Capability and Limitations of DFIG based Wind Turbines concerning Negative Sequence Control

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***Abstract*— Modern wind turbine systems based on doubly-fed induction generator (DFIG) technology offer negative sequence control capability during grid faults or unsymmetrical system operation. This paper deals especially with the effects of current and voltage limitation of a typically rated converter system design based on positive sequence control requirements. At first a short summary of the most common alternative negative sequence control objectives is given. Then the corresponding rotor side converter (RSC) control algorithms are described. This is followed by typical characteristics of current capabilities as well as voltage constraints. Finally detailed calculations regarding control possibilities and limitations in the positive and negative sequence are shown.**

***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 main field inductance
r_S, r_R	Stator /rotor resistance
r_{GSC}, l_{GSC}	Converter choke resistance /inductance
ω_S, ω_R	Stator /rotor space phasor rotational 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

II. Introduction

In the past symmetrical faults have been the focus of grid integration studies with high levels of wind energy generation. Therefore requirements such as those given in [1] and capabilities of modern wind turbines in the positive sequence have been broadly analyzed and discussed [2], [3]. But the most common faults in the power system are of unsymmetrical type where also the negative sequence component in the wind turbine voltage must be handled.

Previous wind turbine systems used standard vector control with no separation of positive and negative sequence values. However, the interaction between positive and negative sequence components can lead to undesirable system behavior or the activation of protection circuits to prevent instability. Modern wind turbine systems have overcome this problem by the decoupled control of positive and negative sequence variables as well as DC-link stabilization using braking chopper. The most common alternative methods for negative sequence control of DFIGs are described in detail in [4]. For the RSC, these are:

a) No negative sequence compensation
b) Compensation of stator current imbalance
c) Compensation of unbalance in rotor current
d) Compensation of the oscillatory torque

and for the GSC:

e) Compensation of GSC current imbalance
f) Pulsating voltage suppression in the intermediate DC circuit

In the following paragraphs the limitations of these alternatives, depending on the type of fault and operating point of the DFIG system, will be derived in detail. Cross coupling effects between the positive sequence control objectives (torque) and voltage support will also be discussed.

III. Basic Equations and RSC Control Schemes

A. Basic DFIG Equations

Positive and negative sequence components of the stator and rotor currents obviously are of interest for all alternative control approaches. The basic DFIG model is given in Fig. 1. A zero sequence current does not appear at the stator or the grid side converter (GSC) terminals of the DFIG system due to Dy connection of the transformer linking the machine to the grid, and thus it will not be considered here. With the small resistances in both circuits neglected, the stator and rotor positive sequence currents, respectively, are:

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$$\underline{i}_{S1}^{\angle\omega_S} = j\frac{1}{\omega_S\sigma l_S}\left(\underline{v}_{S1}^{\angle\omega_S} - \frac{l_m}{l_R}\frac{\underline{v}_{R1}^{\angle\omega_S}}{s}\right) = j\frac{1}{\omega_S l_S}\underline{v}_{S1}^{\angle\omega_S} - \frac{l_m}{l_S}\underline{i}_{R1}^{\angle\omega_S} \quad (1)$$

$$\underline{i}_{R1}^{\angle\omega_S} = j\frac{1}{\omega_S\sigma l_R}\left(-\frac{l_m}{l_S}\underline{v}_{S1}^{\angle\omega_S} + \frac{\underline{v}_{R1}^{\angle\omega_S}}{s}\right) = j\frac{1}{\omega_S l_m}\underline{v}_{S1}^{\angle\omega_S} - \frac{l_S}{l_m}\underline{i}_{S1}^{\angle\omega_S} \quad (2)$$

Stator and rotor negative sequence currents are:

$$\underline{i}_{S2}^{\angle-\omega_S} = j\frac{1}{\omega_S\sigma l_S}\left(\underline{v}_{S2}^{\angle-\omega_S} - \frac{l_m}{l_R}\frac{\underline{v}_{R2}^{\angle-\omega_S}}{2-s}\right) = j\frac{1}{\omega_S l_S}\underline{v}_{S2}^{\angle-\omega_S} - \frac{l_m}{l_S}\underline{i}_{R2}^{\angle-\omega_S} \quad (3)$$

$$\underline{i}_{R2}^{\angle-\omega_S} = j\frac{1}{\omega_S\sigma l_R}\left(-\frac{l_m}{l_S}\underline{v}_{S2}^{\angle-\omega_S} + \frac{\underline{v}_{R2}^{\angle-\omega_S}}{2-s}\right) = j\frac{1}{\omega_S l_m}\underline{v}_{S2}^{\angle-\omega_S} - \frac{l_S}{l_m}\underline{i}_{S2}^{\angle-\omega_S} \quad (4)$$

with the leakage coefficient defined as:

$$\sigma = 1 - \frac{l_m^2}{l_S \cdot l_R} \quad . \quad (5)$$

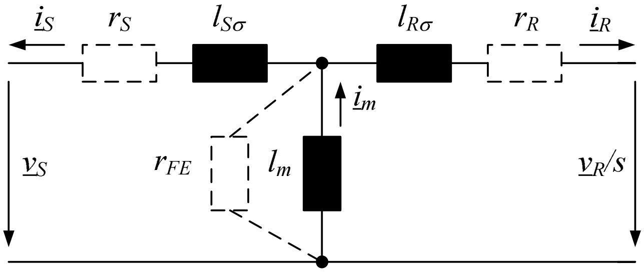

Fig. 1 DFIG single line

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

$$\tilde{t}_{el}(t) = \frac{1}{\omega_S}\mathrm{Re}\left\{\underline{v}_{S1}^{\angle\omega_S}\,\underline{i}_{S2}^{\angle-\omega_S}e^{j2\omega_S t} - \left(\underline{v}_{S2}^{\angle-\omega_S}\,\underline{i}_{S1}^{\angle\omega_S}e^{j2\omega_S t}\right)^*\right\} \quad (6)$$

B. Controller Design

Fig. 2 shows the positive sequence rotor current controller of the RSC. The controllers are derived from the steady state equations (1) and (2) of the DFIG where all derivatives are set to zero and neglecting the stator and rotor resistance. Note that in the block diagram complex parameters are used for simplicity although the two controllers, one each for d, q components, are used. The rotor current set values are calculated from active and reactive power reference values as explained in detail in [2].

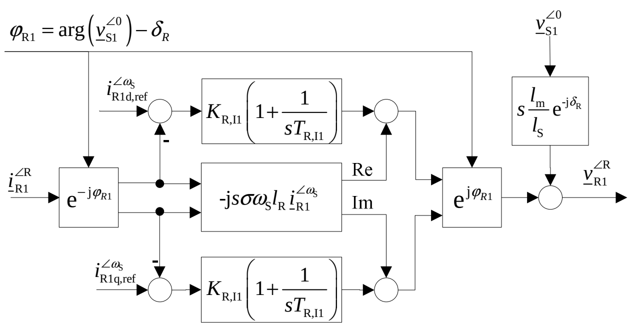

Fig. 2 Positive sequence rotor current controller

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

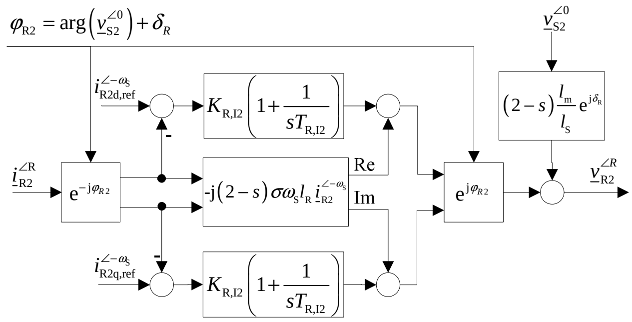

Fig. 3 Negative sequence rotor current controller

The negative sequence rotor current reference depends on the objective the controller has to fulfill. This is described in detail in [4] and can be summarized as follows:

a) DFG without negative sequence compensation

$$\underline{v}_{R2}^{\angle R} = 0 \quad (7)$$

b) Compensation of stator current imbalance

$$\underline{i}_{R2,ref}^{\angle-\omega_S} = j\frac{\underline{v}_{S2}^{\angle-\omega_S}}{\omega_S l_m} \quad (8)$$

c) Compensation of unbalance in rotor current

$$\underline{i}_{R2,ref}^{\angle-\omega_S} = 0 \quad (9)$$

d) Compensation of the oscillatory torque

$$\underline{i}_{R2,ref}^{\angle-\omega_S} = \left(-\frac{l_S}{l_m}\frac{\underline{i}_{S1}^{\angle\omega_S}}{\underline{v}_{S1}^{\angle\omega_S}} + j\frac{1}{\omega_S l_m}\right)\underline{v}_{S2}^{\angle-\omega_S} \quad (10)$$

For clarity the controller implementations for the rotor voltage and current limitations explained in the following sections are not included in Fig. 2 and 3. Also not included here are the GSC controllers for both sequences since they have a similar structure as the RSC controllers as shown in [4].

