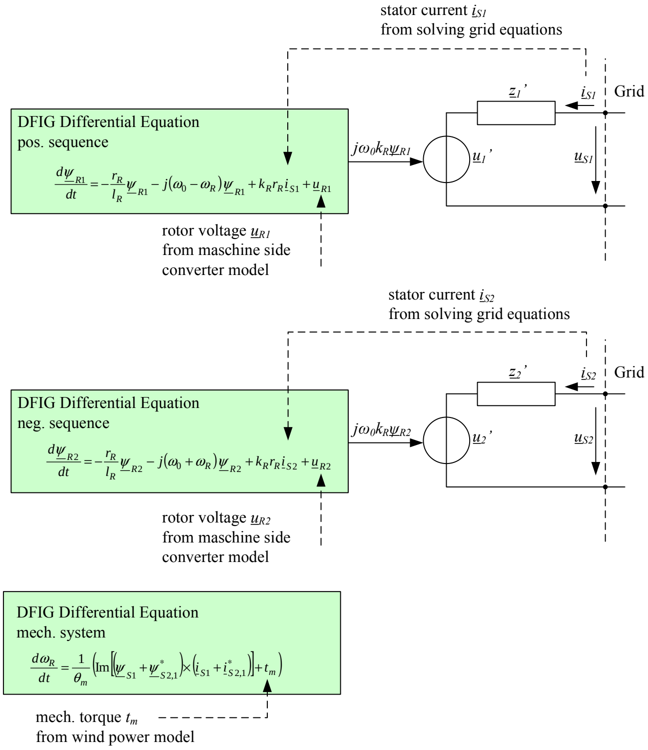

Fig. 3 Reduced order DFIG model with negative sequence

C. *RSC positive sequence control*

The positive sequence control of the RSC has been described in detail in [3]. The power controller model is shown in Fig. 4. Input variables are the reference real power p_{WT_ref} of the wind turbine speed controller and the reactive power q_{WT_ref} which can be chosen arbitrarily within the current and voltage limits of the converter. The reference power values are passed through lag blocks for taking communication delays into account. To get the stator reference power for the positive sequence the power through the LSC and the active power of the negative system are subtracted from these values. The set values of the rotor current controllers in stator voltage oriented coordinates can be calculated from eq. (1) and (3) by neglecting the derivative term and stator resistance r_S.

$$i_{R1d}^{\angle u_{S1}} = -\frac{x_S}{x_h} i_{S1d}^{\angle u_{S1}} \quad (20) \qquad i_{R1q}^{\angle u_{S1}} = -\frac{x_S}{x_h} i_{S1q}^{\angle u_{S1}} - \frac{|\underline{u}_{S1}|}{x_h} \quad (21)$$

The term u_{S1} / x_h represents the magnetization current that has to be provided from the rotor side. To keep the rotor current within the maximum permissible limits a magnitude limiter may reduce either active or reactive current, depending on which option is more expedient at the given condition.

With increasing penetration and diffusion of WT in the power system, the voltage control capability of the DFIG has become an important issue [8]. Therefore a fast-acting voltage controller has been augmented. The chosen gain and time constants depend on the stability requirements of the system that has always to be guaranteed. Sometimes it is reasonable to include a dead band into the voltage control loop to avoid unnecessary control actions.

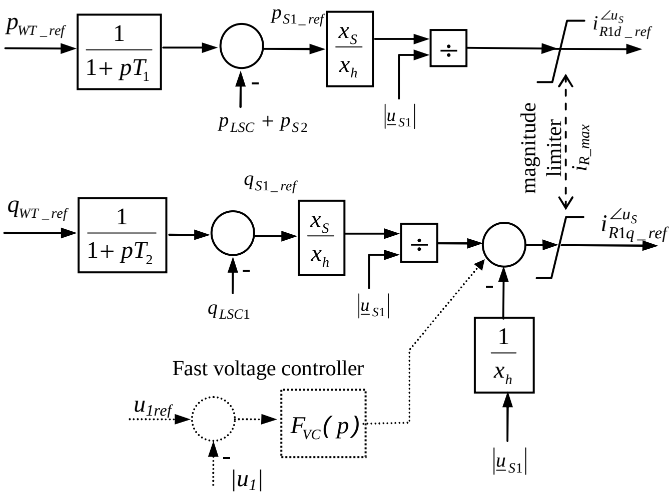

Fig. 4. Structure for generating rotor current reference values

Fig. 5 shows the complementary rotor current controller of the RSC. From the basic equations (1)-(4) the cross coupling terms for the steady state in the stator coordinate reference frame can be derived by setting all derivatives to zero and neglecting the stator resistance r_S:

$$u_{R1d}^{\angle u_{S1}} = r_R i_{R1d}^{\angle u_{S1}} + s\left(\frac{x_h}{x_S}|\underline{u}_{S1}| - i_{R1q}^{\angle u_{S1}}\,\sigma\, x_R\right) \qquad (22)$$

$$u_{R1q}^{\angle u_{S1}} = r_R i_{R1q}^{\angle u_{S1}} + s\, i_{R1d}^{\angle u_{S1}}\,\sigma\, x_R \qquad (23)$$

where leakage coefficient $\sigma = (1 - x_h^2 / x_R x_S)$ is introduced.

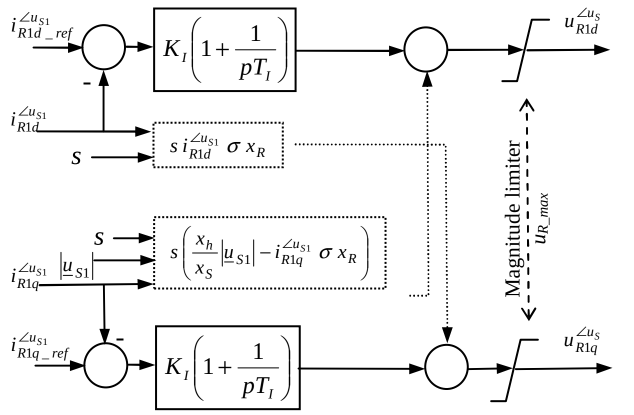

Fig. 5 Rotor current control positive sequence system

With PI controllers, the control transfer function then is:

$$u'^{\angle u_{S1}}_{R1d} = r_R i_{R1d}^{\angle u_{S1}} = K_I\left(1 + \frac{1}{pT_I}\right)\cdot\left(i_{R1d\_ref}^{\angle u_{S1}} - i_{R1d}^{\angle u_{S1}}\right) \qquad (24)$$

$$u'^{\angle u_{S1}}_{R1q} = r_R i_{R1q}^{\angle u_{S1}} = K_I\left(1 + \frac{1}{pT_I}\right)\cdot\left(i_{R1q\_ref}^{\angle u_{S1}} - i_{R1q}^{\angle u_{S1}}\right) \qquad (25)$$

The outputs of the current controller have to be transformed to the common reference frame

$$\underline{u}_{R1} = \underline{u}_{R1}^{\angle u_{S1}} \cdot e^{j\varphi_{us1}} \tag{26}$$

where φ_{us1} represents the stator voltage angle. Then, $\underline{u}_R$ can be passed on to the corresponding state equation (15), (16) which are described in the common synchronous reference frame. The maximum PWM of the converter is represented by a magnitude limiter. Depending on active or reactive current priority the corresponding voltage component is reduced at first.

D. RSC negative sequence control

In [5] and [6] several possibilities to control the negative sequence current were presented. Objectives of the negative sequence control can be ripple torque reduction, negative sequence current compensation or negative sequence voltage reduction. The negative sequence current control is shown in Fig. 6. It can be derived the same way as for the positive sequence by feed forward of the cross coupling terms for the steady state in the stator coordinate reference frame. Also all derivatives are set to zero and the stator resistance r_S is neglected.

