Power Electronics in Modern Wind Turbines

Mini-Project 12b in TET4190 Power Electronics for Renewable Energy

Group G & U: Ida L. Loen, Andrea Sætre, Krishna Raju Vulchi
Contact person: Jarle Eek, Statkraft
11/2/2012
Abstract

This report is a result of a project in the subject TET4190 – Power Electronics for Renewable Energy, concerning power electronics in modern wind turbines.

Converters are used in wind energy systems for several reasons. Converters used today are power electronic devices, and as technology develops and the cost drops, the importance of power electronic devices in wind turbine systems increases rapidly. Power converters are used in variable-speed wind turbines, in generator starters and in isolated networks.

When applying power electronic converters to wind turbines, most manufactures have chosen a solution based on the two-level voltage source converter, combined with a doubly fed induction generator. This topology consists of two power converters, connected by an energy storage element.

An alternative to the conventional converters is the matrix converter. The matrix converter might become a competitive alternative to the conventional back-to-back voltage source converter. The matrix converter preforms a direct AC to AC conversion, by which the large energy storage element of conventional converters is avoided. Due to the lack of energy storing element, it is expected to have a more compact design.

The report highlights advantages and drawbacks of the matrix converter compared to the more conventional back-to-back voltage source converter. In spite of some advantages the matrix converter is still not widely used in practice. It still requires more investigation and optimization, to gain a significant share in industry applications.
# Table of Contents

1.0 Introduction........................................................................................................... 3

2.0 Wind power............................................................................................................. 3

  2.1 Current Technologies .......................................................................................... 3

  2.2 Variable-speed wind turbines ............................................................................ 3

3.0 Power Electronics .................................................................................................. 4

  3.1 Synchronous generator ...................................................................................... 5

  3.2 Induction generator ............................................................................................ 6

    3.2.1 Squirrel cage induction generator ............................................................... 6

    3.2.2 Wound rotor induction generator ............................................................... 6

4.0 Development trends .............................................................................................. 7

5.0 Doubly-fed back-to-back two level voltage source converter ............................... 7

  5.1 General Configuration ....................................................................................... 7

    5.1.1 Power flow .................................................................................................. 8

  5.2 Principle of Operation ....................................................................................... 9

    5.2.1 Rectifier operation ..................................................................................... 10

    5.2.2 DC-link ..................................................................................................... 10

    5.2.3 Inverter operation ...................................................................................... 10

      5.2.3.1 PWM (switching) ............................................................................... 11

  5.3 Two-level vs. Three-level inverter ..................................................................... 12

  5.4 Main Advantages ............................................................................................ 13

  5.5 Main Drawbacks .............................................................................................. 13

6.0 Matrix Converter ................................................................................................. 13

  6.1 Principle of Operation ....................................................................................... 14

  6.2 Performance Analysis ..................................................................................... 15

    6.2.1 Output Voltage ......................................................................................... 15

    6.2.2 Input Current ............................................................................................ 16

    6.2.3 Input Power Factor ..................................................................................... 17

  6.3 Control Technology ......................................................................................... 18

  6.4 Commutation and Protection ........................................................................... 18

  6.5 Main Advantages ............................................................................................ 19

  6.6 Main Drawbacks .............................................................................................. 19

7.0 Converter Comparison ........................................................................................ 19

  7.1 Component Count ............................................................................................ 19

  7.2 Efficiency .......................................................................................................... 20

  7.3 Switch Utilization ............................................................................................. 20

  7.4 Output Voltage Waveforms ............................................................................. 21

  7.5 Converter Losses ............................................................................................. 22

8.0 Conclusions ......................................................................................................... 23

9.0 References ........................................................................................................... 24
1.0 Introduction

During the energy crisis in the 1970’s the oil became very expensive. This motivated the research of alternative energy sources. Later, the energy crisis was resolved and oil prices declined, yet the leaps in the innovation of wind power remained. Wind power has been around ever since humans put sails into the wind, and for more than millennia, windmills have pumped water and ground grain. However, the technology was greatly improved as a result of the oil crisis. More recently, following the issue of climate change, there is again a growing interest worldwide for renewable energy. Wind power is a relatively well-explored technology, and can compete with other energy sources on several aspects. Wind is one of the most environmental friendly sources of large-scale power production available today.

As the report is a result of a project in the subject TET4190 – Power Electronics for Renewable Energy, it focuses mainly on the power electronics used in wind power technologies. Most wind turbines today use power electronic converters for several reasons. The main interest in this report is to give an overview of the converters used in commercially available wind turbines. And to benchmark the major benefits and drawbacks with the use of the less known matrix converter compared to the conventional converters.

2.0 Wind power

2.1 Current Technologies

The most commonly used turbine today is called “the Danish turbine”. This is a horizontal axis turbine with three blades, which takes advantage of a lifting force over the blades. The current commercial wind turbines often have a rotating diameter of more than 80m, held at an even higher elevation by a tall tower. Such commercial wind turbines are usually grouped in wind farms outside residential or commercial areas, and connected to the power grid.

2.2 Variable-speed wind turbines

The main advantage of a constant speed wind turbine is the possibility to use a simple and safe generator. For small turbines this might still be profitable, but for greater turbines and wind parks, variable-speed wind turbines are convenient for several reasons. For wind speeds below the rated speed, a greater amount of energy can be extracted if the tip speed is kept constant. This can only be obtained if the rotor speed varies with the wind speed. Variable speed operation can also reduce the stresses and tearing on the turbine components. The challenge related to wind turbines at variable speed, is to generate AC electricity at constant frequency. Variable speed operation of the turbine is possible either with synchronous generators or induction generators.
3.0 Power Electronics

Converters are used in wind energy systems for several reasons. Converters used today are power electronic devices, and as technology develops and the cost drops, the importance of power electronic devices in wind turbine systems increases rapidly. Power converters are used in variable-speed wind turbines, in generator starters and in isolated networks.

Converters are necessary to allow variable-speed operation of wind turbines. When applying power electronic converters to wind turbines, most manufactures have chosen a solution based on the two-level voltage source inverter [1]. This converter is used to rectify and thereafter invert the voltage to a desired grid frequency.

The two most common types of generators encountered in wind turbines, are induction (asynchronous) generators and synchronous generators. For some smaller turbines, also DC generators have been used. The different topologies are described below and shown in figure1.
### 3.1 Synchronous generator

To use a synchronous generator in a variable-speed wind turbine, the generator output first needs to be rectified to DC, and then converted back to AC, as shown in the second column in figure 1. In this case a full-scale converter is needed to synchronize the frequency with the grid frequency, as the output frequency is a direct function of the generator and its number of poles.

For the synchronous generator, the full-scale grid connection via DC link is the most commonly used alternative. This is possible either by using a synchronous machine whose field is separately excited, or one whose field is provided by permanent magnets. Normally
the arrangement exists of a gearbox, generator, rectifier, DC-link, inverter and grid. In some cases where a multiple poles synchronous generator is used, the number of poles is sufficient to connect the generator directly to the main shaft, and no gearbox is needed.

3.2 Induction generator

Induction machines are now the most commonly used generator in wind turbines. This kind of machine is normally preferred because it is simple, has a rugged construction, is relatively inexpensive, and is quite simple to connect and disconnect to the grid.

There are mainly two types of induction machines. The most common type is called squirrel cage machine. This machine has no windings on the rotor, but conducting bars in a laminated core. The other type has windings on the rotor, in addition to the stator windings, and is called wound rotor machine. Even though they are more expensive and less rugged than squirrel cage machines, wound rotor machines are often used in wind turbines with variable speed. The main advantage with this type of machine is that power may be sent to or taken from rotor as well as stator.

3.2.1 Squirrel cage induction generator

The use of a squirrel cage induction generator in a variable-speed wind turbine is conceptually more complicated than the use of a synchronous machine. As it requires a source of reactive power, it needs to be supplied by a power electronic converter. This converter is expensive, and increases the total losses in the system. For high power wind turbines, over 2MW, a squirrel cage induction machine with full-scale grid connection via DC-link might be a good alternative.

3.2.2 Wound rotor induction generator

As mentioned the difference between the wound rotor induction machine and the squirrel cage induction generator, is the rotor. In contrast to the squirrel cage machine the wound rotor machine has windings on the rotor as well as the stator. The main advantage with this generator is that all the power does not have to go through the converter, which makes it possible to have variable-speed operation where the power converters can be of 1/3 of the capacity, compared to the case where all the power goes through the converter[9]. This type of generator is also compact and quite rugged, and it is less expensive than the synchronous machine. The wound rotor generator is the most common generator in variable-speed wind turbine systems today.

There are mainly three possible wind turbine systems, based on the doubly-fed induction generator and the two level voltage source converter. The three systems are shown in figure 2. It is possible to use unidirectional converters in the system, but a higher efficiency is achieved by use of bidirectional converters. In figure 2a and 2b, a diode rectifier is used. This makes the system unable to generate power either over or under synchronous speed. The system in fig 2c is bidirectional and the only alternative which allows power generation both over and under synchronous speed. This is called the back-to-back two-level voltage source topology and can also provide reactive power control, and harmonic compensation [1]. This topology has since early nineties been used in most variable-speed wind turbines.
4.0 Development trends

The most common converter and topology in wind turbine systems today, is a wound rotor induction machine with a bi-directional power converter, where two two-level voltage source converters are coupled back-to-back. With this converter, called doubly fed back-to-back two-level voltage source converter, both active and reactive power can be controlled in both directions.

While the doubly fed induction generator uses a partially scaled converter, other topologies use a full-scaled power converter where the converter processes the full power of the system. Full-scale converters are typically used for wind turbines with higher power ratings (>2MW) and with squirrel cage induction generators or synchronous generators.