IV. DFIG Voltage and Current Limitations

In this chapter quantities not underlined represent the magnitude of the corresponding complex variables.

A. Voltage Limitations

To avoid high level of harmonics the converter is normally operated in the linear modulation range as explained in [5]. With this precondition the amplitude of the RSC voltage vector can be calculated by:

$$v_R = v_{R1} + v_{R2} \quad (11)$$

In case the maximum voltage limit is violated, one can obviously reduce either the positive or the negative sequence rotor voltage. In most cases the positive sequence is accorded priority for a DFIG system, the negative sequence voltage can then be limited in accordance with:

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

If negative sequence priority is chosen we have the relationship:

$$v_{R1,max} = v_{R,max} - v_{R2} \quad (13)$$

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 $v_{R,max}$. The positive sequence voltage is proportional to the slip. Therefore the maximum voltage that is available depends on the speed level as shown in Fig. 4.

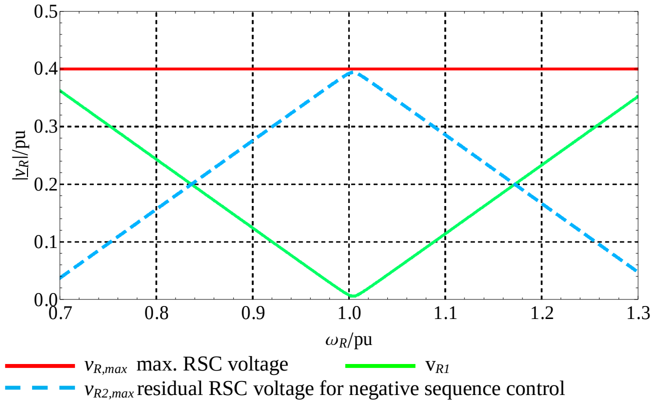

Fig. 4 Maximum rotor voltage for negative sequence control with positive sequence priority

The characteristic behavior of the DFIG 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.

B. Current Capabilities and Limitations

The negative sequence stator voltage has very different effects on GSC and RSC instantaneous currents. Whereas for the GSC and the stator of the DFIG the amplitudes of the three line currents differ in relation to the level of the asymmetry, the RSC currents are always symmetrical due to the rotation of the rotor. This is shown in the generic waveforms in Fig. 5 which do not relate to a specific FRT operating point but should give a general understanding of the different shapes.

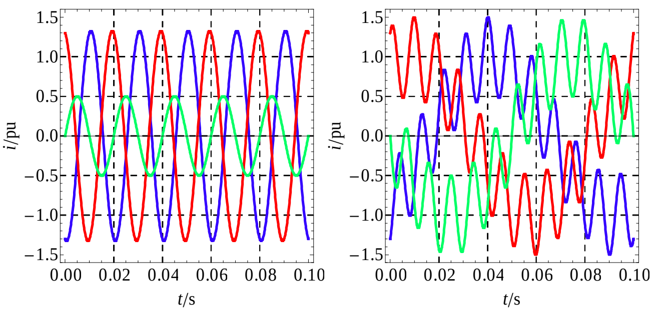

Fig. 5 Typical current waveforms with 1 pu pos. seq. and 0.5 pu neg. seq. left: stator or GSC current waveform, right: RSC current waveforms

For a simplified analysis the losses should be assumed here as proportional to the integral of the square of the currents. Then for this example the average losses of the GSC resulting from the additional negative sequence current increase to 175% in the two phases and decrease to 25% in the third. For the RSC the average losses increase equally to 125% in all three phases. These results must be considered in dealing with the overload capability of the system. This consequently leads to the following general control strategy for the DFIG: Negative sequence current should preferably be delivered by the RSC and the GSC should be operated with symmetrical currents during overload conditions.

The simplified loss model is also often used to implement overload protection algorithms (I^2t protection) resulting in a characteristic as shown in Fig. 6. The maximum permissible overload current in practical applications is limited by various factors. The most important of them are maximum IGBT-module rating or linearity range of the GSC choke.

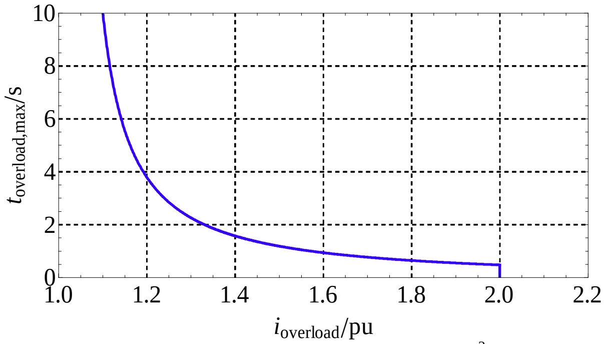

Fig. 6 Typical maximum overload current over time with I^2t-protection

As indicated above positive sequence priority is commonly used, and limiting negative sequence current control objectives due to the RSC voltage limitations is explained in chapter *C*. With this and consideration of the loss distribution, the positive sequence current capability of the RSC can be calculated to:

$$i_{\mathrm{R1,max}} = \sqrt{i_{\mathrm{R,max}}^2 - i_{\mathrm{R2}}^2} \tag{14}$$

For the GSC, the unsymmetrical loss distribution can be taken into account with:

$$i_{\mathrm{GSC1,max}} = \frac{i_{\mathrm{GSC,max}}}{\max\left(\sqrt{\frac{1}{T}\int_0^T i_{\mathrm{GSC,L}n}{}^2 dt}\right)}, n = 1..3 \tag{15}$$

An equivalent method can also be used for the stator current limitation, if necessary.

V. Negative Sequence Characteristics

In this section typical DFIG characteristics for the alternative negative sequence control methods presented above are shown with emphasis on the limitations described in the previous chapter. The parameters used are given in the appendix. As can be seen in (1) - (4) the rotor voltage and current limitations explained in chapter IV, especially depend on the positive and negative sequence stator voltage as well as the rotor speed. In order to present a realistic picture, it was assumed that the sum of the positive and negative sequence voltages is 1.0 p.u. Due to the presence of the wind turbine transformer, the negative sequence voltage at the stator terminals is maximum 0.4 pu even for the worst case grid faults. Therefore only this range is considered here. According to (3) the minimum negative sequence current is always inductive when the rotor voltage is limited hence tending to reduce the negative sequence stator voltage compared to a given negative sequence grid voltage considering an inductive grid [4]. As explained in the prior section it is preferable to operate the GSC with symmetrical currents, and therefore in practical applications this is more common than suppression of the pulsating voltage in the intermediate DC circuit, which will not be considered further here.

A. DFIG without negative sequence compensation

In this mode the speed dependency on the negative sequence variables is negligible. Table I shows the negative sequence currents and oscillatory air gap torque that result from this strategy. Even at low asymmetry levels considerable negative sequence current can be observed. Depending on the value of the leakage reactance, this current can already exceed the rated value when the stator negative sequence voltage assumes a value of about 20 - 25 % of the nominal voltage. Obviously a DFIG design with higher leakage reactance would be favorable in this regard. Taking into account a typical overload capability as shown in Fig. 6 the positive sequence current has to be reduced depending on the duration of the fault. Torque and voltage support capabilities are limited.

TABLE I
CURRENTS AND TORQUE AT DIFFERENT LEVEL OF VOLTAGE UNBALANCE

$\lvert \underline{v}_{S2} \rvert$ pu	$\lvert \underline{i}_{S2} \rvert$ pu	$\lvert \underline{i}_{R2} \rvert$ pu	$\tilde{t}_{el,max}$ [1)] pu	$\tilde{t}_{el,max}$ [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

B. Compensation of stator current imbalance

As shown in Fig. 7 to 9 this control can significantly reduce the thermal and mechanical stress on the system for negative sequence voltage of up to 0.05-0.1 pu over a broad speed range.

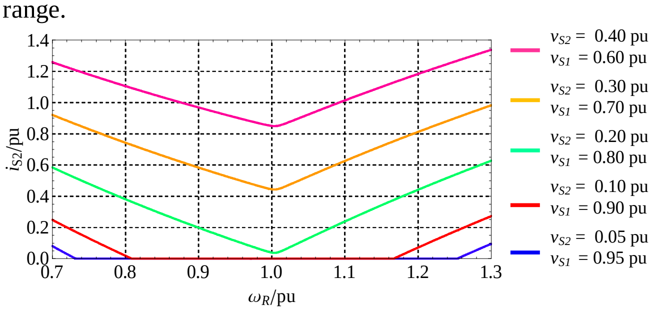

Fig. 7 Maximum value of the negative sequence stator current as a function of negative sequence voltage and rotor speed with stator current asymmetry compensation (at rated current in the positive sequence and pos. seq. priority)

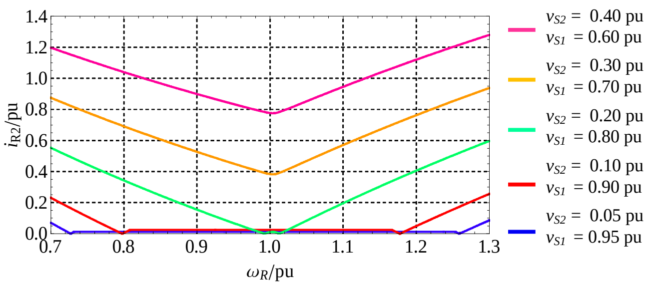

Fig. 8 Amplitude of the negative sequence rotor current with stator current asymmetry compensation in dependence of the negative sequence voltage and rotor speed (at rated current in the positive sequence and pos. seq. priority)

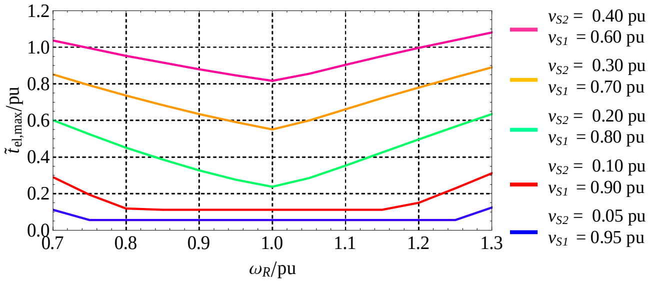

Fig. 9 Amplitude of the oscillatory air gap torque with stator current asymmetry compensation in dependence on the negative sequence voltage and rotor speed (at rated current in the positive sequence and pos. seq. priority)

During grid faults the negative sequence current reduction compared to the results with uncontrolled mode allows for higher positive sequence currents. This is beneficial for the voltage support or torque control capabilities.

C. Compensation of the oscillatory torque

First the results with positive sequence priority are presented in Fig. 10 and Fig. 11. The oscillatory torque can be eliminated up to 0.05-0.1 pu negative sequence voltage in a wide speed range which can reduce mechanical stress to the drive train especially under steady voltage imbalances. The negative sequence current is then reduced to the level of the negative sequence voltage but slightly reduces positive sequence capabilities according to chapter IV. The compensation capabilities during grid faults are limited in the same way as with stator current imbalance reduction but nevertheless significant compared to the uncontrolled mode.

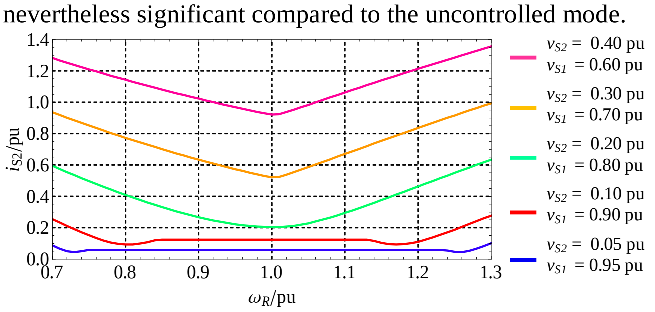

Fig. 10 Maximum value of the negative sequence rotor current as a function of the negative sequence voltage and rotor speed with oscillatory torque compensation (at rated current in the positive sequence and pos. seq. priority)

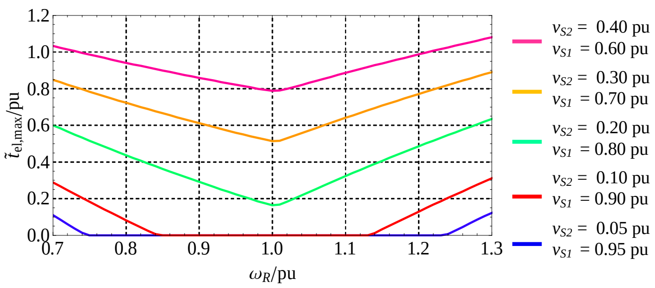

Fig. 11 Amplitude of the oscillatory air gap torque with oscillatory torque compensation as a function of the negative sequence voltage and rotor speed (at rated current in the positive sequence and pos. seq. priority)