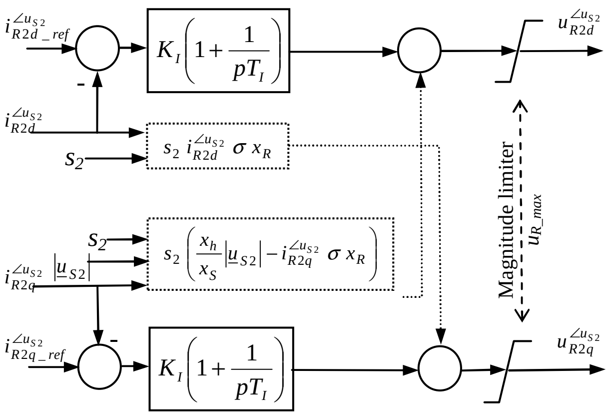

Fig. 6 Rotor current control negative sequence system

Due to the output voltage limitation of the converter, the negative sequence voltage has to be limited. In general the positive control has priority therefore the maximum voltage to avoid over-modulation can be calculated with

$$\left|\underline{u}^*_{R2,\max}\right| = u_{R,\max} - \left|\underline{u}_{R1}\right| \tag{27}$$

As shown in [9] the DFIG system without negative sequence control symmetrizes the grid and will be considered in the simulations in section IV. The negative sequence rotor voltage u_{R2} can then be set to zero and the model further simplified. After elimination of the negative sequence rotor flux the transfer function of the Thévenin voltage source is

$$\underline{u}_2{}' = \frac{\omega_0 k_R{}^2 r_R}{(\omega_0 + \omega_R) - j\left(p + \frac{r_R}{l_R}\right)} \underline{i}_{S2} \tag{28}$$

and corresponds to a time dependent impedance with an initial value of zero (p->∞). For typical DFIG systems the steady state value of this impedance is approximately $r_R/2$ since $k_R \sim 1$, $\frac{r_R}{l_R} << (\omega_0 + \omega_R)$ and $\frac{\omega_0}{(\omega_0 + \omega_R)} \sim \frac{1}{2}$.

Thus the internal transient impedance $\underline{z}_2'$ for DFIG systems without negative sequence control can be modified to

$$\underline{z}_2{}' = r_S + \frac{r_R}{2} + j\omega_0\left(l_S - \frac{l_h{}^2}{l_R}\right) \tag{29}$$

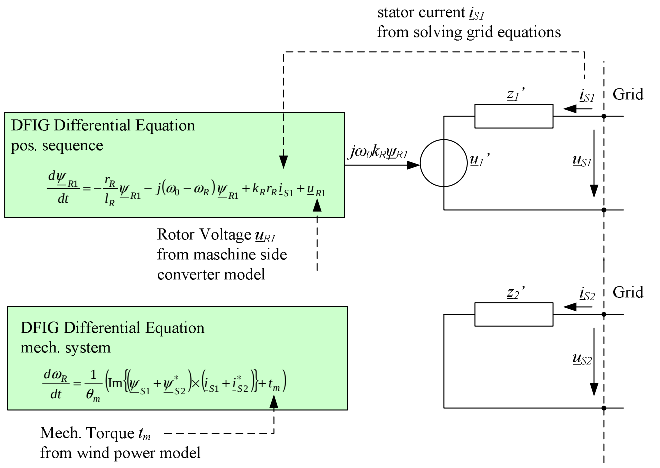

Fig. 7 ROM of DFIG without negative sequence control

E. RSC current limitation during voltage asymmetry

As described in *C* the RSC current has to be limited to the nominal rating of the converter. The negative sequence rotor current is not controlled here and therefore reduces the maximum rotor current of the positive sequence system. According to eq. (2) and (6) the positive and negative sequence components have different frequencies due to the rotation of the rotor. The thermal restrictions of the converter refer to the rms value of the rotor current. Therefore the maximum positive sequence current can be calculated as follows

$$\left|\underline{i}_{R1,\max}\right| = \sqrt{i_{R,\max}{}^2 - \left|\underline{i}^*_{R2}\right|^2} \tag{30}$$

F. Line Side Converter Control

The line side converter (LSC) has to transmit the active power from the DC-link to the grid so that the DC-link voltage is kept within limits. Unlike the RSC the LSC can completely compensate the negative sequence voltage [10] and only the positive sequence has to be taken into account. The corresponding controller and converter model is shown in the upper part of Fig. 8. The output is the active current which is injected into the grid node. Depending on the software used, this current can be converted into an equivalent power.

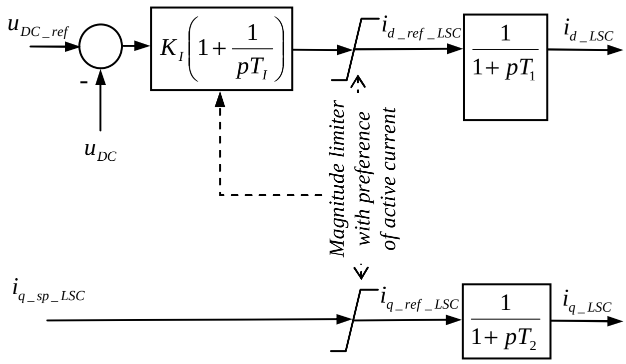

Fig. 8 Block diagram of line side converter model

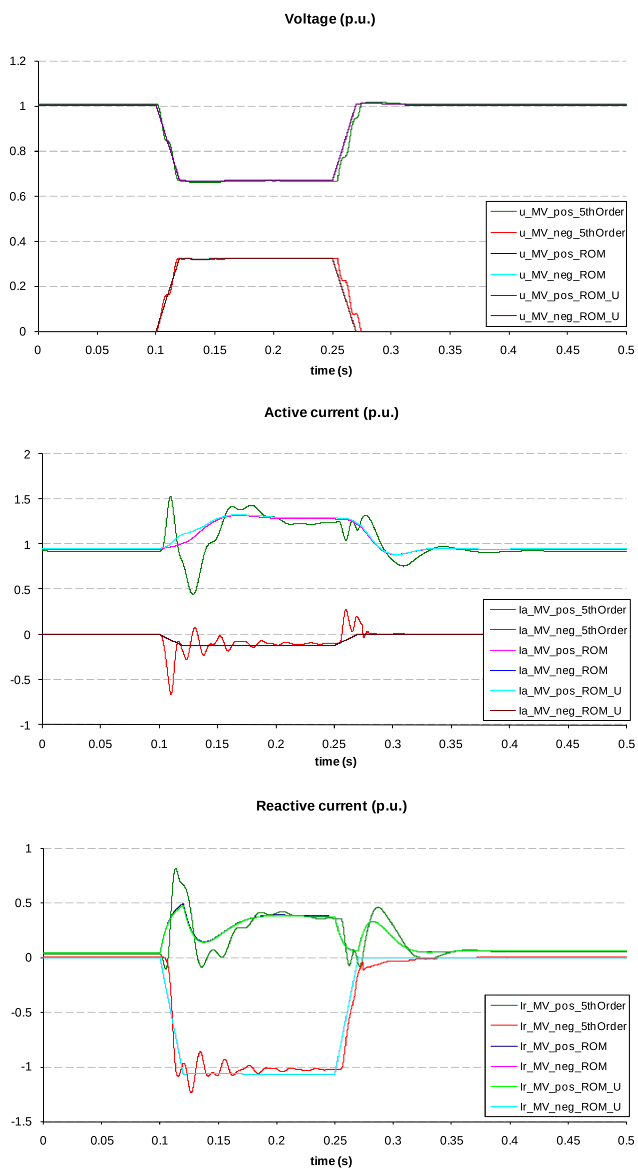

Fig. 9a Simulation of an earth fault on the MV side of a 2MW wind turbine transformer, voltage and current on MV side
(notice that sign convention has been changed for better clarity: in this diagram generated active current and capacitive current are positive)

