Power Converters for Grid Integration of Wind Power Systems

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Abstract:
This paper presents the different power converters for grid integration of wind power systems. In wind power systems while integrating with grid, power quality issues are becoming more predominant. This can solve by using power electronics converters like two level back to back converter and matrix converters. Converters are compared on the basis of efficiencies, voltage conversion ratios and THDs.

Key words: Wind energy systems, power quality, two level back to back converter, three level and matrix converter.

1. Introduction
World Market for Wind Turbines sets a new record of 42 GW of new capacity in 2011, worldwide total capacity at 239 GW enough to cover 3% of the world’s electricity demand. Renewable delivered close to 20% of global electricity supply in 2010 and by early 2011 they comprised one quarter of global power capacity from all the sources. In several countries renewable represent a rapidly growing share of total energy supply. India added an estimated 2.7GW of grid connected renewables during 2010 mainly from wind but also from biomass, small hydropower and solar capacity for a total of nearly 19GW by January2011. Direct driven turbine designs captured 18% of the global market. The increasing share of wind in power generation will change considerably the dynamic behaviour of the power system and may lead to a new strategy for power system frequency regulation in order to avoid degradation of frequency quality. Hence, network operators have to ensure that power quality is not compromised at consumer end. New technical challenges emerge due to increased wind power penetration, dynamic stability and power quality. Power electronic converters have been developed for integrating wind power with the electrical grid. The use of power electronic converters allows for variable speed operation of the wind turbine and enhancement in power extraction. In variable speed operation, sophisticated control methods require extracting maximum power from the turbine and providing constant voltage and frequency to the grid is required. In India out of installed capacity only 15% wind turbines are connected to the grid through power electronics converters. There is a ample scope in India for the use of power converters in wind power systems. During recent years different converter topologies have been investigated as to whether they can be applied in wind turbines such as Back-to-back, Multilevel, Tandem, Matrix, Resonant Converters. This paper is concerned of a wind energy system with different topologies for the power converters, mainly a two-level converter, three level and matrix converter providing constant voltage and frequency to the grid. Grid quality characteristics and limit values in accordance with DIN EN 50 160 and the VDEW give directives for in-plant generation. Converters are compared on the basis of efficiencies, voltage conversion ratios and THDs. Fig. 1 shows different converter applied in wind power systems.

2. Turbine and Electric Machine
The mechanical power of the turbine is given by:

\[ P_m = \frac{1}{2} \rho A u^3 c_p \]

(1)

where \( P_m \) is the power extracted from the airflow, \( \rho \) is the air density, \( A \) is the area covered by the rotor, \( u \) is the wind speed upstream of the rotor, and \( c_p \) is the performance coefficient or power coefficient. The power coefficient is a function of the pitch angle of rotor blades \( \theta \) and of the tip speed ratio \( \lambda \), which is the ratio between blade tip speed and wind speed upstream of the rotor. The computation of the power coefficient requires the use of blade element theory and the knowledge of blade geometry. We consider the blade geometry using the numerical approximation developed in...
assuming that the power coefficient is given by:

\[ C_p = 0.73 \lambda_e \frac{\lambda_i}{\lambda_{ii}} e^{-18.4} \]  

where \( \lambda_e \) and \( \lambda_{ii} \) are respectively given by:

\[ \lambda_e = \frac{151}{\lambda_{ii}} - 0.58 \theta - 0.002 \theta^2 + 13.2 \]  

\[ \lambda_{ii} = \frac{1}{(\lambda - 0.02 \theta)} \frac{0.003}{(\theta^2 + 1)} \]  

The maximum power coefficient is given for a null pitch angle and is equal to:

\[ C_{p,\text{max}} = 0.4412 \]  

where the optimum tip speed ratio is equal to

\[ \lambda_{opt} = 7.057 \]  

The power coefficient is illustrated in Figure 1 as a function of the tip speed ratio.

![Fig. 1. Power coefficient curves versus tip speed ratio](image)

\[ P_e = \begin{bmatrix} u_d & u_q & u_f \end{bmatrix} \begin{bmatrix} i_d & i_q & i_f \end{bmatrix}^T \]  

where \( i_f \) is the equivalent rotor current, \( M \) is the mutual inductance, \( p \) is the number of pairs of poles; and where in \( d \)- \( q \) axes \( i_d \) and \( i_q \) are the stator currents, \( L_d \) and \( L_q \) are the stator inductances, \( R_d \) and \( R_q \) are the stator resistances, \( u_d \) and \( u_q \) are the stator voltages. A unity power factor is imposed to the electric machine, implying a null \( Q_e \). The electric power \( P_e \) is given by:

The output power injected in the electric network characterized by \( P \) and \( Q \) in \( \alpha-\beta \) axes is given by:

\[ S = \left( P^2 + Q^2 + H^2 \right)^{1/2} \]  

where \( H \) is the harmonic power.

