Wind Turbine Negative Sequence Current Control and its Effect on Power System Protection

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Abstract**-- This paper focuses on the control of the negative sequence component of the wind turbine (WT) short circuit current. In many applications the negative sequence component is suppressed partially or entirely. Full negative sequence current suppression control would reduce the line-to-line short circuit current to the level of the load current or even to zero, thus interfering with the proper functioning of the conventional protection devices. To overcome this problem, the extension of the existing grid code has been proposed, which would require WT to inject a clearly defined level of negative sequence current. The injected current will additionally reduce the negative sequence voltage and improve the voltage phase symmetry. However, negative sequence current injection will limit the control capability of the WT in the positive sequence. The effect of different control options has been demonstrated using simulation on a test network and conclusions deduced.**

Index Terms**-- Negative Sequence Control, Renewable Energies, Short Circuit Current, Voltage Control, Wind Power**

I. NTRODUCTION

THE number and penetration of wind turbines (WT) continues to increase and with it the impact of WT on system security. Grid codes as of now make specific requirements regarding the behavior of WT during and in the immediate aftermath of fault only with respect to the positive sequence components. As for the negative sequence components only some vague stipulations are to be found [1]. Compared to the conventional synchronous machines, WT - due to the frequency converters they use - open up more leeway and better flexibility to control the short circuit current or more generally to influence the post fault behavior at the point of common coupling.

This paper focuses on the control of the negative sequence component of the short circuit current originating from WT. As the negative sequence current control would enable the reduction or even total elimination of the negative sequence short circuit current in many modern WT, the paper will discuss the impact this will have on the grid and the protection system and how it can be treated. Then, the need for the extension of the current grid code to include provisions dealing with the negative sequence will be highlighted and how this can be incorporated into the existing control systems will be explained. Finally, the conclusions reached from conceptual discussions will be corroborated by simulation on a test network. Although the WT is the focus of discussion, the basic results and conclusions deduced from them are applicable to the other equipment and systems using voltage source converter (VSC) based converters such as VSC HVDC lines and photovoltaic power plants.

II. SHORT CIRCUIT CONTRIBUTION OF WIND TURBINES

The initial short circuit current contribution of WT depends on the type of WT and is specific to the technology the WT uses. The behavior during the quasi steady state phase is essentially determined by the converter control. The current grid codes do not distinguish between different technologies and same response is required from all WT types.

A. Wind turbine design

One of the more common WT technologies at this point in time is the doubly-fed induction generator (DFIG) where the three-phase rotor windings are fed by the converter with voltages of variable amplitude and frequency. The stator terminals are directly connected to the grid. As a result, the initial transient response following a sudden voltage drop (as a result of grid fault) is dominated by the demagnetization of the induction machine which may result in high stator peak currents. The DFIG WT (Type 3 WT according to the IEEE designation) topology is shown in Fig. 1. The machine side converter (MSC) and the line side converter (LSC) are controlled in two independent channels for active and reactive power [2], respectively. The other alternative is the full scale converter based WT (Type 4) shown in Fig. 2. In Type 4 WT the grid side behavior is essentially determined by the LSC and not by the WT generator. The response time is therefore faster than that of DFIG WT.

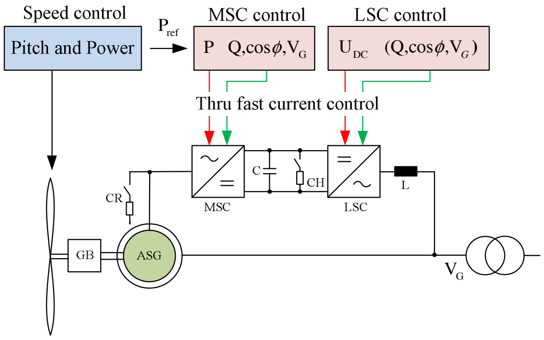

Fig. 1. DFIG based wind turbine (Type 3).

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In the following paragraphs the response of WT to unbalanced grid faults will be explained conceptually using Type 4 WT as an example. Although DFIG based units behave slightly differently, the basic conclusions presented here are valid for both WT types.

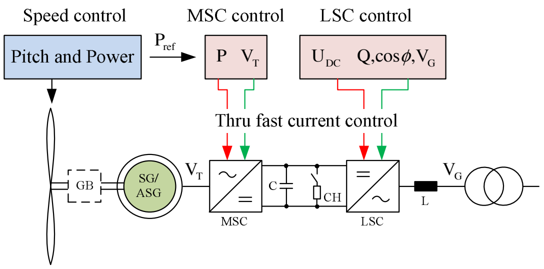


Fig. 2. Full rated converter based wind turbine (Type 4).

B. *Positive Sequence Control*

The basic structure of the LSC current controller for the positive sequence is shown in Fig. 3. It consists of a feed-forward term and two PI blocks. The main control task is performed by the feed-forward block and the PI controllers account for parameter and measurements uncertainties.

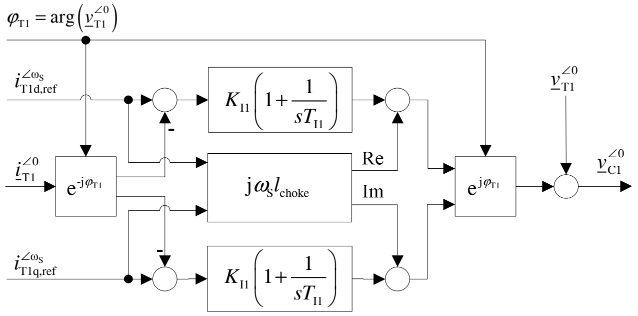


Fig. 3. Positive sequence line side converter control scheme.

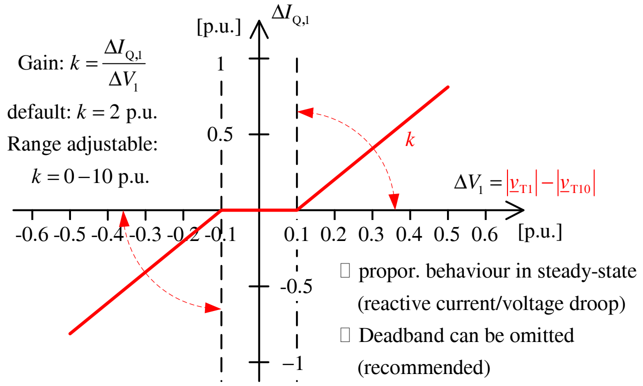


Fig. 4. Reactive current- voltage steady state gain of wind turbines according to the German grid code [1]

The current controller operates in grid synchronous coordinates (the superscript $\angle\omega_s$ denotes grid synchronous reference frame). The active current reference $\underline{i}_{\text{T1d,ref}}^{\angle\omega_s}$ is provided by an outer power or speed controller depending on the prevailing wind speed. Concerning the reactive power supply, it is a common practice to set the reference value to zero (power factor $\cos\varphi = 1$). It should, however, be noted that more and more countries now realize that WT have to participate in grid reactive power control in both steady-state and during faults as well [3], [4], [5]. One of the pioneers in this respect is Germany where WT have to be able to operate in the range of $\cos\varphi = 0.95_{\text{ind}} \ldots 0.925_{\text{cap}}$, in addition to a fast voltage controller to be activated during periods of sudden voltage drops. The range of the prescribed controller gain is shown in Fig. 4. The dead-band can be skipped if the implemented control scheme ensures proper steady state and dynamic characteristic. The required dynamic response of the voltage controller is shown in Fig. 5, in which the rise time and the dynamic settling behavior of the reactive current are also shown.

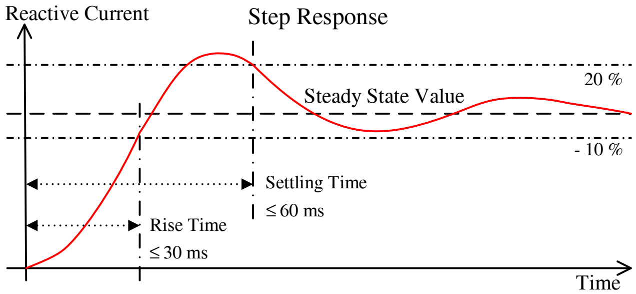


Fig. 5. Response of reactive current supplied by wind turbines to a voltage step change according to the German grid code.

The reactive current mentioned-above is the positive sequence current to boost the positive sequence voltage during the fault period. This is essential to keep loads, especially induction machines and other generation units, running during the fault. Therefore, the corresponding voltage controller has to be implemented for the positive sequence.

The positive sequence short circuit current contribution of WT after the initial transient response has died down (after 50-60 ms) is composed of two components. The first is the load current which can be calculated according to (1).

$$\underline{i}_{\text{Load1}} = \frac{p_{\text{ref10}} - jq_{\text{ref10}}}{|\underline{v}_{\text{T1}}|} e^{j\varphi_{\text{T1}}} \qquad (1)$$

where

$\underline{v}_{\text{T1}} = v_{\text{T1}} \cdot e^{j\varphi_{\text{T1}}}$: positive sequence terminal voltage

$p_{\text{ref10}} + jq_{\text{ref10}}$: steady state active and reactive power reference

Although the active and reactive current references usually do not change considerably during the low voltage period, the load current reference may increase significantly due to the voltage reduction by the fault, on top of the capacitive current injected by the controller. The mathematical expression for the reactive current response of the voltage controller according to [1] is as follows:

$$\underline{i}_{\text{VC1}} = \text{j}\left(|\underline{v}_{\text{T1}}| - |\underline{v}_{\text{T10}}|\right) \cdot k \cdot e^{j\varphi_{\text{T1}}} \qquad (2)$$

where

$\underline{v}_{\text{T10}}$: pre-fault average positive sequence terminal voltage

$k = \dfrac{\Delta i_{Q1}}{\Delta v_{T1}}$: steady state reactive current - voltage gain

Neglecting the dead-band (shown in Fig. 4), eq. (1) and (2) correspond with the equivalent circuit shown in Fig. 6. Both current components $\underline{i}_{VC1}$ and $\underline{i}_{Load1}$ are in the same range of magnitude. Therefore, neglecting the load current as is commonly done in the standard short circuit current calculation [6] would result in a significant error.

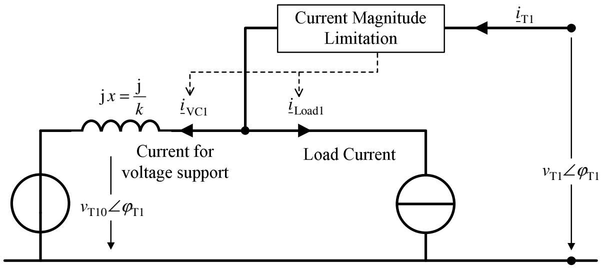


Fig. 6. Positive Sequence steady-state equivalent circuit of WT considering voltage control, steady-state load and current limitation.

Incorporating WTs into the grid short circuit calculation, as per Fig. 6, will require an iterative procedure since the calculation of both current components, $\underline{i}_{Load1}$ and $\underline{i}_{VC1}$, presupposes knowledge of the terminal voltage magnitude and phase angle. Furthermore, the magnitude limitation for protecting the converter has to be considered. Depending on the priority implemented the active or reactive current references are limited, also affecting the current supplied.

C. Negative Sequence Control

Grid codes make no specific prescriptions concerning negative sequence currents supplied by WT. Therefore, in Type 4 WT sometimes the negative sequence current is suppressed using control measures by applying, for example, the negative sequence voltage at the controller output as the reference. A more thorough approach would include an additional dedicated negative sequence current controller as shown in Fig. 7. Current suppression control in this context implies setting the reference active and reactive currents $i_{T2d,ref}^{\angle-\omega_s}$ and $i_{T2q,ref}^{\angle-\omega_s}$ to zero. Suppression of negative sequence currents in its entirety is usually possible in Type 4 WT. The controllability of negative sequence currents in Type 3 WT, however, is limited due to the availability of rotor voltage.

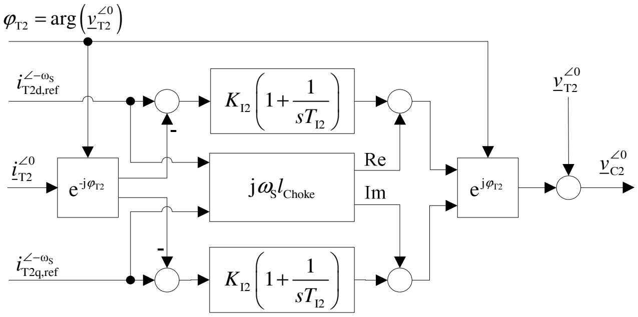


Fig. 7. Line side converter negative sequence control scheme.

The corresponding equivalent circuit that basically offsets the short circuit current is shown in Fig. 8 a). The reference voltage to be applied by the converter is calculated by the superposition of positive and negative sequence components according to (3)

$$\underline{v}_{C}^{\angle 0} = \underline{v}_{C1}^{\angle 0} + \underline{v}_{C2}^{*\angle 0} \tag{3}$$

The superscript "*" denotes the conjugate complex quantity. Note that the same negative sequence current control approach can be implemented in photovoltaic power plants or VSC HVDC.

D. Consequences of Suppressing Negative Sequence Current

Assume now a hypothetical grid where the entire supply comes via converters. Assume further that all of them control the negative sequence currents to zero. The result is that no short circuit current would flow in the event of a line-to-line fault. Offshore wind farm connected to the grid via VSC HVDC is an example of such a grid.

When the generation units are interrupted in the negative sequence (as a result of the control measures implemented) the current can only flow through loads and line/cable capacitances. That means the short circuit current lies in the range of load or capacitive charging current. It is obvious that conventional protection devices will have difficulty to sense this current and to protect the system.

E. Proposal for the Definition of Negative Sequence Current Supplied by Converter Based Generation Units

To overcome the possible problem arising from the current suppression control, a working group in Germany has proposed the extension of the current grid codes to include a provision requiring WT and other converter based units to supply negative sequence current during fault. The inductive negative sequence current to be injected is proportional to the negative sequence voltage at the terminal (so called V2P control). The proportionality factor k is the same as the gain defined for the positive sequence voltage controller. Mathematically this can be formulated as:

$$\underline{i}_{V2P} = -jk\underline{v}_{T2}e^{j\varphi_{T2}} = k\left|\underline{v}_{T2}\right|e^{j\left(\varphi_{T2}-\pi/2\right)} \tag{4}$$

The corresponding equivalent circuit can then be used in the standard short circuit calculation as shown in Fig. 8 b).

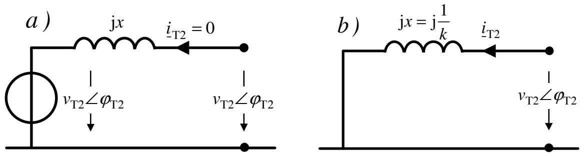


Fig. 8. Negative Sequence steady-state equivalent circuits of wind turbines for different control methods.
a) current suppression control b) current V2P control

As a consequence of this requirement separate negative sequence controller has to be implemented where the reference values are calculated in accordance with (4). Concerning the dynamic response of the negative sequence current, the same requirements already defined for the positive sequence (see Fig. 5) may be retained. Positive and negative sequence currents form an oscillating space vector as shown in Fig. 9 .

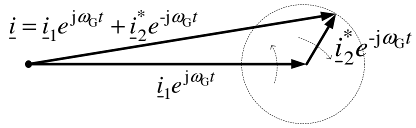


Fig. 9. Current space vector consisting of positive and negative sequence components.

For the current limitation in the converter it is reasonable to use the condition

$$\left|\underline{i}_1\right| + \left|\underline{i}_2\right| \le i_{\max} \qquad (5)$$

When the current needs to be limited both positive and negative sequence currents are to be treated equally. According to the proposal a dead-band can be used in the negative sequence voltage in (4), so that small unbalances caused by grid or load asymmetry are handled differently.

III. SIMULATION EXAMPLE

In the test network shown in Fig. 10 different options for positive and negative sequence control and grid connection have been simulated.

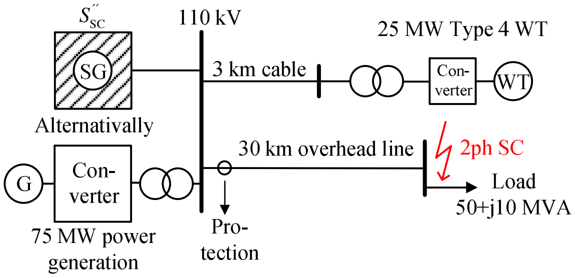
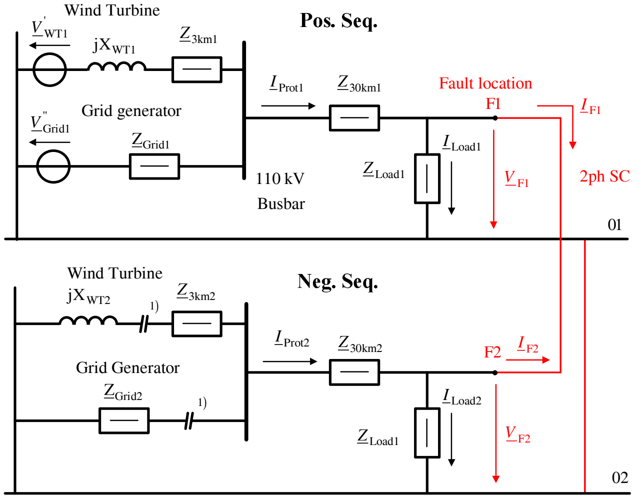


Fig. 10. Test grid



1) in case of converter supply and negative sequence suppressing control, branch is interrupted

Fig. 11. Steady-state equivalent circuit for 2-ph line to line fault current calculation

The equivalent circuit for line-to-line fault is given in Fig. 10. For simplicity the grid and the WT are represented in this figure using the Thevenin equivalent. However, in the simulation both the WT and the grid converter are modeled in detail including the control options discussed above.

