

Negative Sequence Control of DFG based Wind Turbines

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Abstract-- The paper deals with the control of negative sequence voltages and currents in wind turbine systems caused by grid fault or unsymmetrical system operation. The ensuing stator and rotor currents lead to additional thermal stress. Moreover, the interaction between the different sequence components of the current and voltage in the stator as well as rotor cause oscillating torque leading to mechanical strain on the drive-train. A control approach for limiting or eliminating the negative sequence current and the resulting alternating torque is discussed. This is followed by the description and derivation of the rotor side converter (RSC) for the positive as well as negative sequence current controllers. The procedure is repeated for the grid side converter (GSC), and the limitations imposed on the controllers by practical operational considerations are explained. On the basis of simulation examples using representative wind turbine system data, the effectiveness of the proposed control methods has been demonstrated.

Index Terms-- wind turbine, doubly-fed induction generator, DFIG, negative sequence control

I. NOMENCLATURE

$\underline{v}_{s1}, \underline{v}_{s2}, \underline{i}_{s1}, \underline{i}_{s2}$	Stator positive /negative sequence voltage /current
$\underline{v}_{r1}, \underline{v}_{r2}, \underline{i}_{r1}, \underline{i}_{r2}$	Rotor positive/negative sequence voltage/ current
$\underline{\psi}_{s1}, \underline{\psi}_{s2}$	Stator positive /negative sequence flux
$\underline{\psi}_{r1}, \underline{\psi}_{r2}$	Rotor positive /negative sequence flux
v_{dc}	Direct current (DC) link voltage
l_s, l_r, l_m	Stator, rotor and mutual main field inductance
r_s, r_r	Stator /rotor resistance
r_{GSC}, l_{GSC}	Converter choke resistance /inductance
ω_s, ω_r	Stator /rotor angular speed
s	Rotor slip
t_{el}	Electrical torque
$\angle x$	Superscript; x : rotational speed of the reference frame
dq	Subscript ; direct/quadrature axis component
1,2	Subscript ; positive/negative sequence component

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II. INTRODUCTION

THE most common faults in power system are of unsymmetrical type. During periods of such faults wind turbines sense negative sequence components, in addition to the positive sequence values. As opposed to the conventional large generators, modern wind turbines equipped with frequency converters, in principle, lend themselves to active intervention to control the negative sequence components. The prescribed performance requirements during disturbances for wind based units are formulated currently only in relation to the positive sequence components. With regard to the negative sequence components which might be caused by the fault, sometimes only vague (mostly no) stipulations are to be found. In [1] concrete requirements applicable to Germany are spelt out, which, among other things, states that wind turbines must be capable of providing voltage support corresponding to at least 0.4 pu positive sequence reactive current in the event of an unsymmetrical fault.

Negative sequence currents resulting from system faults must be considered in dimensioning the machine and the converters since they lead to additional heating. Moreover, the oscillating torque caused by the interaction between the different sequence components of current and voltage in the stator and rotor can cause significant structural load on the drive-train, particularly on the gear box. In this paper the low voltage fault ride through (LVRT) behavior of wind turbines based on the doubly fed generators (DFG) (also known as doubly fed induction generator DFIG) with emphasis on unbalanced grid conditions is investigated. Although the focus here is on LVRT, the control system to be presented can be used also under unsymmetrical steady state conditions. Alternative approaches for the control of the negative sequence components in DFG during unbalanced conditions are also discussed. The pros and cons of each of the alternative control approaches in relation to the voltage and current operational limits of the machine are highlighted.

As a baseline scenario for comparison, the discussion starts with no control of the negative sequence. Then, the negative sequence current limitations needed to ease the thermal stress in the stator as well as rotor circuits of the machine are included in the consideration. An additional control objective is the reduction of the structural load on the drive train resulting from the negative sequence components. A control approach for limiting the alternating torque is introduced and discussed. This is followed by the description and derivation of the rotor side converter (RSC) positive as well as negative sequence current controller. Finally possible measures for the compensation of the negative sequence components in the grid

side converter (GSC) are discussed and the corresponding current controller developed. On the basis of simulation examples, the authors demonstrate the effectiveness of the control methods.

III. BASIC EQUATIONS

The negative sequence currents in the stator and rotor currents obviously are of interest for all alternative control approaches to be introduced. With the small resistances in both circuits neglected, the stator and rotor negative sequence currents, respectively, are:

$$\underline{i}_{S2}^{\angle -\omega_s} = j \frac{1}{\omega_s \sigma l_s} \left(\underline{v}_{S2}^{\angle -\omega_s} - \frac{l_m}{l_r} \frac{\underline{v}_{R2}^{\angle -\omega_s}}{2-s} \right) = j \frac{1}{\omega_s l_s} \underline{v}_{S2}^{\angle -\omega_s} - \frac{l_m}{l_s} \underline{i}_{R2}^{\angle -\omega_s} \quad (1)$$

$$\underline{i}_{R2}^{\angle -\omega_s} = j \frac{1}{\omega_s \sigma l_r} \left(-\frac{l_m}{l_s} \underline{v}_{S2}^{\angle -\omega_s} + \frac{\underline{v}_{R2}^{\angle -\omega_s}}{2-s} \right) = j \frac{1}{\omega_s l_m} \underline{v}_{S2}^{\angle -\omega_s} - \frac{l_s}{l_m} \underline{i}_{S2}^{\angle -\omega_s} \quad (2)$$

with the leakage coefficient defined as:

$$\sigma = 1 - \frac{l_m^2}{l_s \cdot l_r} \quad (3)$$

The oscillatory torque due to the interaction between positive and negative sequence components can then be computed using the relationship:

$$\tilde{i}_{el}(t) = \frac{1}{\omega_s} \operatorname{Re} \left\{ \underline{v}_{S1}^{\angle \omega_s} \underline{i}_{S2}^{\angle -\omega_s} e^{j2\omega_s t} - \left(\underline{v}_{S2}^{\angle -\omega_s} \underline{i}_{S1}^{\angle \omega_s} e^{j2\omega_s t} \right)^* \right\} \quad (4)$$

Intermediate steps leading to the above expressions based on basic DFG equations are described in [2],[3] and[4]. Further background material regarding negative sequence control can be found in [5]-[10].