### 3. Two-Level and Three Level Converters

The two-level converter is an AC/DC/AC converter, with six unidirectional commanded IGBT’s SiC, used as a rectifier, and with the same number of IGBT’s, used as an inverter. The rectifier is connected between an electric machine and a capacity bank. The inverter is connected between this capacity bank and a filter, which in turn is connected to an electric network. A three-phase symmetrical circuit in series models the electric network. The configuration of the system that will be simulated is shown in Figure 3.
The groups of two IGBT’s linked to the same phase constitute a leg \( k \) of the converter. For the two-level converter modelling we assumed that: 1) The IGBT’s are ideal and unidirectional, and they will never be subject to inverse voltages, being this situation guaranteed by the arrangement of connection in anti parallel diodes; 2) The diodes are ideal: in conduction it is null the voltage between its terminals and in blockade it is null the current that passes through it; 3) The continuous voltage in the exit of the rectifier should always be \( v_{dc} > 0 \); 4) Each leg \( k \) of the converter should always have one IGBT in conduction. For the switching function of each IGBT, the switching variable \( \gamma_k \) is used to identify the state of the IGBT \( i \) in the leg \( k \) of the converter. The index \( i \) with \( i \in \{1,2\} \) identifies the IGBT. The index \( k \) with \( k \in \{1,2,3\} \) identifies the leg for the rectifier and \( k \in \{4,5,6\} \) identifies the leg for the inverter. The two valid conditions for the switching variable of each leg \( k \) are as follows:

\[
\gamma_k = \begin{cases} 
1, & S_{ik} = 1 \\
0, & S_{ik} = 1
\end{cases} \quad \text{for } i \in \{1,2\} \text{ and } k \in \{1,\ldots,6\} \quad (14)
\]

The topological restriction for the leg \( k \) is given by

\[
\sum_{i=1}^{2} S_{ik} = 1 \quad k \in \{1,\ldots,6\} \quad (15)
\]

Hence, each switching variable depends on the conduction and blockade states of the IGBT’s. The phase currents injected in the electric network are modelled by the state equation:

\[
\frac{di_k}{dt} = \frac{1}{(L_c + L_f)} (u_{ik} - R_i i_k - u_{ik}) \quad k \in \{4,5,6\} \quad (16)
\]

The output continuous voltage of the rectifier is modelled by the state equation:

\[
\frac{dv_{dc}}{dt} = \frac{1}{C} \left( \sum_{i=1}^{3} \gamma_k i_k - \sum_{k=4}^{6} \gamma_k i_k \right) \quad (17)
\]

Hence, (14) to (17) model the two-level converter.
conduction in order to achieve continuity in the voltage between the phases [10]. The configuration of the system that will be simulated is shown in Figure 2. The IGBT’s commands \( S_{ij} \) are given in function of the on and off states as follows:

\[
S_{ij} = \begin{cases}
1, & (\text{on}) \\
0, & (\text{off})
\end{cases} \quad i, j \in \{1, 2, 3\} \tag{18}
\]

The vector of output phase voltages is related to the command matrix, as follows:

\[
\begin{bmatrix}
v_A \\
v_B \\
v_c
\end{bmatrix} =
\begin{bmatrix}
S_{11} & S_{12} & S_{13} \\
S_{21} & S_{22} & S_{23} \\
S_{31} & S_{32} & S_{33}
\end{bmatrix}
\begin{bmatrix}
v_a \\
v_b \\
v_c
\end{bmatrix}
= [S] \begin{bmatrix}
v_a \\
v_b \\
v_c
\end{bmatrix} \tag{20}
\]

The vector of input phase currents is related to the vector of output phase currents through the command matrix, as follows:

\[
\begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix} =
\begin{bmatrix}
S_{11} & S_{12} & S_{13} \\
S_{21} & S_{22} & S_{23} \\
S_{31} & S_{32} & S_{33}
\end{bmatrix}
\begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix} \tag{21}
\]

Hence, (18) to (21) model the matrix converter.

Matrix converters do not require intermediate energy storage and have lower switching losses. Although the matrix converter has six additional switching devices, compared to the back-to-back, two-level, DC-link converter, the absence of the DC-link capacitor may increase the efficiency of the converter. Also, the power semiconductor devices in the matrix converter are switched at average voltages lower than those in the two-level, DC-link converter. The major disadvantage of the matrix converter is the limitation of the voltage

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4. Matrix Converter

The matrix converter is an AC/AC converter, with nine bidirectional commanded IGBT’s \( S_{ij} \). It is connected between the electric machine and a second order filter, which in turn is connected to an electric network. The second order filter is an inductive load that avoids the interruption of the output currents. A three-phase active symmetrical circuit in series models the electric network. For the matrix converter modelling we assumed that:

1) the diodes are ideal: in conduction it is null the voltage between its terminals, and in blockade it is null the current that passes through it; 2) the elements of the command matrix of the converter are bidirectional switches in voltage and current; 3) the command variables \( S_{ij} \) for each \( i \) has for one \( j \) the value one, i.e. only one switch is in conduction in order to achieve continuity in the current in each phase; 4) the command variables \( S_{ij} \) for each \( j \) has for one \( i \) the value one, i.e. only one switch is in conduction.
gain ratio, which leads to poor semiconductor device utilization. Another drawback is the large number of semiconductor devices required to make the matrix converter functional. Although devices with smaller current rating can be employed, they still lead to a large number of gate driver circuits. In addition, with the absence of the DC-link, there is no decoupling between the input and output sides. Any distortion in the input voltage is reflected in the output voltage at different frequencies; as a consequence, sub harmonics can be generated. Many soft-switching techniques have been proposed to improve the efficiency of the matrix converter.

5. Conclusion
The increased wind power penetration in power systems networks leads to new technical challenges, implying research towards more realistic and physical models for wind energy systems. This paper presents a more realistic modelling of generator, power electronics converter used in wind power systems. Mainly three power converter topologies integrating wind power with the electrical grid: two-level, three level and matrix converters are discussed in depth with its ample scope in wind energy sector in India. Technical comparison between the two level, three level and matrix converter are also given.

References: