Impact of Network Side Converter Reference Frame Selection on Wind Turbine Operation under Asymmetrical Grid Voltage

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Abstract

This paper studies the impact of network voltage asymmetry on the operation of full-power converter wind turbine with different network side converter (NSC) control methods. The aim of the study is to investigate the impact of NSC reference frame selection on quality of generated power. The studied reference frames are oriented to converter voltage and network voltage. It is shown that network voltage asymmetry has great operational impact if control system of NSC is oriented to the converter voltage. This may lead to power quality problems especially when wind turbines are connected to weak networks.

1. Introduction

This paper focuses on the generated power quality by the wind turbine (WT) under the presence of network voltage asymmetry. If the power quality of WT is degrated as a result of the network voltage asymmetry the amount of WTs installed in wind farm may need to be limited. The power quality issue is emphasized because it is common that WTs and wind farms are built in remote areas at the end of long transmission lines making the power system in the point of connection to be weak. [1] Thus, it is vital that the operation of WTs does not deteriorate the power quality when network voltages are asymmetrical.

The frequency converter of full-power converter WT consists of a generator side converter which controls the speed and active power of the generator, and a network side converter (NSC) which controls the DC-link voltage and the reactive power. Typically, the vector control of NSC is done in reference frame synchronized to the network voltage. When the angle of the rotating network voltage vector is known, the control system of NSC produces a current vector that rotates with the same angular frequency with the network voltage. Moreover, the current vector can be divided into active and reactive current components which, in turn, can be controlled independently from each other. In addition, under steady state operation with symmetrical network voltages, the active and reactive current references are constants. Thus, the current components can be controlled to the reference values using traditional PI-controllers without steady state error. [2]

When the control system of NSC is carried out in synchronous reference frame, the WT currents are sinusoidal and balanced if the following two conditions are fulfilled: 1) the synchronous reference frame is rotating with constant angular frequency (fundamental frequency of the network voltage positive sequence component), 2) the d- and q-axis current references are constants and the current control operates without steady state error.

The network voltage vector in stationary reference frame, when only fundamental frequency component is considered, is expressed as follows: [3]

$$\underline{u}_{\alpha\beta} = \begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = U^+ \begin{bmatrix} \cos\left(\omega t + \varphi^+\right) \\ \sin\left(\omega t + \varphi^+\right) \end{bmatrix} + U^- \begin{bmatrix} \cos\left(-\omega t + \varphi^-\right) \\ \sin\left(-\omega t + \varphi^-\right) \end{bmatrix} \tag{1}$$

where U is the phase voltage peak value, ω is the grid voltage angular frequency and φ is the initial angle. Superscripts + and – correspond to the positive and the negative sequence references. If the network voltages are symmetrical the U^- in (1) is zero. Thus, the network voltage vector rotates with constant ω. Hence, in steady state, the above mentioned conditions 1) and 2) are fulfilled if the NSC is synchronized directly to the network voltage.

If the network voltages are asymmetrical, the U^- in (1) is not zero anymore. The appearance of negative sequence voltage component causes the angular frequency of network voltage vector to vary. Thus, the condition 1) is not fulfilled anymore if the NSC is synchronized to network voltage. In addition, the negative sequence component causes an additional 100Hz component to the DC-link voltage of the frequency converter. Depending on the tuning of DC-link voltage controller, the variation in DC-link voltage causes also the active current reference to oscillate. Thus, the condition 2) is not fulfilled either. In addition, the steady state error may not be zero anymore depending on the bandwidths of the current controllers. Hence, the network voltage asymmetry has impact on the currents produced by the wind turbine and to the generated power quality, if the NSC is synchronized directly to the network voltage. In order to avoid the aforementioned problem, the synchronization should be done to the positive sequence component of the network voltage which is symmetrical component and has constant angular frequency.

This paper investigates the impact of NSC reference frame selection to the power quality under the presence of network voltage asymmetry. The studied reference frames are oriented to the converter voltage directly and to the network voltage via synchronization circuit. Special attention is paid to the ability of NSC to fulfil the condition 1) i.e. the ability to maintain the constant angular frequency of the synchronous reference frame.