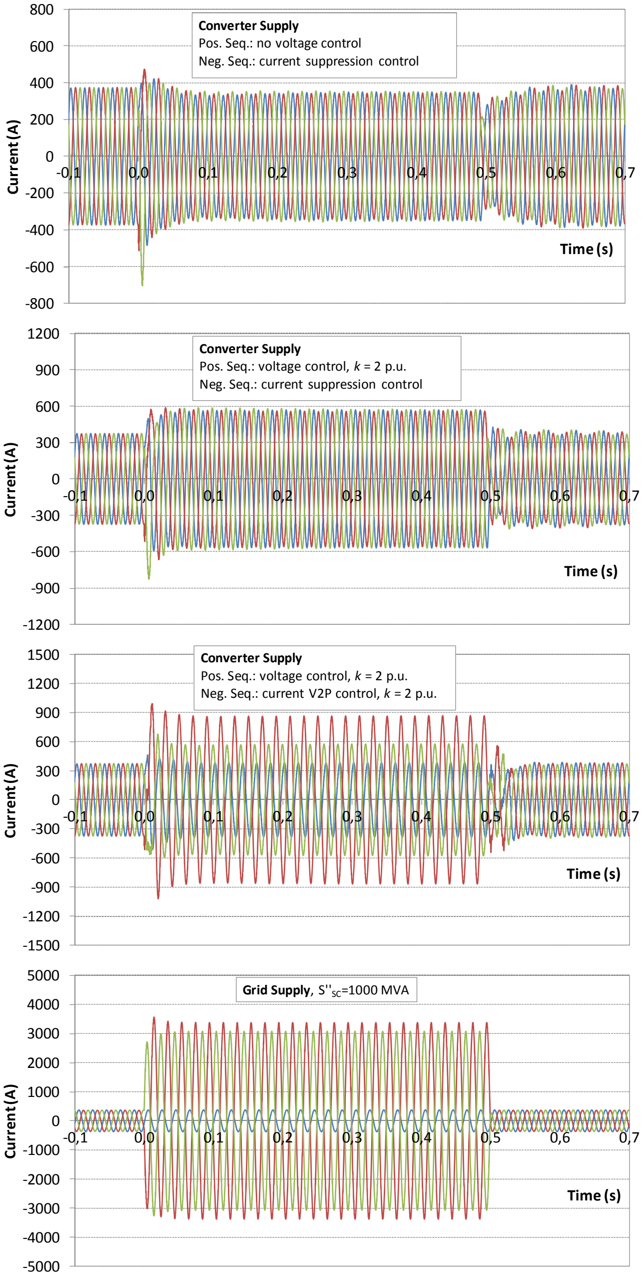
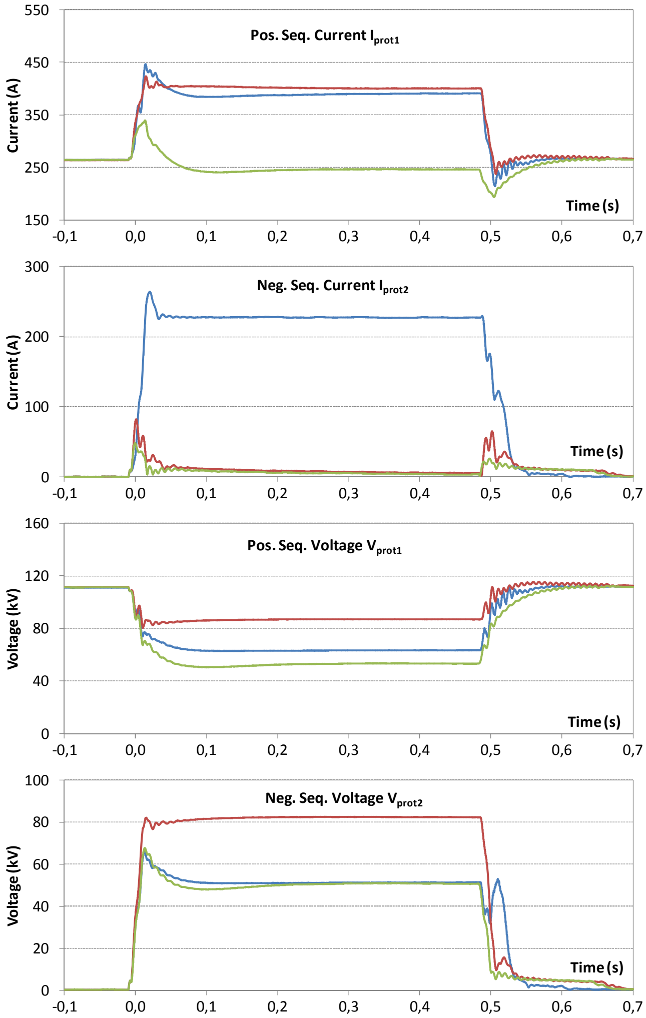


Fig. 12. Instantaneous currents at protection location for different grid supply and converter control methods.

From Fig. 12 it is obvious that in case of converter supply together with suppression control the short circuit current is determined by the load only. As shown in the first diagram in Fig. 12 if there is no voltage control in the positive sequence and the converters suppress the negative sequence current, the short circuit current sensed by the protection is even lower (slightly) than the pre-fault load current. The positive sequence voltage control lets the current increase slightly (second diagram in Fig. 12). However, it is basically a positive sequence current and therefore, the three phases remain symmetrical. With the suggested V2P control the short circuit current increases further and becomes even more unsymmetrical due to the additional negative sequence current driven by the converter (third diagram in Fig. 12). If the overlay grid is represented by the classical Thevenin equivalent with $S''_{\mathrm{SC}} = 1000\mathrm{MVA}$ the current reaches a real short circuit current level, several fold of the load current.

In Fig. **13** the positive and negative sequence currents and voltages as observed at the location of the protection system are shown. Both are calculated from the instantaneous three phase currents and voltages and therefore, show a small measurement delay. Without V2P control the negative sequence current remains close to zero and only the positive sequence current flows. Voltage control will result in less voltage drop in the positive sequence but the negative sequence voltage during the fault will also increase significantly. The negative sequence voltage, on the other hand, can affect the loads connected to the grid adversely and represents basically increased voltage unbalance.



Pos. Seq.: no voltage control; Neg. Seq.: current suppression control
Pos. Seq.: voltage control, k=2 pu; Neg. Seq.: current suppression control
Pos. Seq.: voltage control, k=2 pu; Neg. Seq.: current V2P control, k=2 pu

Fig. 13. Positive and negative sequence currents in protection location by different converter control methods.

By using the V2P control a considerable residual negative sequence current appears. The effect of voltage control in the positive sequence is less significant due to the current limitation applied equally to the sum of positive and negative sequence currents. However, the negative sequence voltage during the fault is reduced as well. It can generally be concluded that increasing negative sequence current will result in reduced negative sequence voltage and consequently in lower voltage unbalance. However, the negative sequence current supply will also limit the capability of positive sequence voltage control. Despite this drawback the negative sequence V2P control is indispensable, especially when one considers that the short circuit current otherwise is determined only by the load and is very small or even zero if no load is connected to the grid.

IV. CONCLUSIONS

Modern WT are capable of controlling positive and negative sequence current components separately. The negative sequence control capability of the DFIG is limited, whereas the full rated converter WT is able to suppress the negative sequence current completely. As the number of WT and other units connected to the grid via converter steadily increases, it is easy to imagine that negative sequence suppression would lead to a line-to-line short circuit current in the range of the load current. Under no load conditions the line-to-line fault would even result in zero fault-current. The conventional protection devices would thus have difficulty to sense and clear the fault.

To overcome this problem and to establish a clearly defined condition following faults, the extension of the current grid code is proposed. As per the proposal WT are to be required to inject a certain level of negative sequence short circuit current proportional to the negative sequence voltage. This will result not only in higher short circuit current but also in the reduction of the negative sequence voltage and thus better phase voltage symmetry. With the proposed negative sequence control the short circuit current of WT and other converter based units will not be determined by the load only. However, injection of the negative sequence current will limit the control capability of WT in the positive sequence. The effect of different control options has been demonstrated using simulation on a test network.

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