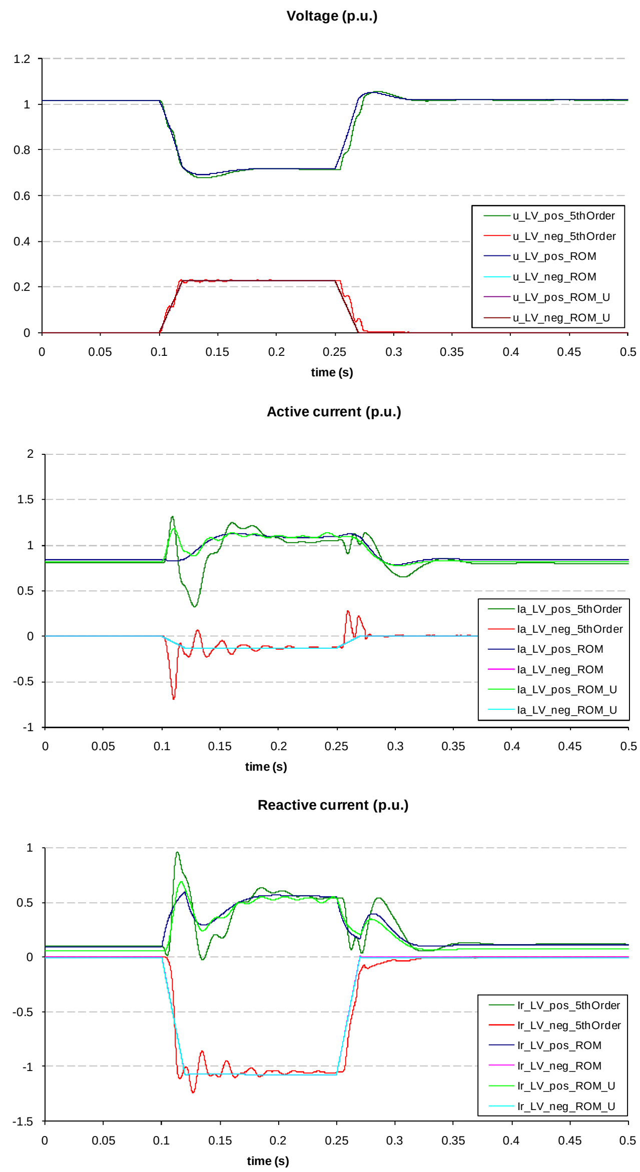

Fig. 9b Simulation of an earth fault on the MV side of a 2MW wind turbine transformer, stator voltage and current on LV side
(notice that sign convention has been changed for better clarity: in this diagram generated active current and capacitive current are positive)

Concerning reactive current generation the system provides an additional degree of freedom that can be used, e.g. for providing enhanced voltage support to the grid during faults or optimizing system efficiency. Reactive current support always has lower priority to ensure DC-link voltage stability if the current limits should be exceeded.

IV. Simulation

The proposed reduced order models are verified by simulations of typical unsymmetrical grid faults for a modern 2MW wind turbine. According to chapter II the investigated DFIG system contains a well dimensioned DC-link chopper to avoid crowbar firing during the fault. The wind turbine transformer is connected in Dyn, so that there is no overvoltage at the LV side in case of an earth fault in the medium voltage network. A negative sequence control is not implemented. The simulation results for three different models are presented.

The reference simulation is made with the 5^{th} order DFIG model according to eq. (1) to (9). The results of that model will be compared to the proposed ROM with Thévenin voltage source (subscript: ROM_U, eq. 25) and without Thévenin voltage source (subscript: ROM, eq. 26). The control algorithms for all models are equal. Prior to the fault the generation unit is operating at nominal active power at a power factor of unity. For a reasonable comparison of the different models, rms values for the 5^{th} order model are shown. Therefore the presented currents for this model do not contain the dc-component of the instantaneous currents. Fig. 9 shows the results for an earth fault in the MV grid at time t = 0 for 150ms. In the upper part of the figure rms values for the positive and negative sequence voltage are shown, in the middle part positive and negative sequence active current and in the lower part positive and negative sequence reactive current for all three models. In Fig. 8a values at the MV side of the wind turbine transformer are presented, in Fig. 8b values at the LV stator terminal of the

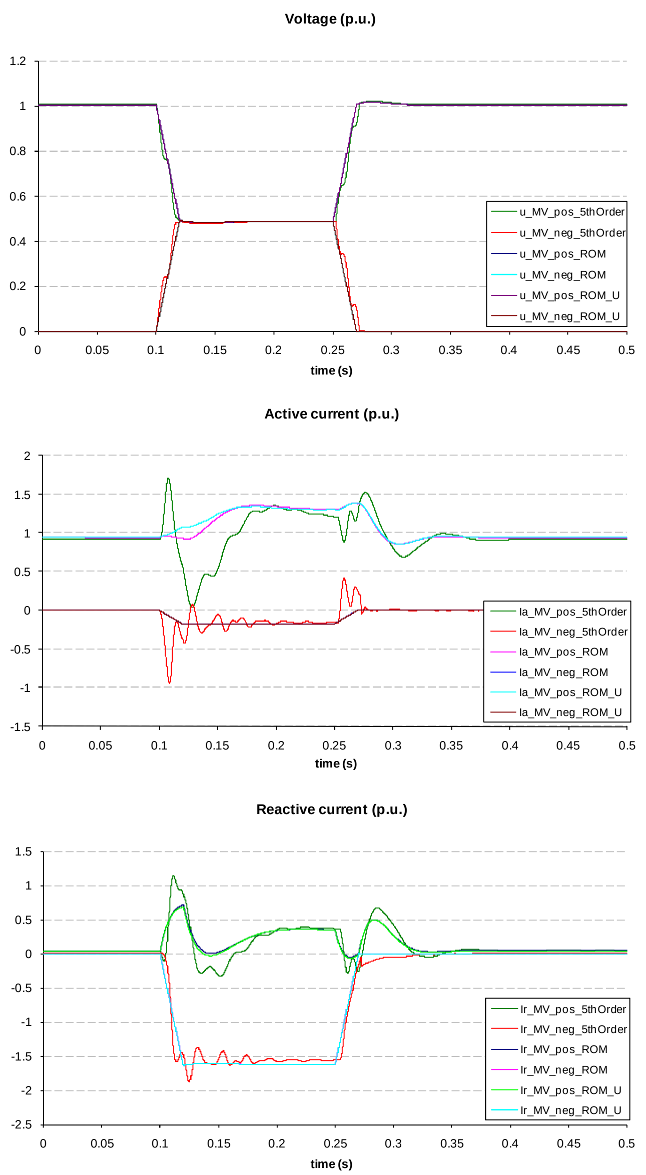

Fig. 10a Simulation of a two phase fault without earth contact on the MV side of a 2MW wind turbine transformer, voltage and current on MV side *(notice that sign convention has been changed for better clarity: in this diagram generated active current and capacitive current are positive)*