2. System modeling

The vector control system of WT NSC in network voltage reference frame is shown in Fig. 1a. The output of the dc-link voltage controller is the reference for active converter current $i_{L1,d}^*$. In this study, the reference for reactive current $i_{L1,q}^*$ is set to zero. The PI controllers are used to control the current components and the outputs of the controllers are the voltage components over LCL-filter inductors u_{Ld}^* and u_{Lq}^*. Removing the cross-coupling terms and with the help of the measured connection point voltage components $u_{sync,d}$ and $u_{sync,q}$, the NSC voltage reference components $u_{conv,d}^*$ and $u_{conv,q}^*$ can be calculated. [4]

The phase angle of the synchronous reference frame θ_{sync} is the output of the synchronizing block *Sync*. In this study, the used synchronization methods are the synchronous reference frame – phase locked loop (SRF-PLL) and dual second order generalized integrator – frequency locked loop (DSOGI-FLL). The performance of WT during asymmetrical network voltages is mainly determined by the ability of these methods to detect the positive sequence component of the network voltage. The methods are presented in detail in [3] and the parameter tuning is discussed in [5]. The SRF-PLL and DSOGI-FLL were tuned to have following parameters: $\omega_n = 2\pi 15$, $\zeta=0.707$ and $k_{SOGI}=0.5$, $\Gamma=387$, respectively.

The control system of the NSC using reference frame oriented to the converter voltage is shown in Fig. 1b [6]. Contrary to the control system shown in Fig. 1a there is no need to measure the voltage $\underline{u}_{sync}$ for synchronization purpose and no dedicated locking loop for synchronization is needed. Again, the DC-link voltage is controlled via d-axis current and the reference for q-axis current is set to zero. However, the d-axis current controller output is the switching function *sw* which is needed to determine the converter voltage d-component. The reactive current is controlled via the frequency of the converter voltage. Thus, the reference frame angle is attained from the q-axis current controller. Hence, the performance of WT under network voltage asymmetry is mainly determined by the performance of this controller. The q-axis current controller is an interacting PID controller that is PD and PI controllers connected in series [2]. Converter voltage q-component in this reference frame is zero. [6]

The controller parameters of both control systems are tuned to have identical bandwidths in order to make comparable simulation results. The d-axis and q-axis current controllers and the DC-link voltage controller bandwidths are 320Hz, 290Hz and 25Hz, respectively. The switching actions of the NSC are not taken into account because the consideration is restricted purely on the phenomena caused by the control system operation.

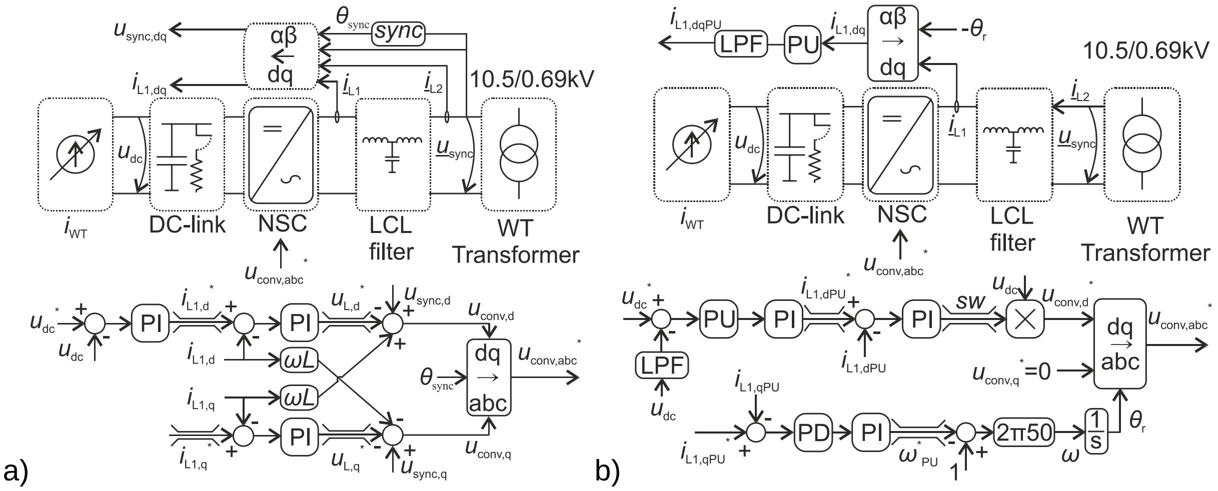

Fig. 1. Control system of NSC: a) network voltage, b) converter voltage reference frame.

