Methods for Reduction of Voltage Unbalance in Weak Grids Connected to Wind Plants

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1 INTRODUCTION
The location of wind turbines is based on wind properties. Normally, areas with good wind resources are geographical remote. The cost of the electrical power grid connecting the wind plants should be as low as possible. The voltage quality in a weak power grid may be poor, and unbalanced voltages can occur. Induction machines are attractive as wind turbine generators due to their low cost, ruggedness and the need for little or no maintenance. If an induction machine is connected to even a low unbalanced voltage, its stator currents will be highly unbalanced. The unbalanced current creates unequal heating on the stator winding and torque pulsations in the generator. At a field trip to the wind plants on Buffalo Ridge (Minnesota) during the fall of 2001, the problems caused by unbalanced voltages were pointed out. A representative from Enron Wind confirmed that wind turbines without unbalanced voltage correction schemes had to be disconnected under unbalanced voltage conditions.

A double fed induction generator with converter and control is shown in Fig. 1. The main task for the back-to-back converter control is to regulate the active and the reactive power of the induction machine. The converter can thus reduce the mechanical stresses on the wind turbine and the fluctuations in the delivered power. The PWM converter connected to the power grid can also be used for other tasks, it may be controlled as a STATCOM or as an active filter to reduce unbalance in the grid voltages.

The capacitor, the PWM inverter and the transformer may also function as a STATCOM as indicated by the block in Fig. 1. Then the back-to-back inverter may be seen as a STATCOM when designing the control system for handle unbalance in the power grid. A method to measure unbalanced conditions by using a synchronous rotation frame for each phase together with symmetrical components theory is used. Lasseter and Hochgraf have developed this measurement method [1]. In this project the method is implemented in a PSCAD/EMTDC simulation of the case indicated in Fig. 1 and the resulting power flow is compared to an analytical analyses of the symmetrical components in the time domain.

Further the measurement method is used to compute the necessary current injection from the converter to maintain a balanced voltage to the asynchronous generator.

2 SYMMETRICAL COMPONENTS IN THE TIME DOMAIN
The symmetrical components are in the following text expressed in the time domain. This is done to express the power flow under unbalanced conditions analytical. By introducing the operator $a = e^{j120°} = 1/\sqrt{3}$, the sequence voltages can be written:

$$v_a(t) = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \end{bmatrix} v(t)$$

$$v_b(t) = \begin{bmatrix} 1 & a & a^2 \end{bmatrix} v(t)$$

$$v_c(t) = \begin{bmatrix} 1 & a^2 & a \end{bmatrix} v(t)$$

Eq.1

The sequence voltages can be transferred back to phase voltages as follows:

$$v_a(t) = \begin{bmatrix} 1 & 1 & 1 \end{bmatrix} v(t)$$

$$v_b(t) = \begin{bmatrix} 1 & a & a^2 \end{bmatrix} v(t)$$

$$v_c(t) = \begin{bmatrix} 1 & a^2 & a \end{bmatrix} v(t)$$

Eq.2

Fig. 1. Double Fed Asynchronous Machine Model.

Eq.1 and Eq.2 can also be used for the currents.
By using Eq.2 and the fact that each sequence component represents a symmetrical system the power flow may be computed as follows:

\[
\begin{align*}
& p(t) = i_1 v_1 + i_2 v_1 + i_3 v_1 + i_4 v_1 + \ldots \\
& = (i_1^0 + i_2^0 + i_3^0 + i_4^0) (v_1^0 + v_1^0 + v_1^0 + v_1^0) \\
& + (i_1^1 + i_2^1 + i_3^1 + i_4^1) (v_1^1 + v_1^1 + v_1^1 + v_1^1) \quad (\text{symmetrical}) \\
& = (i_1 + i_2 + i_3 + i_4) (v_1 + v_1 + v_1 + v_1) \\
& \quad \text{(symmetrical)}
\end{align*}
\]

Eq. 3

Inserting the time domain sequence components in Eq. 3 the following expression can be established:

\[
\begin{align*}
& p(t) = v_1^0 i_1^0 + v_1^0 i_2^0 + v_1^0 i_3^0 + v_1^0 i_4^0 \\
& = 3 |v| |i| \cos (\phi_0 - \phi_0) \\
& \quad \text{(symmetrical)}
\end{align*}
\]

Eq. 4

Eq. 4 shows that combining a positive-sequence voltage and a positive-sequence current will result in a constant power flow. The voltages and currents in a power system will mainly consist of positive-sequence components. This combination will then represent the majority of the power in the load. Combining a positive-sequence component and a negative-sequence component will result in a second harmonic power ripple. The combination of a zero-sequence component and a positive- or negative-sequence component will have no influence on the power flow. The combination of a zero-sequence voltage and a zero-sequence current will not exist in a case as illustrated in Fig.1. From this it can be concluded that it is not necessary to compensate for the zero-sequence components.

3 FROM AC-QUANTITIES TO DC-QUANTITIES

To eliminate the need for three phase symmetry, a single-phase synchronous frame transform is used. The single-phase synchronous frame transform was introduced in [1]. Imagine the phase voltage \(V_a\), shown in Fig.2, rotates around the origin by a speed of 60Hz. Then let the dq frame also rotate with 60Hz around its origin. The quantities \(V_{qa}\) and \(V_{da}\) are dc values and can be calculated by the angle \(\phi_a\) and the absolute value \(|V_a|\). The synchronously rotating qd-axes for phase A are shown in Fig.2 and the transform is described in the following text.

![Fig. 2. The Synchronously Rotating qd-axes for Phase A.](image)

From [1], the \(V_q^*\) is defined as:

\[
\begin{align*}
V_q^* &= |v(t)| \cdot 2 \cos(\omega t) \\
V_q^* &= |v| \sin(\omega t + \phi) \cdot 2 \cos(\omega t) \\
V_q^* &= V |\sin(2 \omega t + \phi)| \sin(\phi)
\end{align*}
\]

Eq.5

The \(V_q^*\) quantity from Eq.5 contains a dc value and a second harmonic ripple. The second harmonic ripple, \(\sin(2 \omega t + \phi)\), is filtered out from \(V_q^*\) and the dc-component which represents the q-quantity remains:

\[
V_q = |v| \sin(\phi)
\]

Eq.6

From [1], the \(V_d^*\) is defined as:

\[
\begin{align*}
V_d^* &= |v(t)| \cdot 2 \sin(\omega t) \\
V_d^* &= |v| \sin(\omega t + \phi) \cdot 2 \sin(\omega t) \\
V_d^* &= V |\cos(\phi - \cos(2 \omega t + \phi))| \cos(\omega t + \phi)
\end{align*}
\]

Eq. 7
The Vd' quantity from Eq. 7 contains a dc value and a second harmonic ripple. The second harmonic ripple, \( \cos(2\omega t + \phi) \), is filtered out as in the previous case:
\[
V_d = |V| \cos(\phi)
\]

**Eq. 8**

To transform the dq-quantities back to time domain phase quantities the definition in [1] is used:
\[
v(t) = V_q \cos(\omega t) + V_d \sin(\omega t)
\]
\[
v(t) = |V| \sin(\phi) \cos(\omega t) + |V| \cos(\phi) \sin(\omega t)
\]
\[
v(t) = |V| \left[ \frac{1}{2} \sin(\omega t + \phi) + \sin(\phi - \omega t) \right] + \frac{1}{2} \sin(\omega t + \phi) + \sin(\phi - \omega t)
\]
\[
v(t) = |V| \left[ 2 \sin(\omega t + \phi) + \sin(\phi \cos(\omega t)) - [\cos(\phi) \sin(\omega t)] \right] + \frac{1}{2} \sin(\omega t + \phi) + \sin(\phi - \omega t)
\]
\[
v(t) = |V| \sin(\omega t + \phi)
\]

**Eq. 9**

The time domains voltages and currents can be transferred to dc quantities and back to time alternating values with this transform. This transform, however, suffers from an additional delay imposed by its requirement for filtering of the large second harmonic ripple.