According to the sign conventions used in this paper the complex power (defined by the equation $p + jq = \underline{v} \cdot \underline{i}^*$) yields positive values for generated active power and capacitive (overexcited) reactive power.

The parameters used for the calculation of examples shown in the paper are summarized in the Appendix.

IV. NEGATIVE SEQUENCE CONTROL USING DFG RSC

A. DFG without negative sequence compensation

In this mode of operation, no active control of the negative sequence components takes place. It is the simplest case to consider since the negative sequence component of rotor voltage v_{R2} is always zero and thus the negative sequence equivalent circuit can be assumed to be short-circuited on the rotor side. The currents in the stator and rotor are now a function only of the negative sequence stator voltage. The behavior of the system in this mode of operation roughly resembles that of the synchronous machine with damper windings. In line with (1) and (2) (and considering $v_{R2} = 0$ together with the simplifying assumption that stator and rotor resistances are negligible), we have:

$$\underline{i}_{S2}^{\angle -\omega_s} = j \frac{\underline{v}_{S2}^{\angle -\omega_s}}{\omega_s \sigma l_s} \quad (5)$$

$$\underline{i}_{R2}^{\angle -\omega_s} = -\frac{l_m}{l_r} \underline{i}_{S2}^{\angle -\omega_s} \quad (6)$$

The dependency of the currents on the rotational speed of the machine is negligible. Table I summarizes negative

sequence current values for various stator negative sequence voltages and typical machine parameters.

TABLE I
CURRENTS AND TORQUE AT DIFFERENT LEVEL OF VOLTAGE UNBALANCE

$ \underline{v}_{S2} $ pu	$ \underline{i}_{S2} $ pu	$ \underline{i}_{R2} $ pu	$\tilde{i}_{el,max}^{1)}$ pu	$\tilde{i}_{el,max}^{2)}$ pu
0.05	0.20	0.20	0.19	0.22
0.10	0.41	0.39	0.37	0.43
0.20	0.81	0.79	0.65	0.78
0.30	1.22	1.18	0.85	1.05
0.40	1.62	1.57	0.97	1.25

1) No positive sequence load

2) Nominal positive sequence current

1) and 2) $v_{s1} + v_{s2} = 1.0$ pu

Depending on the value of the leakage reactance, the negative sequence current in the stator and rotor can already exceed the machine rated current when the stator negative sequence voltage assumes a value of about 20 - 25 % of the nominal voltage. This leads to a significant thermal overloading of the machine windings and calls for the reduction of the positive sequence currents. DFG with large leakage reactance exhibit a more favorable behavior in this respect as the negative sequence current is smaller.

Eliminating the rotor negative sequence current from (4) using (5), we have for the oscillatory torque:

$$\tilde{i}_{el}(t) = \frac{1}{\omega_s} \operatorname{Re} \left\{ j \underline{v}_{S1}^{\angle \omega_s} \frac{\underline{v}_{S2}^{\angle -\omega_s}}{\omega_s \sigma l_s} e^{j2\omega_s t} - \left(\underline{v}_{S2}^{\angle -\omega_s} \underline{i}_{S1}^{\angle \omega_s} e^{j2\omega_s t} \right)^* \right\} \quad (7)$$

It is interesting to note that, within the bounds allowable voltage values, the value of the torque essentially depends on the leakage reactance. The first term in the expression for the torque (depending on the steady state operating point) can be up to four times larger than the second term. However, during disturbances the second term can also lead to significant torque. In Table I the amplitudes of the quasi stationary oscillatory torque on no load and on load but with rated positive sequence current are put together. In order to present a realistic picture, it was assumed that the sum of the positive and negative sequence voltages is 1.0 pu.

B. Compensation of stator current imbalance

In this approach the rotor negative sequence voltage is controlled in such a way that the stator negative sequence current is minimized or in the ideal case eliminated altogether. With $\underline{i}_{S2} = 0$, the thermal overload on the machine as well as the level of the oscillatory torque can be reduced. The necessary rotor voltage under quasi stationary conditions is given by:

$$\underline{v}_{R2}^{\angle -\omega_s} = \frac{(2-s)l_r}{l_m} \underline{v}_{S2}^{\angle -\omega_s} \quad (8)$$

The residual negative sequence rotor current then becomes:

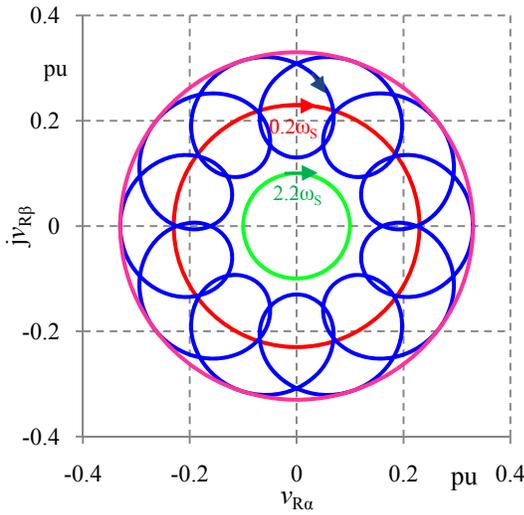
$$\underline{i}_{R2}^{\angle -\omega_s} = j \frac{\underline{v}_{S2}^{\angle -\omega_s}}{\omega_s l_m} \quad (9)$$

To assess the feasibility of total compensation of the negative sequence, the voltage limitations in RSC need to be considered. The rotor voltage is the vector sum of the positive sequence voltage with the complex conjugate of the negative sequence voltage. Thus:

$$\underline{v}_R^{\angle} = \underline{v}_{R1}^{\angle} + \left(\underline{v}_{R2}^{\angle}\right)^* \quad (10)$$

The corresponding loci of the positive and negative sequence voltages in the complex plane are both circular paths, which traverse the complex plane with the slip frequency for the positive sequence and with approximately twice the fundamental frequency for the negative sequence. The overall loci of both are shown in Fig. 1.

To preclude high level of harmonics due to saturation, it is preferable in a practical application to limit the positive and negative sequence components individually rather than putting a cap the space vector \underline{v}_R^{\angle} .



Rotor voltage: $\underline{v}_{R1}^{\angle R} + \left(\underline{v}_{R2}^{\angle R}\right)^*$; Pos. sequence rotor voltage: $\underline{v}_{R1}^{\angle R}$

Neg. sequence rotor voltage: $\left(\underline{v}_{R2}^{\angle R}\right)^*$

Sum of pos. and neg. sequence voltage: $\left|\underline{v}_{R1}^{\angle R}\right| + \left|\underline{v}_{R2}^{\angle R}\right|$

Fig. 1. Locus of rotor voltage in rotor coordinates for $|\underline{v}_{R1}| = 0.23$ pu, $|\underline{v}_{R2}| = 0.1$ pu and rotor speed $\omega_R = 1.2$

In case the maximum voltage limit is violated, one can obviously reduce either the positive or the negative sequence rotor voltage. If the positive sequence is accorded priority, the negative sequence voltage can be limited in accordance with:

$$v_{R2,max} = v_{R,max} - v_{R1} \quad (11)$$

and conversely for reducing the positive sequence, we have the relationship:

$$v_{R1,max} = v_{R,max} - v_{R2} \quad (12)$$

It should be noted that these relationships are valid under the assumption that the voltage component with the higher priority is also limited to a maximum voltage $v_{R,max}$. For reducing the stator current asymmetry, prioritizing the positive sequence control is more common. The characteristic behavior of the DFG is such that near the upper and lower speed ranges only a small rotor negative sequence voltage is available for control. In the rated speed range of the machine,

approximately 40-50 % of the RSC-voltage can be used for negative sequence control.

C. Compensation of unbalance in rotor current

This approach permits the minimization of the thermal stress on the rotor and the RSC during periods of asymmetry. The steps needed to reduce the negative sequence currents are equivalent to those discussed in the previous section. With $\dot{i}_{R2} = 0$ and considering (2), the negative sequence rotor voltage needed for the complete elimination is:

$$\underline{v}_{R2}^{\angle-\omega_s} = (2-s) \frac{l_m}{l_s} \underline{v}_{S2}^{\angle-\omega_s} \quad (13)$$

and the remaining negative sequence current in the stator according to (1) is:

$$\underline{i}_{S2}^{\angle-\omega_s} = j \frac{\underline{v}_{S2}^{\angle-\omega_s}}{\omega_s l_s} \quad (14)$$

With regard to the limitation of the rotor voltage, the statements made in the previous section and as a result also eq. (11) and (12) are still valid. In the event of partial compensation, the stator and rotor currents exhibit the same level of asymmetry reduction and almost similar system behavior.

D. Compensation of the oscillatory torque

The primary objective of this approach is to reduce the oscillating air gap torque during periods of asymmetry so that the drive-train of the wind turbine is not subjected to the resulting stress. The necessary condition for the complete elimination of the oscillating torque according to (4) is:

$$\text{Re}\left\{\underline{v}_{S1}^{\angle\omega_s} \underline{i}_{S2}^{\angle-\omega_s} e^{j2\omega_s t}\right\} - \text{Re}\left\{\left(\underline{v}_{S2}^{\angle-\omega_s} \underline{i}_{S1}^{\angle\omega_s} e^{j2\omega_s t}\right)^*\right\} = 0 \quad (15)$$

This condition is only fulfilled when:

$$\underline{v}_{S1}^{\angle\omega_s} \underline{i}_{S2}^{\angle-\omega_s} = \underline{v}_{S2}^{\angle-\omega_s} \underline{i}_{S1}^{\angle\omega_s} \quad (16)$$

leading to the solution for the negative sequence stator current:

$$\underline{i}_{S2}^{\angle-\omega_s} = \underline{i}_{S1}^{\angle\omega_s} \frac{\underline{v}_{S2}^{\angle-\omega_s}}{\underline{v}_{S1}^{\angle\omega_s}} \quad (17)$$

Using (2), it follows from the preceding relationship that:

$$\underline{i}_{R2}^{\angle-\omega_s} = \left(-\frac{l_s}{l_m} \frac{\underline{i}_{S1}^{\angle\omega_s}}{\underline{v}_{S1}^{\angle\omega_s}} + j \frac{1}{\omega_s l_m}\right) \underline{v}_{S2}^{\angle-\omega_s} \quad (18)$$

$$\underline{v}_{R2}^{\angle-\omega_s} = \left(1 + j \omega_s \sigma l_s \frac{\underline{i}_{S1}^{\angle\omega_s}}{\underline{v}_{S1}^{\angle\omega_s}}\right) \frac{l_R}{l_m} (2-s) \underline{v}_{S2}^{\angle-\omega_s} \quad (19)$$

If sufficient rotor voltage is not available for control, both possibilities for reducing the voltage according to (11) and (12) should be considered.

First, the negative sequence rotor voltage is to be limited in accordance with (11), meaning that the positive sequence rotor voltage has priority. The amplitude of the alternating torque attains the minimum value if the amplitude of the negative sequence rotor voltage is limited to its maximum possible value and its phase angle is kept constant. Thus:

$$\underline{v}_{R2,limited}^{\angle-\omega_s} = v_{R2,max} e^{j \arg(\underline{v}_{R2,max}^{\angle-\omega_s})} \quad (20)$$

A detailed derivation of the expression is given in [4].