Network model

The network model used in the study is shown in Fig. 2. The model consists of 5 (500kW) WTs which are connected to 10.5 kV voltage level. WT and LCL-filter parameters can be found from [7]. The unbalanced load is connected to 66 kV network causing asymmetrical voltages to the point of common coupling (PCC). Table 1 and Table 2 show the control parameters of NSC when synchronous reference frame is oriented to the network voltage and to the converter voltage, respectively. Network parameters are depicted in Table 3.

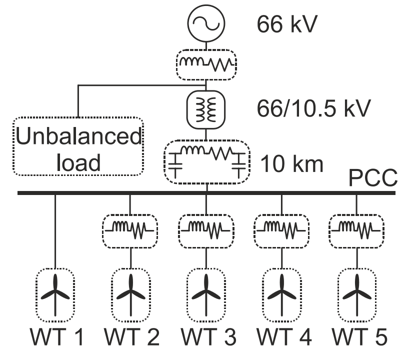

Fig. 2. Network model.

Table 1. Control parameters of NSC in network voltage frame

Current control d-axis	Current control q-axis	DC-link control
$k_{i,d}$=0.44	$k_{i,q}$=0.46	k_{udc}=3.2
$T_{i,q}$=0.0045s	$T_{i,q}$=0.014s	$T_{i,udc}$=0.05s

Table 2. Control parameters of NSC in converter voltage frame

Current control d-axis	Current control q-axis	DC-link control
$k_{i,d,pu}$=0.38	$k_{i,q,pu}$=0.43	$k_{udc,pu}$=6.1
$T_{i,q}$=0.0045s	$T_{i,q}$=0.014s	$T_{i,udc}$=0.05s
	PD=1+(8s/(s+2700))	

Table 3. Network parameters

Z (66kV)	Load	66/10.5 kV transf.	WT transf.
R=24mΩ	Phase a=10MW	S_n=16.7MVA	S_n=600kVA
L=7,7mH	Phase b=45MW	R_{pu}=0.0056	R_{pu}=0.009
	Phase c=35MW	$L_{\sigma pu}$=0.00029	$L_{\sigma pu}$=0.06

3. Simulation results

The comparison of WT performance, which uses the aforementioned NSC reference frames, under network voltage unbalance is carried out in following section. The simulations were made using MatLab/Simulink SimPowerSystems. The evolution of total harmonic distortion (THD) [8] as the number of nominal active power generating WTs increases is shown in Table 4. U_{sync} and i_{L2} shown in Fig 1a and 1b are measured from the secondary side of the WT1 transformer and U_{aPCC} and I_{aPCC} are measured from the PCC, Fig. 2. The PCC voltage unbalance before WT connections is 2,18%.

When the converter voltage reference frame is used the THDs of $U_{\mathrm{a,sync}}$ and $I_{\mathrm{a,L2}}$ increase significantly as the number of nominal power generating WTs increase. In addition, the PCC THDs increase steadily. When the control systems of the WTs are synchronized to the network voltage, the voltage and current THD levels are not impacted by the number of active power generating WTs. It can be concluded that the negative sequence component of the network voltage does not have significant impact on the currents generated by the WT, if the control system of NSC is oriented to the grid voltage via SRF-PLL or DSOGI-FLL.

Table 4. THD evolution as number of active power generating WTs increases.

Reference frame	Measure	Number of wind turbines				
		1	2	3	4	5
Converter voltage	THD $U_{\mathrm{a,sync}}$	0.54%	0.77%	1%	1.3%	1.7%
	THD $I_{\mathrm{a,L2}}$	3.3%	3.5%	3.8%	4.2%	4.6%
	THD U_{aPCC}	0.26%	0.35%	0.52%	0.74%	1%
	THD I_{aPCC}	4.9%	3.6%	3.7%	4.1%	4.5%
Network voltage SRF-PLL	THD $U_{\mathrm{a,sync}}$	0.06%	0.07%	0.08%	0.09%	0.11%
	THD $I_{\mathrm{a,L2}}$	0.3%	0.3%	0.31%	0.31%	0.31%
	THD U_{aPCC}	0.01%	0.03%	0.04%	0.05%	0.06%
	THD I_{aPCC}	0.3%	0.31%	0.31%	0.31%	0.31%
Network voltage DSOGI-FLL	THD $I_{\mathrm{a,L2}}$	0.15%	0.15%	0.15%	0.15%	0.16%
	THD I_{aPCC}	0.15%	0.15%	0.16%	0.16%	0.16%

The electrical angular frequency of the converter voltage reference frame for WT1 is shown in Fig. 3a. The active power of WT1 is increased from zero to nominal value at 0.3s. The power of second, third, fourth and fifth WT is increased to nominal value at 0.6s, 0.9s, 1.2s and 1.5s, respectively. The 100Hz oscillations of the angular frequency caused by the negative sequence component of the network voltage increases as the number of active power generating WTs increases. Due to the nonlinear behavior of the synchronizing angle the voltage and current THDs increase. It should be noticed that significant 100Hz component is imposed to the frequency of the reference frame even when all five WTs generate zero power. This indicates that currents needed to maintain the DC-link voltage during zero power generation are greatly influenced by the network voltage asymmetry. This also explains the significant THDI_{aPCC} in Table 4 after power increase of WT1 only. When network voltage reference frame with SRF-PLL synchronizing method is used the angular frequency oscillations are smaller as shown in Fig. 3b. This is due to the action of loop filter of SRF-PLL which is typically PI-controller. [5] In addition, the active power of other wind turbines does not have impact on the angular frequency. The DSOGI-FLL first detects the positive sequence component from the grid voltage and then synchronizes the

NSC control system to the angle of the positive sequence component. Thus, the impact of negative sequence component to the angular frequency of DSOGI-FLL is very limited and the frequency shown in Fig. 3c is free from 100Hz oscillations.

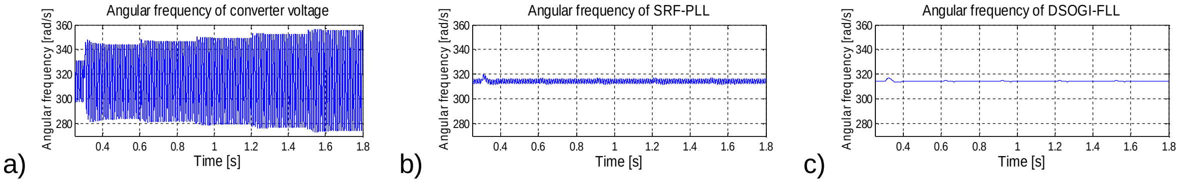

Fig. 3. Angular frequency of reference frame: a) converter voltage reference frame, b) network voltage reference frame using SRF-PLL, c) network voltage reference frame using DSOGI-FLL.

The PCC currents after nominal operation of five WTs, which use the converter voltage reference frame, are shown in Fig. 4a. The currents are significantly distorted as a result of the network voltage unbalance. The PCC currents when the WT is synchronized to the network voltage via SRF-PLL and DSOGI-FLL are shown in Figs. 4b and 4c. The voltage unbalance does not generate distortion to the currents as Table 4 indicates.

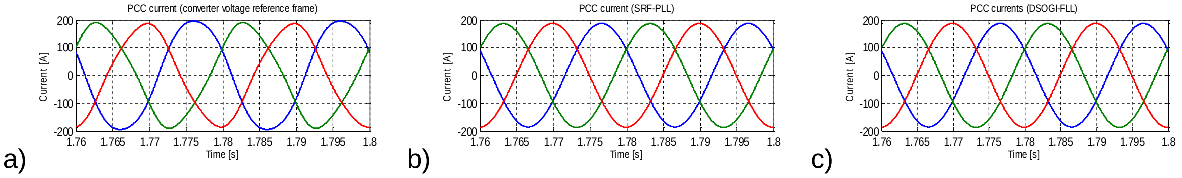

Fig. 4. PCC currents after 500kW operation of five WTs: a) converter voltage reference frame, b) network voltage reference frame (SRF-PLL), c) network voltage reference frame (DSOGI-FLL).

Gain reduction in q-axis current controller

The simulation results shown in Figs. 3a and 4a indicate that the operation performance of WT synchronized to the converter voltage reference frame may be significantly reduced due to the asymmetrical network voltage. Since the synchronizing frequency is the output of the q-axis current controller, it seems reasonable to reduce the bandwidth of the controller. The simulation results shown in Table 4 are repeated in Table 5 with decreased gain in the q-axis current controller. The bandwidth after gain reduction is 95Hz.

The operation of adjacent WTs does not have an impact on the WT1 voltage and current THDs. In addition, the voltage THD measured from the PCC does not increase remarkably as the active power of adjacent WTs increase. Also the PCC current THD rather decreases than increases as a result of increased active power of other WTs. However, very high PCC current THD values are measured when only WT1 is operating at full power. Thus, the operation performance under zero or partial power is deteriorated as a result of the q-axis current controller bandwidth reduction.

Table 5. THD evolution as number of active power generating WTs increases. (reduced gain)

Reference frame	Measure	Number of wind turbines				
		1	2	3	4	5
Converter voltage (reduced gain)	THD $U_{a,sync}$	0.94%	0.94%	0.95%	0.95%	0.98%
	THD $I_{a,L2}$	3%	2.9%	2.9%	2.9%	2.9%
	THD U_{aPCC}	0.56%	0.56%	0.57%	0.58%	0.59%
	THD I_{aPCC}	11%	6%	4.2%	3.3%	2.7%

With the reduced gain the angular frequency of the converter voltage reference frame is not influenced by the operation of adjacent wind turbines as shown in Fig. 5a. In addition, the 100Hz oscillating component is significantly reduced compared to previous case. The PCC currents contain much less distortion when five WTs are operating at nominal power as can be seen from Fig. 5b. However, as illustrated in Fig. 5c, the WT currents during zero active power production are highly distorted. This explains the high THD of the PCC current when only WT1 is operating at nominal value and other WTs are operating at zero active power.

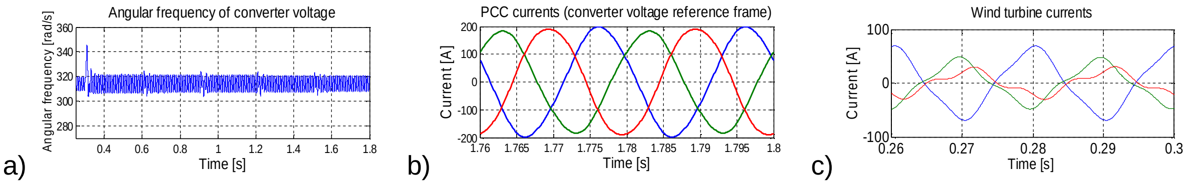

Fig. 5. Converter voltage reference frame: a) angular frequency, b) PCC currents when five WTs are operating with nominal power, c) WT1 currents when WT is operating at zero active power.

4. Conclusion

This paper studied the impact of network voltage asymmetry on the operation of full-power converter wind turbine. The aim of the study was to investigate the impact of the reference frame selection of the NSC control system on quality of generated power. The studied reference frames were oriented to converter voltage and network voltage. The control system oriented to the network voltage via SRF-PLL or DSOGI-FLL was not affected significantly by the network voltage asymmetry with used tuning parameters. However, it was shown that the control system of NSC oriented to converter voltage is very vulnerable to network voltage asymmetry. It was shown that the voltage and current THD increases as the number of active power generating wind turbines in wind farm increases. In order to eliminate this, the q-axis current control bandwidth was decreased. However, this had the consequence of decreasing the performance of current control. Thus, special attention need to be paid to the q-axis current control in order to improve the performance of NSC oriented to the converter voltage reference frame to an acceptable level. Otherwise, the amount of wind turbines in wind farm needs to be limited. It is common that wind turbines are connected to the weak power system which emphasizes this issue.

5. Literature

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