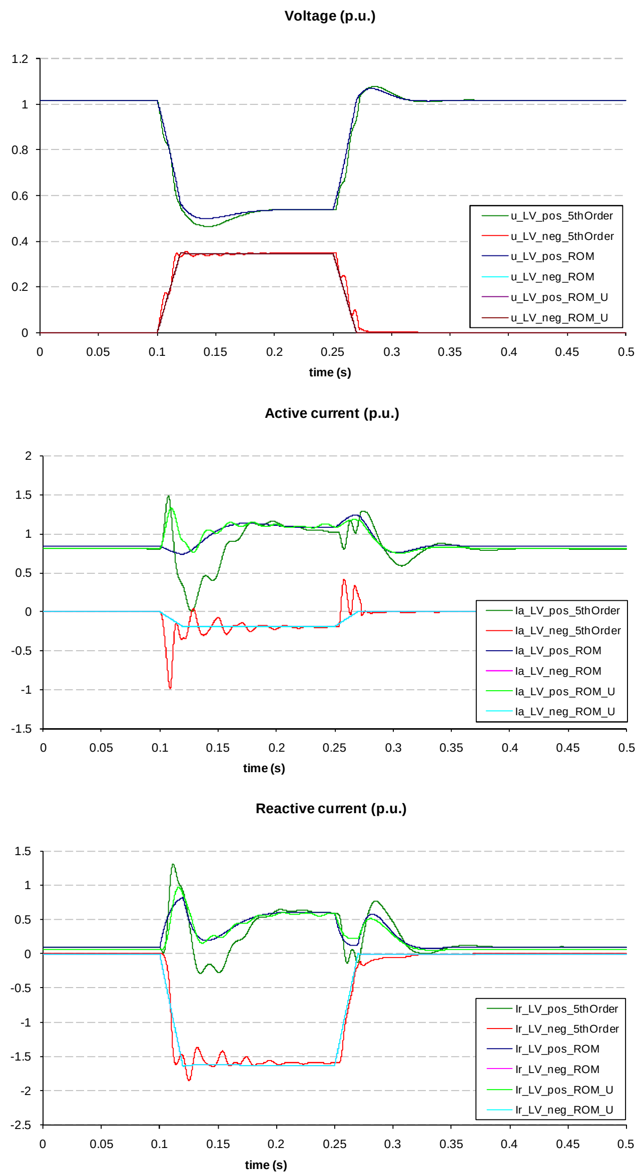

Fig. 10b Simulation of a two phase fault without earth contact on the MV side of a 2MW wind turbine transformer, stator voltage and current on LV side *(notice that sign convention has been changed for better clarity: in this diagram generated active current and capacitive current are positive)*

generator. The results of all models especially for the negative sequence are corresponding very well. As described in chapter III the Thévenin voltage source can be neglected for DFIG systems without negative sequence control.

The uncontrolled negative sequence current during the earth fault is approximately nominal current, the active stator current is limited to a value of 1.1 pu. due to thermal restrictions of the RSC. Therefore the voltage support during unsymmetrical faults must be ensured by the LSC. The requirement of a minimum value for the reactive positive sequence current of 0.4 pu. at the stator terminals in [11] can normally be fulfilled with a standard converter.

Fig. 10 shows results for a two phase fault without earth connection. Again the results for all three models correlate well. The negative sequence current is around 1.7 pu. , the active stator current again is limited to a value of 1.1 pu. due to thermal restrictions of the RSC. As in the previous case the voltage support can be applied via the LSC.

The negative sequence current, which flows through the DFIG stator, lowers the negative sequence voltage within the grid, which might be more favorable to the grid.

The voltage levels for both simulations fulfill the new requirement in [12] that the voltage in the phases which are not affected by the fault does not exceed a level of 1.1 pu.

V. Conclusion

In this paper an extension for the negative sequence of the well known reduced order models for wind turbines with DFIG systems for power system stability studies has been presented. Due to the fact that modern DFIG systems do not fire the crowbar during low voltage events, the extension remains relatively simple. The proposed model was verified by simulation and compared to results with the detailed 5th order DFIG model for the most common unsymmetrical faults. All simulations show a good correlation especially for the negative sequence values. Modeling of different versions for the negative sequence control which have not been investigated here could easily be realized via the proposed ROM with negative sequence Thévenin voltage source. Only the appropriate model of the negative sequence control has to be implemented additionally.

A topic of future work could be a model extension for older DFIG systems with crowbar firing during unsymmetrical faults.

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VII. Biographies

Stephan Engelhardt (1967) received his Dipl.-Ing. degree in electrical engineering from the University Hannover, Germany, in 1997. Since 1997 he is with Woodward SEG GmbH & Co. KG, Kempen/Germany, presently head of the group Converter Technology and responsible for system designs and simulations, control strategies and patents.

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His research interests are focused on wind energy generation, control, integration and dynamic interaction with electrical grid.

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