4 INTRODUCE THE SYNCHRONOUS FRAME TRANSFORM TO THE SYMMETRIC COMPONENTS

The synchronous frame quantities, shown in Fig.2, may be represented as a real and an imaginary value:
\[
V = V_d + jV_q
\]

**Eq. 10**

Using the synchronous frame transform on each phase voltage these may be expressed as:
\[
V^{abc} = V_d^{abc} + jV_q^{abc}
\]

**Eq. 11**

The phase voltages in Eq.1 are expressed as dq-components as shown in Eq.11. The transform from phase voltages treated as dq-quantities to sequence components represented as dq-quantities will for a three-phase system be:
\[
\begin{bmatrix}
V_{d}^\ast \\
V_{q}^\ast \\
V_{d}^b \\
V_{q}^b \\
V_{d}^c \\
V_{q}^c
\end{bmatrix} =
\begin{bmatrix}
\frac{1}{3} & 0 & -\frac{1}{6} & \frac{\sqrt{3}}{6} & -\frac{1}{6} & -\frac{1}{6} & \frac{1}{6} & 0 & \frac{1}{3} \\
\frac{1}{3} & -\frac{\sqrt{3}}{6} & -\frac{1}{6} & -\frac{1}{6} & \frac{\sqrt{3}}{6} & -\frac{1}{6} & -\frac{1}{6} & \frac{1}{6} & 0 \\
\frac{1}{3} & -\frac{1}{6} & -\frac{\sqrt{3}}{6} & -\frac{1}{6} & -\frac{1}{6} & -\frac{1}{6} & \frac{\sqrt{3}}{6} & 0 & \frac{1}{3} \\
\frac{1}{3} & -\frac{1}{6} & -\frac{1}{6} & \frac{1}{6} & \frac{1}{6} & -\frac{1}{6} & -\frac{1}{6} & \frac{1}{6} & 0 \\
\frac{1}{3} & 0 & \frac{1}{3} & 0 & \frac{1}{3} & 0 & \frac{1}{3} & 0 & \frac{1}{3}
\end{bmatrix}
\]

**Eq.12**

The symmetrical components are then represented as:
\[
V_i^{d-q} = V_d^{d-q} + jV_q^{d-q}
\]

**Eq.13**

Eq.13 is introduced in Eq.2 to transform the sequence components back to the synchronous frame quantities:
\[
\begin{bmatrix}
V_v^+ \\
V_v^- \\
V_v^0
\end{bmatrix} =
\begin{bmatrix}
1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
V_d^+ \\
V_d^- \\
V_d^0
\end{bmatrix}
\]

**Eq.14**

The alternating phase voltages and phase currents will be represented by dc quantities in sequence components by using the synchronous frame transform and the transform in Eq.12. This means that the alternating phase values will be divided into its respective positive, negative and zero system as time domain dc values. Thus the sequence voltages may be regulated by an ordinary control component such as a PI-controller.

5 SIMULATION MODELS

A power system model, similar to the illustration in Fig.3, was implemented in PSCAD/EMTDC. The phase voltages at the source can be regulated independently. An unbalanced load voltage is created by decrease the phase A voltage at the source.

Fig.3. The Power System Model Implemented in PSCAD/EMTDC.

By making the phase voltages unequal to each other at the source the symmetrical components can be treated as decoupled since the phase impedances are remained equal to each other. Then the power system shown in Fig.3 can be separated into three decoupled sequence systems. The sequence systems are illustrated in Fig.4.
The STATCOM was simulated with a pulse-width modulated converter. The switches in the converter were replaced with voltage sources. By doing this the simulation speed will be improved and the harmonic distortion from the switches are cancelled. The converter model is designed to respond on the capacitor voltage and thus maintain its dynamic behaviour. An illustration of the converter model is shown in Fig.5.

From [2] the duty-ratio, \( d \), of the converter legs is defined as the ratio of the pulse width to the switching time period \( T_s \).

\[
d = \frac{1}{2} + \frac{1}{2} \frac{v_c}{V_{tri}} \quad (0 \leq d \leq 1)
\]

Eq.15

Where the \( v_c \) is the control signal and \( V_{tri} \) is the amplitude of the triangular signal. The control voltage continuously varies with time, but much more slowly compared to the switching frequency waveform of \( v_{in} \). Therefore, the duty ratio in Eq.15 can be treated as continuous function of time and the phase voltage, without the disturbance from the switches, can be calculated by:

\[
\nu_{AN}(t) = d_A(t)v_d(t)
\]

\[
\nu_{BN}(t) = d_B(t)v_d(t)
\]

\[
\nu_{CN}(t) = d_C(t)v_d(t)
\]

Eq.16

Where the duty ratios are given from the control system and the capacitor voltage \( v_d(t) \) is taken from the simulation result. The capacitor current can be found by:

\[
\dot{i}_d(t) = d_A(t)\dot{i}_A(t) + d_B(t)\dot{i}_B(t) + d_C(t)\dot{i}_C(t)
\]

Eq.17

The duty ratios are given by the control system and the phase currents are taken from the simulation results. Then the dynamic behavior of the converter’s dc and ac terminals is maintained and a control system for these dynamics is build.

### 6 CONTROL SYSTEM

To find the dynamical behaviour of the negative-sequence voltage system a regulation system, as illustrated in Fig.6, was implemented in PSCAD/EMTDC.

![Fig.6. STATCOM Negative-Sequence Voltage Regulation.](image)

Since it is not easy to determine the response of the power system analytically this investigation was done by simulations in PSCAD/EMTDC. A power system model as illustrated in Fig.3 is used in these simulations. The converter in the STATCOM is modelled with a dc source instead of a capacitor. This is done to maintain the dc voltage at its operating point.

The first step was to determine how the negative-sequence system responds on the injected compensating current with different levels of negative-sequence voltage. To create a negative-sequence load voltage the phase A source voltage was decreased below the phase B and phase C voltages. Then a negative-sequence current was injected from the STATCOM to compensate for the unbalanced load voltage. The current was created by increase the negative-sequence voltage from the STATCOM. An illustration of the regulator system is shown in Fig.6. When the negative-sequence load voltage is decreased to 70% under the negative-sequence source voltage the voltages and currents in the power system begins to oscillate. Thus, the negative-sequence load voltage was decreased to 70% under the negative-sequence source voltage the voltages and currents in the power system begins to oscillate. Thus, the negative-sequence load voltage was decreased to 70% under the negative-sequence source voltage. The data form the test is illustrated in Fig.7. This figure shows that the system have a linearly respond to the injected negative-sequence current. This means that a control system designed for one degree of
unbalanced voltage will be valid for all degrees of unbalanced voltage.

Fig.7. The Compensation Current as a Function of the Negative-Sequence Source Voltage

The negative-sequence voltage control loop is shown in Fig.8. The measured negative-sequence voltage is compared to the negative-sequence reference voltage, and then the resulting error is feed into a proportional controller. The ordered negative-sequence voltage to the STATCOM is given from the P-controller. This negative-sequence voltage is transferred together with the other sequence-voltages, which is not controlled, to the ordered dq-voltages. The dq-voltages are transferred to phase voltages and fed into the STATCOM model. The STATCOM model will give out the ordered phase voltages to the power system. The responding load voltage are measured and transferred to sequence voltages.

Fig.8. Illustration of the Negative-Sequence Voltage Control Loop.

The control parameters was found by the bode diagram of the open loop frequency respond of the negative-sequence voltage control system. The open loop frequency response was found experimentally by inject sinus shaped permutations and compare these with the load voltage respond. The permutation signals were injected by the $V_{\text{injected}}$ shown in Fig.6. If the amplitude of the injected permutations is to small the noise will dominate the respond signal. If the amplitude is chosen to large the system may go out of the operation region where the response is linear. The amplitude of the permutation signal has to be a value where these to restrictions are taken in consideration.

The injected signal:

$$v_{\text{injected}}(t) = V_i \sin(\omega_i t) = \Delta V_i(t)$$

Eq 18

Where $V_i$ is the amplitude of the permutation and $\omega_i$ is the permutation frequency.

The respond signal in steady state:

$$\Delta V_{\text{measured}}(t) = V_m \sin(\omega_m t + \phi_m)$$

Eq 19

Where $V_m$ is the amplitude of the respond signal and $\phi_m$ is the phase shift of the respond signal. The frequencies $\omega_i$ and $\omega_m$ are equal.

The amplitude gain and phase shift was found for each permutation signal. The gain and phase shift was plotted in a bode diagram as shown in Fig.9. It can be established, from the bode plot, that the amplitude gain is almost constant to the signal reach 10Hz. After 10Hz the gain will begin to decrease. When the permutation is in the 60Hz area the positive sequence voltage will begin to oscillate with the negative-sequence current. The response between the negative and positive system causes the increasing gain in the 60Hz area. This means that the positive and negative system cannot be treated as decoupled systems in the 60Hz area. Thus operating in this area should be avoided. After the 60Hz area the gain will continue to decrease to it reach the 120Hz area. In this area the permutation signal have the same frequency as the noise from the dq-transformation. This causes the disturbance seen in the gain and phase shift plots at 120Hz.
The bandwidth of the controller is chosen to 10Hz. The respond time will be relatively slow with this bandwidth. Avoiding the control system to operate in the 60Hz and 120Hz area is the advantage by choosing a small bandwidth like this. By using a proportional controller the gain respond can be increased. Choosing $K_P = 3.7 \text{dB}$ the gain at 10Hz will be 0dB. From the phase shift plot it can be seen that the phase shift margin is very good at 10Hz. A P-controller will produce a steady state error. As explained the power system will be unstable if the negative-sequence voltage is decreased to zero. The steady state error produced by the P-controller will avoid the negative-sequence voltage to reach zero.

The same method as explained in the previous text was used to find the parameters in the dc-bus voltage controllers. The control system for the dc-bus voltage is shown in Fig.10.

The dc-bus reference voltage is compared to the actual dc-bus voltage, the error is fed into a P-controller. The $P_{\text{ref}}$ is given from the P-controller. $P_{\text{ref}}$ is compared to the actual power flowing in the STATCOM. The error is fed into a lead-lag controller. The ordered phase shift in the positive-sequence voltage is given from the lead-lag controller. The actual power flow in the STATCOM is computed by Eq.4. The only combinations of sequence voltages and currents that gives an average power flow is $P^+$, $P^-$ and $P^{00}$. Since the positive-sequence voltage is much larger than the negative and zero-sequence voltages only the contribution from the positive-sequence voltage and positive-sequence current is taken into account.

The design of the dc-bus voltage control system is not straightforward. The operation point off the control system was assumed to be the reference voltage of the dc-bus. Since this control system is not linear the controllers will not function as they should if the dc-bus voltage is too far away from its operating point. This can be avoided by increase the capacitor. Then the ripple in the dc-bus voltage will be decreased. An alternative is to design a control system that regulates the duty-ratio to maintain constant output voltages from the converter when the dc-bus voltage varies. When the output voltage is remained constant the fluctuations in the power flow into the converter $P^+$ will be reduced. In this project it was chosen a relatively large capacitor. An illustration of the control system used in the EMTDC/PSCAD simulations is shown in Fig.11.

In Fig.12 the negative-sequence components, at $t_1$ (without compensating) and $t_2$ (with compensating), are illustrated as vector components. As seen from the figure the line current is relatively small at $t_1$, when injecting a large current from the STATCOM, at $t_2$, the line current will be dominated by the STATCOM current. The impedance between the converter and the power system is almost inductive, due to this the injected current will be nearly $90^\circ$ shifted to the load voltage. The line current, which is dominated
by the STATCOM current, will then lay almost 90° after the source voltage. The line impedance is almost purely inductive and then the line voltage will lay 90° after the negative-sequence line current. The source voltage will be the same at t₁ and t₂, thus the load voltage has to change when the line voltage changes. Since the line current is almost perpendicular to the source voltage the negative-sequence line voltage will lay parallel to the source voltage. Thus the negative-sequence load voltage will decrease in amplitude and be parallel to the source voltage. The voltage drop over the line impedance will increase if the line impedance increases. Then the needed compensation current from the STATCOM to decrease the negative-sequence load voltage will be less. This means that the needed STATCOM current to decrease the negative-sequence load voltage depends on the line impedance.

In Fig.13 are some simulations result shown. The power flowing into the load is plotted in the 1st graph. The power ripple will not be totally damped because the power system will begin to oscillate if the negative-sequence voltage is driven to near zero. From the 2nd graph it can be seen that the power flowing into the STATCOM will mainly consist of a second harmonic oscillation. The average power flow will be small and will only compensate for the losses in the STATCOM. The 3rd graph shows the positive-voltage component over the load. With unbalanced voltage compensating the positive-sequence voltage will drop less than without unbalanced voltage compensation. In the 4th graph the negative-sequence voltage over the load is plotted. These voltage components contain some ripple. This noise is mainly caused by the synchronous frame transform. The negative-sequence load voltage will be almost zero with compensation. Without compensation there will be a large negative-sequence load voltage. From the 5th graph it can be seen that the dc-bus voltage will have a second harmonic ripple. The capacitor current shown in the 6th graph causes this ripple. The current will have an average value near zero. The small average value of the current will compensate for the losses in the capacitor.

**Fig.12. The Negative-Sequence Components Before and After Injecting a Negative-Sequence current Into the Power System.**

**Fig.13. Simulation Results Whit and Without Unbalanced Voltage Compensation.**

**REFERENCES**