The compensation of the alternating torque is incomplete when the rotor negative sequence limitation becomes active.

As an additional option, limiting the rotor voltage according to (12) with priority for the negative sequence control can be considered. We have for the negative sequence rotor voltage (considering the compensation requirement given in (17)):

$$\underline{v}_{R2}^{\angle-\omega_s} = \frac{(2-s)}{s} \frac{\underline{v}_{S2}^{\angle-\omega_s}}{\underline{v}_{S1}^{\angle\omega_s}} \underline{v}_{R1}^{\angle\omega_s} \quad (21)$$

With eq. (12), it becomes:

$$v_{R1,\max} = \frac{|s| |\underline{v}_{S1}|}{|s| |\underline{v}_{S1}| + |2-s| |\underline{v}_{S2}|} v_{R,\max} \quad (22)$$

and

$$v_{R2,\max} = \frac{|2-s| |\underline{v}_{S2}|}{|s| |\underline{v}_{S1}| + |2-s| |\underline{v}_{S2}|} u_{R,\max} \quad (23)$$

As a result of the limitation of the positive sequence rotor voltage, range of possible operating points for the stator current now become more constrained. The resulting positive and negative sequence values for the current, respectively, are:

$$\underline{i}_{S1}^{\angle\omega_s} = \frac{l_m}{l_R s} v_{R1,\max} e^{j\varphi_{VR1}} - \underline{v}_{S1}^{\angle\omega_s} \quad (24)$$

$$\underline{i}_{S2}^{\angle-\omega_s} = \frac{l_m}{l_R (2-s)} v_{R2,\max} e^{j\varphi_{VR2}} - \underline{v}_{S2}^{\angle-\omega_s} \quad (25)$$

The phase angle of the positive sequence rotor voltage φ_{VR1} is freely adjustable, and φ_{VR2} can then be deduced from (21). In cases of significant asymmetry this control option is constrained by positive sequence active and reactive current injection limitations. Typical wind turbine systems under these conditions would need to be operated in under-excited mode as a result of the rotor voltage limitation. Since the current limits cannot be exceeded even for a short period of time, the positive sequence active current will have to be reduced depending on the degree of the asymmetry.

Grid faults also lead to DC components in the fault current with a possible duration of a few cycles, which also give rise to additional alternating torque in the drive-train. The reader is referred to [4] for the analytical evaluation of the limitations imposed by this torque vis-à-vis the rotor voltage and the possible control measures for its elimination. It can, however, be stated generally that the compensation of DC components leads to a further degrading of torque and reactive power control capability of the DFG.

E. Comparison of different RSC control alternatives

The essential characteristics of alternative options for the control of the negative system components can be summarized as follows. Without the negative sequence control, the thermal stress experienced by the DFG system resulting from the negative sequence currents induced by the asymmetry is most severe, and the stress on the drive train of the turbine as a result of the alternating torque is greatest.

The control of negative sequence stator or rotor current enables the reduction of the thermal stress in the corresponding circuit in a targeted way. The level of compensation is limited by the availability of the necessary rotor voltage to offset the stress. The oscillatory torque in this

case is significantly less than that without negative sequence control. The effects of the control on the rotor or the stator are not significantly different from one another. In the alternating torque compensation option, by injecting a negative sequence current the torque is offset completely. This procedure is particularly effective for small imbalances since limitations with regard to positive sequence control are not to be expected. The negative sequence currents are comparatively small and typically cause only limited additional stress. In cases of large asymmetry and a priority for positive sequence control, both current and torque reduction approaches are almost equivalent due to the rotor current limitation. A control approach to completely offset the alternating torque would, in principle, be possible by according the negative sequence control a priority. But the flip side is that this would under circumstances significantly reduce the operational range for positive sequence control and lead to an increased load current. Providing voltage support as per the grid code requirements would normally be no longer possible.

F. RSC current controller

Fig. 2 shows the positive sequence rotor current controller of the RSC. The controller is derived from the steady state equations of the DFG by setting all derivatives to zero and neglecting the stator resistance r_s as shown in detail in [2]. Note that in the block diagram (in Fig. 2) complex parameters are used for simplicity although the two controllers, one each for d, q components, are used.

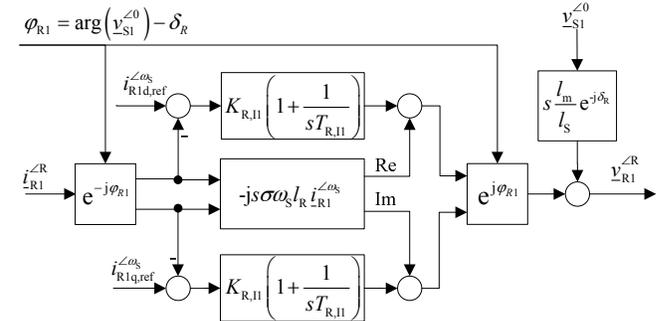


Fig. 2. Positive sequence rotor current controller

According to the steady state equations of the DFG the two PI controllers are not necessarily required, but they are included to compensate parameter uncertainties and to improve the dynamic controller behavior. Due to the stator voltage reference frame used the d-component of rotor current is responsible for active stator current and thus the reference is derived from the required stator active power. The reactive rotor current reference in the q-axis is calculated from the reactive power to be delivered through the machine including the DFG magnetizing current and the reactive current contribution of the voltage controller. Due to space constraints the controller implementations for the rotor voltage and current limitations are not included, and the same applies to all controllers introduced in the following sections.

The negative sequence current control is shown in Fig. 3. It is derived in the same way as that for the positive sequence but in the negative sequence rotating reference frame.

The negative sequence rotor current reference depends on the objective the controller has to fulfill.

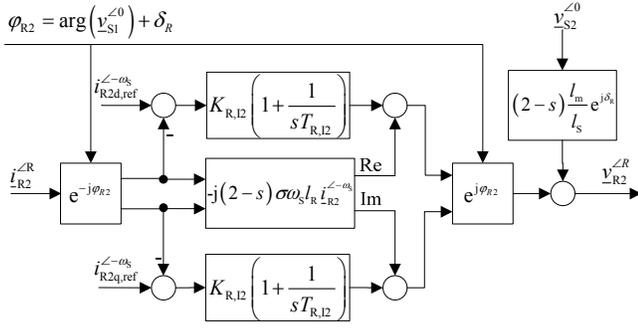


Fig. 3. Negative sequence rotor current controller

For stator current unbalance compensation, the rotor current required is as given by (9). Compensation of the rotor current unbalance in its entirety means that the reference value is zero. Oscillating torque compensation is achieved when the reference for the negative sequence rotor current is calculated using (18).

The resulting rotor voltage composed of both positive and negative sequence components is given by (10).

V. NEGATIVE SEQUENCE CONTROL BY GSC

A. GSC control objective

GSC has to ensure that the DC link voltage is always close to the nominal value. The DC voltage is described by the power balance equation:

$$v_{DC} = \frac{1}{C_{DC}} \int (-p_{RSC} - p_{GSC} - p_{losses}) dt \quad (26)$$

The power is calculated according to:

$$p_{GSC} = \text{Re} \left\{ \underline{v}_{GSC}^{\angle} \left(\underline{i}_{GSC}^{\angle} \right)^* \right\} \quad (27)$$

$$p_{RSC} = \text{Re} \left\{ \underline{v}_{RSC}^{\angle} \left(\underline{i}_{RSC}^{\angle} \right)^* \right\} \quad (28)$$

Notice that considering the sign convention used here, the relationship between the RSC and rotor powers is:

$$p_{RSC} = -p_R \quad (29)$$

The power balance in the DC link and thus the DC voltage is controlled by the grid side converter in the d-axis control channel. The q-component of the current can be used in the positive sequence to provide reactive power to the grid as long as the RSC current magnitude does not exceed the upper threshold. The control schema is shown in Fig. 4.

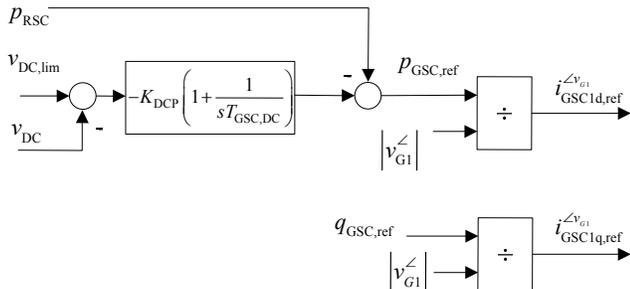


Fig. 4. DC link voltage controller

The output of the DC link voltage controller is the reference for the underlying current controller.

B. DC voltage control during grid unbalance

During asymmetry the active power passing through RSC and GSC in general contains components pulsating at twice the grid frequency, which can superimpose a ripple on the DC voltage pulsating at the same frequency. The instantaneous value of the active power in the GSC due to positive and negative sequence components is:

$$p_{GSC} = \text{Re} \left\{ \left(\underline{v}_{GSC1}^{\angle 0} + \left(\underline{v}_{GSC2}^{\angle 0} \right)^* \right) \cdot \left(\underline{i}_{GSC1}^{\angle 0} + \underline{i}_{GSC2}^{\angle 0} \right) \right\} \quad (30)$$

The pulsating component of the instantaneous power then becomes:

$$\tilde{p}_{GSC}(t) = \text{Re} \left\{ \underline{v}_{GSC1}^{\angle \omega_s} \cdot \underline{i}_{GSC2}^{\angle -\omega_s} \cdot e^{j2\omega_s t} + \left(\underline{v}_{GSC2}^{\angle -\omega_s} \cdot \underline{i}_{GSC1}^{\angle \omega_s} \cdot e^{j2\omega_s t} \right)^* \right\} \quad (31)$$

and in the expanded form:

$$\begin{aligned} \tilde{p}_{GSC}(t) = & \left(v_{GSC1d}^{\angle \omega_s} i_{GSC2d}^{\angle -\omega_s} - v_{GSC1q}^{\angle \omega_s} i_{GSC2q}^{\angle -\omega_s} + v_{GSC2d}^{\angle -\omega_s} i_{GSC1d}^{\angle \omega_s} - v_{GSC2q}^{\angle -\omega_s} i_{GSC1q}^{\angle \omega_s} \right) \cos(2\omega_s t) \\ & - \left(v_{GSC1d}^{\angle \omega_s} i_{GSC2q}^{\angle -\omega_s} + v_{GSC1q}^{\angle \omega_s} i_{GSC2d}^{\angle -\omega_s} + v_{GSC2d}^{\angle -\omega_s} i_{GSC1q}^{\angle \omega_s} + v_{GSC2q}^{\angle -\omega_s} i_{GSC1d}^{\angle \omega_s} \right) \sin(2\omega_s t) \end{aligned} \quad (32)$$

Analogous expressions can be derived also for the RSC, which in compact form (for better clarity) is:

$$\tilde{p}_{RSC}(t) = \tilde{p}_{RSCc} \cos(2\omega_s t) + \tilde{p}_{RSCs} \sin(2\omega_s t) \quad (33)$$

With:

$$\tilde{p}_{RSCc} = \left(v_{RSC1d}^{\angle \omega_s} i_{RSC2d}^{\angle -\omega_s} - v_{RSC1q}^{\angle \omega_s} i_{RSC2q}^{\angle -\omega_s} + v_{RSC2d}^{\angle -\omega_s} i_{RSC1d}^{\angle \omega_s} - v_{RSC2q}^{\angle -\omega_s} i_{RSC1q}^{\angle \omega_s} \right) \quad (34)$$

$$\tilde{p}_{RSCs} = - \left(v_{RSC1d}^{\angle \omega_s} i_{RSC2q}^{\angle -\omega_s} + v_{RSC1q}^{\angle \omega_s} i_{RSC2d}^{\angle -\omega_s} + v_{RSC2d}^{\angle -\omega_s} i_{RSC1q}^{\angle \omega_s} + v_{RSC2q}^{\angle -\omega_s} i_{RSC1d}^{\angle \omega_s} \right) \quad (35)$$

This expression can further be simplified by neglecting the pulsating converter losses to obtain:

$$\tilde{p}_{RSC}(t) + \tilde{p}_{GSC}(t) = 0 \quad (36)$$

The pulsating voltage in the intermediate DC circuit can be suppressed by introducing a negative sequence current into the GSC having the value:

$$\underline{i}_{GSC2}^{\angle -\omega_s} = - \frac{\underline{i}_{GSC1}^{\angle \omega_s} \underline{v}_{GSC2}^{\angle -\omega_s} + (\tilde{p}_{RSCc} - j\tilde{p}_{RSCs})}{\underline{v}_{GSC1}^{\angle \omega_s}} \quad (37)$$

Alternatively, the negative sequence current reference value can also be controlled by taking the oscillating component of the DC voltage in the intermediate circuit into consideration. This requires only a limited computational effort, but as an indirect method it is associated with some time delay. But unlike in case of the direct determination of the negative sequence current according to (37), in this approach the losses and measurement errors are taken care of.

The pulsating component of the DC voltage, as stated above, has the frequency corresponding to twice the grid frequency. It can be extracted from the overall signal by using band pass or resonance filter, for example. When the reference value of the intermediate circuit voltage is constant, it is normally sufficient to use the error signal (difference between reference and actual values). The elimination of the error by the control action should be carried out using a rotating reference frame. This will ensure that there is no steady state control error when a PI controller is used. For this, the amplitude and phase angle of the oscillation are needed. These can be obtained using a virtual stationary space vector, which can be defined in the following manner:

$$\tilde{v}_{DC}^{\angle -2\omega_s} = \left(\tilde{v}_{DC}(t) + \frac{j}{2\omega_s} \cdot \frac{d\tilde{v}_{DC}(t)}{dt} \right) e^{-j2\omega_s t} \quad (38)$$

It is now possible to compensate the oscillation in the DC intermediate circuit by controlling the negative sequence current in accordance with Fig. 5.

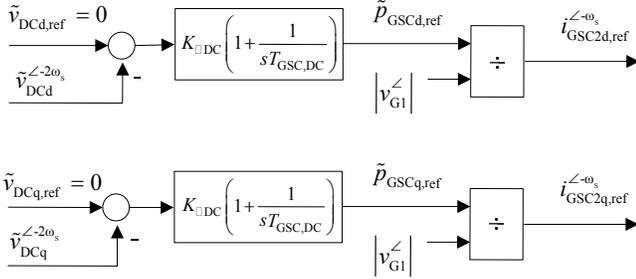


Fig. 5. DC link control to suppress DC voltage oscillations caused by grid unbalance

C. GSC current controller

The control path for the positive sequence control of the GSC can in steady state be described in grid-oriented coordinate system as follows:

$$\underline{v}_{GSC1}^{\angle \omega_s} = (r_{GSC} + j\omega_s l_{GSC}) \cdot \underline{i}_{GSC1,ref}^{\angle \omega_s} + \underline{v}_{G1}^{\angle \omega_s} \quad (39)$$

The GSC controller shown in

Fig. 6 is designed on the basis of this equation. It additionally contains the necessary transformation relationships between stationary and rotating reference frames and two PI controllers to account for parameter uncertainties and to improve the dynamic performance of the controller. The d-axis overlaps the positive sequence voltage reference.

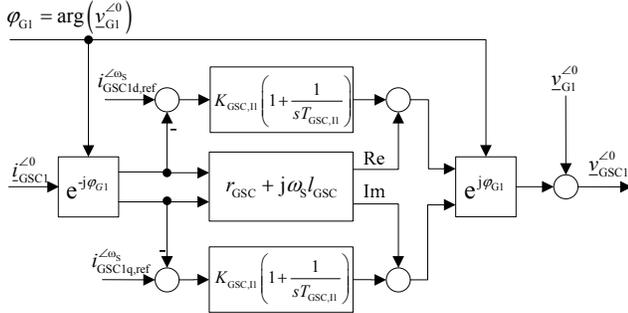


Fig. 6. Positive sequence GSC controller

The structure of the negative sequence NWR current control is given in Fig. 7.

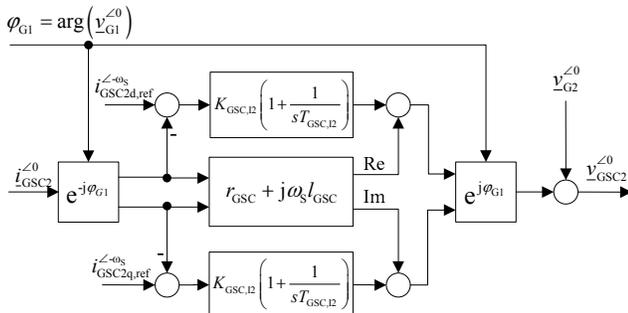


Fig. 7. Negative sequence GSC controller

The basic relationship for the control path in a negative sequence rotating reference frame is:

$$\underline{v}_{GSC2}^{\angle -\omega_s} = (r_{GSC} + j\omega_s l_{GSC}) \cdot \underline{i}_{GSC2,ref}^{\angle -\omega_s} + \underline{v}_{G2}^{\angle -\omega_s} \quad (40)$$

Here also two PI control blocks are inserted. The resulting GSC voltage the converter has to inject is calculated by:

$$\underline{v}_{GSC}^{\angle -\omega_s} = \underline{v}_{GSC1}^{\angle -\omega_s} + \left(\underline{v}_{GSC2}^{\angle -\omega_s} \right)^* \quad (41)$$

In real applications, however, it has to be considered that the required delay compensation is different for positive and negative sequence voltages. The compensation is done before adding both components in (41). Note that similar delay compensation is necessary also on the rotor side (cf. (10)).

The GSC negative sequence control becomes much simpler when the objective is only to suppress negative sequence current. In this case the negative sequence GSC voltage required is:

$$\underline{v}_{GSC2}^{\angle -\omega_s} = \underline{v}_{G2}^{\angle -\omega_s} \quad (42)$$

which can be set directly as controller output as shown in Fig. 7. It is not necessary to implement an explicit negative sequence controller in this case, which means that the left part of controller schema in

Fig. 7 can be omitted. However, as a result of the negative sequence grid voltage and the positive sequence current, an oscillating power component will pass through the GSC causing oscillating (at twice the grid frequency) DC link voltage. As a reaction to this, the DC link voltage controller will inject a d-axis current component which in turn will result in a fundamental frequency negative sequence current on the one hand and in a positive sequence current of three times the fundamental frequency on the other..

VI. SIMULATION EXAMPLES

It will now be demonstrated how the DFG behaves in the event of a single line to ground (SLG) fault. As is well known, SLG is the most common type of fault in power system. In effectively grounded networks this type of fault can cause significant voltage sags. Although the fault gives rise to positive, negative and zero sequence voltages and currents, due to the vector group of a typical WT transformer, only the positive and the negative sequence quantities are observed on the DFG side. The following scenarios are considered in this paper:

- a) No negative sequence control on the rotor side is implemented, i.e. only the positive sequence RSC controller is considered. GSC controller is according to Fig. 6, but instead of positive sequence the full current and voltage space vectors consisting of the positive and negative components are used. (results see Fig. 8).
- a) Negative sequence control is implemented, which compensates the oscillating torque with negative sequence priority (results see Fig. 9).

Simulations were carried out for a DFG with practical values and real-world parameters (Appendix), so that the simulation results are as reflective of the operational reality as possible.

For the power, two different characteristics are shown. The instantaneous active and reactive powers of the positive sequence system, which are used as input for the power controller, are derived using the component separation algorithm according to L \hat{e} [13]. Also, active and reactive

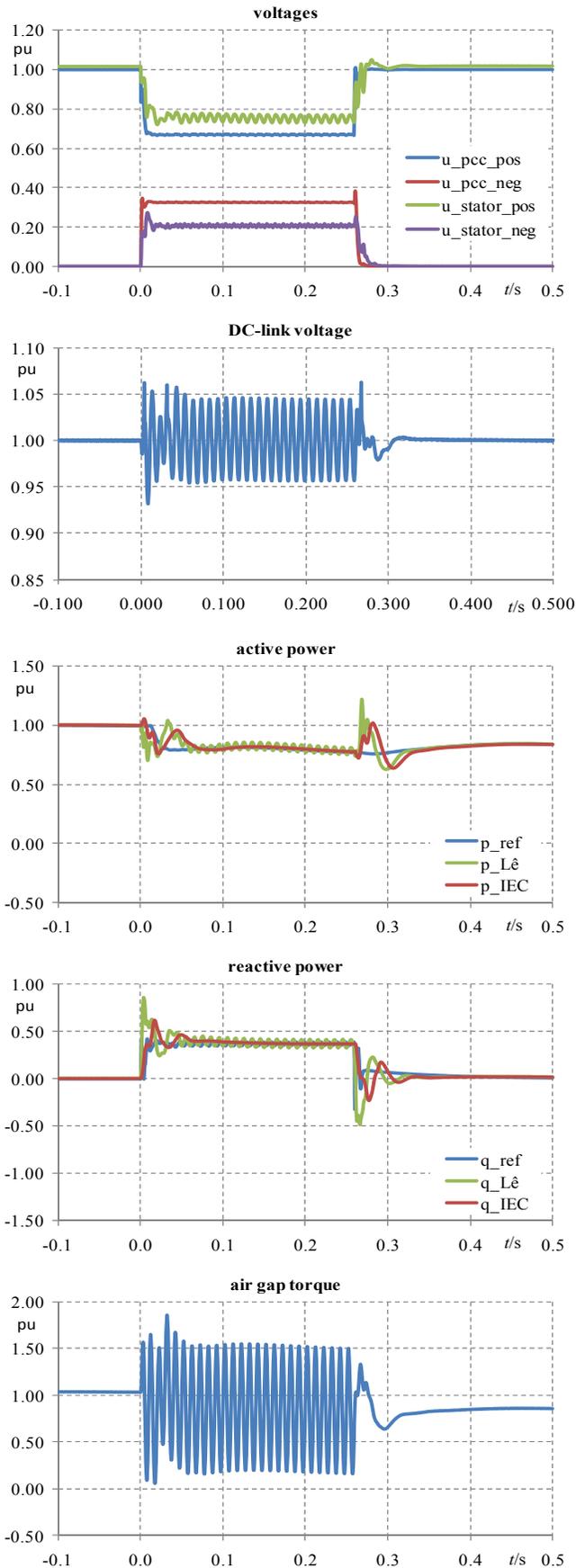


Fig. 8. Response of WT to single line to ground fault without negative sequence control (scenario a)