With negative sequence priority the oscillatory torque can be eliminated for all imbalance levels. The negative sequence current is comparable to the other controlled modes as shown in Fig. 12. However there are substantial limitations for positive sequence control for negative sequence voltages higher than 0.1-0.2 pu. (Fig. 13). Due to the RSC voltage limits the DFIG can only be operated in under-excited mode. Hence voltage support as required by most grid codes is not possible. Furthermore active current must be limited accordance with (14) which reduces torque control capabilities more than what would have been with positive sequence priority. In practical applications a simplified linear limitation of the active stator current according to Fig. 14 can be chosen to avoid complex numerical online calculations.

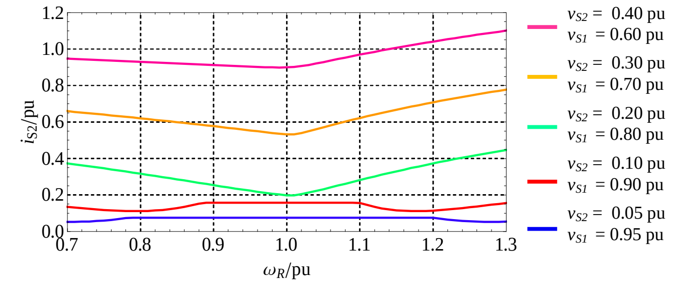

Fig. 12 Amplitude of the negative sequence stator current with elimination of the oscillatory air gap torque in dependence on the negative sequence voltage and rotor speed with neg. seq. priority

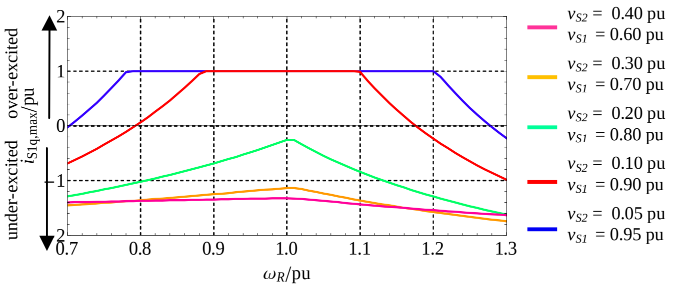

Fig. 13 Maximum reactive stator current in the positive sequence with elimination of the oscillatory air gap torque in relation to the negative sequence voltage and speed with neg. seq. priority

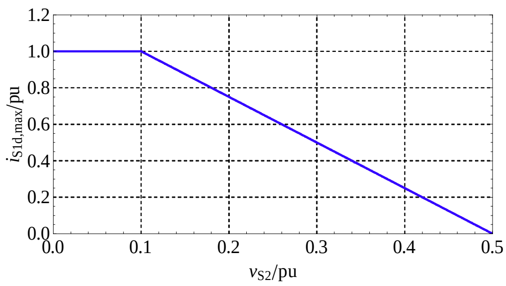

Fig. 14 Simplified characteristic for the maximum active stator current in the positive sequence system with elimination of the oscillatory air gap torque in relation to the negative sequence voltage with neg. seq. priority

VI. Conclusions

During unbalanced conditions in the grid decoupled positive and negative sequence control enable DFIG systems to prioritize the control targets according to grid code requirements or wind turbine system optimization objectives. Usually these are active power generation, voltage control and support in the positive sequence, loss optimization and thermal and mechanical stress reduction. For small imbalances most of these targets can be fulfilled concurrently since no limitations are expected with respect to common voltage and current capabilities of modern DFIG systems. However during severe grid asymmetry significant limitations have to be taken into account. To comply with the current grid code requirements regarding voltage support positive sequence control usually has priority, and therefore negative control objectives can only be partly accomplished.

VII. Appendix

DFIG parameters used in this study

V_r	690 V	r_S	0.006 pu
P_r	2000 kW	r_R	0.006 pu
f_r	50 Hz	l_{GSC}	0.265 pu
ω_r	1.2 pu	r_{GSC}	0.005 pu
l_m	4.000 pu	v_{RSCmax}	0.4 pu
$l_{\sigma S}$	0.125 pu	v_{GSCmax}	1.1 pu
$l_{\sigma R}$	0.125 pu		

The DFIG parameters normally are not constant due to saturation or skin effects. Also the variation depends on the operating point, level of asymmetry or transient conditions. This was not considered here.

VIII. References

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