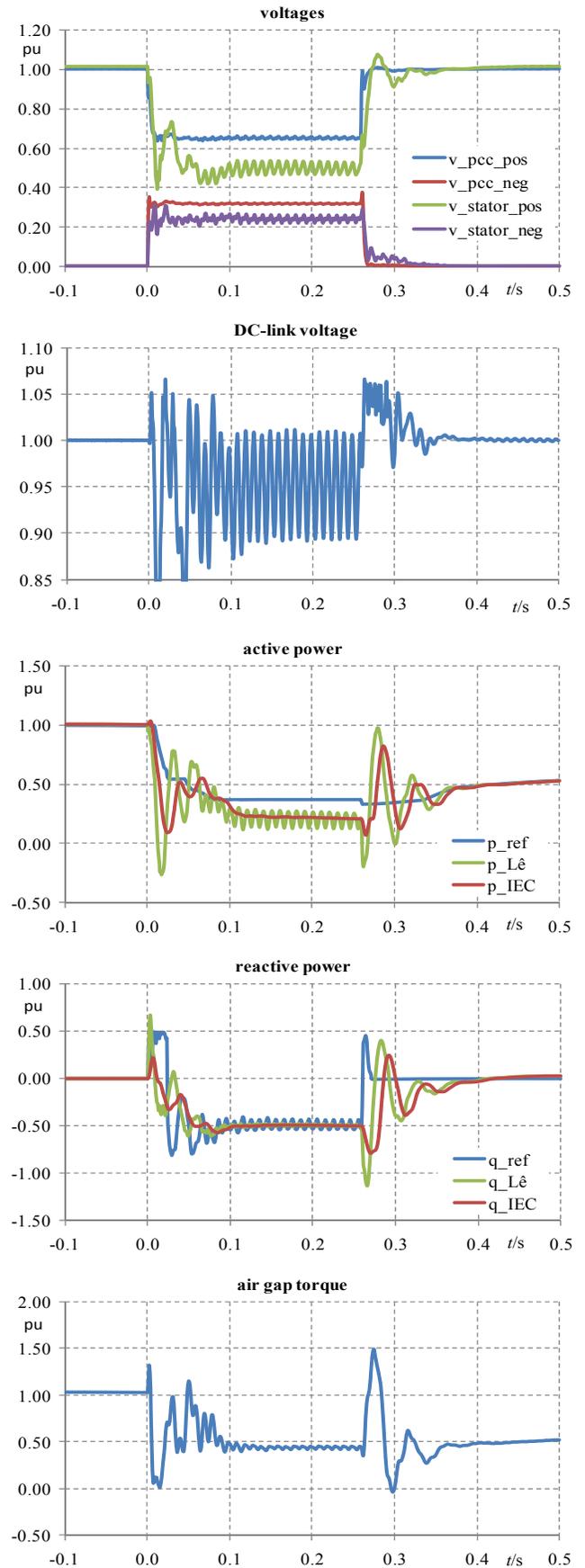


Fig. 9. Response of WT to single line to ground fault with negative sequence control and negative sequence priority (scenario b)

power mean values according to IEC61400-21 [14] are displayed since wind turbine certification procedures usually are based on these characteristics.

The transients of the negative sequence control are as high as those in the positive sequence control due to the need for decoupling to extract the negative sequence components. The reduction of the alternating torque gives rise to oscillating components in the DC voltage of the intermediate circuit, since the GSC during faults is already forced to near its thermal limits by the positive sequence current.

Reducing the average value of the DC voltage by a few percent for a short period of time might be sufficient to forestall the incessant activation of the chopper so that the chopper is used only at the onset and clearing of the fault. The voltage support function required in Germany [1] cannot be met in the event of a prioritized negative sequence control. However, if the use of negative sequence control is coupled with positive sequence priority, the required voltage support could be met for scenarios simulated in this study. Due to space limitations, these cases are not explicitly included in this paper. Since the positive sequence voltage support, as shown in Fig. 9, is limited, the positive sequence voltage level at the stator terminals is smaller than that without negative sequence control. The same is true for the average air-gap torque as a result of the current limitation (together with the low voltage). As a result, the transient change in rotational speed during fault becomes somewhat higher in b) than in a). However, excitations in the region of twice the grid frequency do not occur, which under circumstances can be considered positive since it implies less stress for the gearbox.

VII. CONCLUSIONS

Without negative sequence control, the DFG is exposed to high stator and rotor currents as well as oscillating torque during unbalanced steady state operation and fault conditions. To mitigate the corresponding stress different control options are available. However, all these options are limited by the available rotor voltage. Depending on the control target the priority for positive or negative sequence has to be defined. In the alternating torque compensation alternative, injecting a negative sequence current will offset the torque completely. This procedure is particularly effective for small imbalances since limitations with regard to positive sequence control are not to be expected. In cases of large asymmetry and a priority for positive sequence control, both current and torque reduction approaches are almost equivalent due to the rotor current limitation. A control approach to completely eliminate the alternating torque would, in principle, be possible by according the negative sequence control a priority. However, this would significantly reduce the operational range for positive sequence control and lead to an increased load current. Providing voltage support as per the grid code requirements would be no longer possible. Negative and positive sequence currents and voltages in interaction with each other will always cause on both RSC and GSC sides an oscillating power and thus superimpose a ripple on the DC link voltage. To suppress these oscillations two different GSC control alternatives are introduced. The paper also presents the current controllers required to implement the strategies described for both RSC and GSC.

VIII. APPENDIX

DFIG PARAMETERS USED IN THIS STUDY

V_r	690 V	l_{GSC}	0.265 pu
P_r	2000 kW	r_{GSC}	0.005 pu
f_r	50 Hz	v_{RSCmax}	0.4 pu
ω_t	1.2 pu	v_{GSCmax}	1.1 pu
l_m	4.000 pu	J_G	184 kgm ²
$l_{\sigma S}$	0.125 pu	J_R	1430 kgm ²
$l_{\sigma R}$	0.125 pu	d	3 Nm s/rad
r_S	0.006 pu	c	$5.5 \cdot 10^4$ Nm/rad
r_R	0.006 pu	-	-

J_G, J_R : generator and rotor inertia; d : damping constant of the two mass model used; c : stiffness coefficient of the two mass model used

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