As most wind turbines today are of size around 2MW or smaller, the most common topology today is the doubly-fed induction generator with back-to-back converter. The development shows a greater focus on offshore wind turbines, which are bigger and deliver higher power. For these turbines the squirrel cage induction machine with full-scale grid connection via DC-link, might be a better choice.

5.0 Doubly-fed back-to-back two level voltage source converter

The two level voltage source converter is the most widely used power processing converter for three phase motor drive applications. The converter matured during more than a decade in the drives industry, and was adopted by the wind turbine industry for use in large-scale wind turbines in the late nineties [1][6].

Since the back-to-back two-level voltage source converter seems to be the preferred converter topology in wind turbine applications, this chapter will explain the main operating principles and establish a foundation to compare the back-to-back two-level voltage source converter against the matrix converter.

5.1 General Configuration

Although uni-directional power converters with diode rectifiers are operational, the most efficient operation is achieved by use of a bi-directional power converter. The back-to-back converter topology is shown in figure 3.
According to the operational principles of the wound rotor induction generator, a generator with a unidirectional converter can only operate either above or below synchronous speed. In these cases power can only travel to the rotor or from the rotor, deciding its operational speed. The back-to-back converter system is able to generate power both above and below synchronous speed. The configuration is often called “doubly fed induction generator” (DFIG), which emphasizes the ability to transfer power into or out of the rotor, as well as out of the stator.

The back-to-back converter is connected between the rotor of the DFIG and the three winding transformer (to the grid), while the stator is connected directly to the transformer and then to grid. In this topology, the power converter is partially scaled requiring a rated power of about 30% of the overall generated power [6]. Advantages of using the partially scaled converters are that they are smaller and less expensive than the full-scale converters.

5.1.1 Power flow

An important property of the back-to-back converter is fast control of the power flow. The aim for the grid side converter and the rotor side converter is to achieve a voltage that satisfies the current demand on the generator and grid side. By controlling the power flow to the grid, the DC-link voltage can be held constant. The rotor-side converter is usually controlled to have an optimal power extraction from the wind and a specified reactive power at the generator terminal. Assuming that the converters are lossless, the net power injected by the generator to the grid is:

\[ P_{\text{gen}} = P_s - P_r \]
\[ Q_{\text{gen}} = Q_s \]
Where $P_s$ and $Q_s$ are the active and reactive power going out of the stator. $P_r$ is the active power injected by the rotor-side converter to the rotor circuit [6].

![DFIG Diagram](attachment:image.png)

**Figure 4: Active power flows in the doubly fed induction generator [6]**

### 5.2 Principle of Operation

The back-to-back two level voltage source converter consists of two PWM power converters sharing a common DC link. The topology is shown in figure 5. These power converters are both bi-directional. In super-synchronous operation, the rotor-side converter operates as an inverter and the grid-side converter operates as a rectifier. In sub-synchronous operation the rotor power changes direction. This allows the system to track the optimum tip speed in a larger speed range than the two other systems, which were uni-directional. With this arrangement it is possible to obtain a variation of the speed of the induction machine from approximately 50% below synchronous speed to 50% above [9]. The back-to-back system is also able to provide reactive power control and harmonic compensation both by the grid-side converter and the rotor-side converter [1].

![Back-to-back Topology](attachment:image.png)

**Figure 5: The back-to-back two-level voltage source converter topology [1]**

The use of a doubly fed induction generator with a power converter connected to the rotor allows recovery of the slip power. The power coming from the rotor is AC, but its frequency
is that of the slip multiplied by the line frequency. Accordingly, the slip power cannot be directly fed into the grid. The slip power is made useful by first rectifying it to DC and then inverting the DC to grid frequency AC power [9].

The two converters of the back-to-back two level converter are operated individually and the only difference between the rectifier and inverter is the definition of the power sign. We can therefore explain the operating principles by inspection of only one of the converters.

5.2.1 Rectifier operation

A rectifier is an electrical device that converts alternating current (AC), which periodically reverses direction, to direct current (DC), which flows in only one direction. This simple rectification process produces a type of DC characterized by pulsating voltages and currents (although still unidirectional). Depending on the type of end-use, this type of DC current may be further modified into a relatively constant voltage DC.

Rectifier operation in the back-to-back converter is three-phase, six-pulse, full-wave rectification. A full-wave rectifier converts the whole of the input waveform to one of constant polarity at its output. Six-pulse refers to the number of DC “pulses” for every 360° of electrical rotation, in other words a complete period.

5.2.2 DC-link

The current flow between a rectifier and an inverter is realized by a DC link. The DC link consists of an energy storage element, which, in a voltage source converter, is a capacitor which smoothes out the converter’s DC output ripple and provides a stiff input to the inverter. The capacitor and the load resistance have a typical time constant $\tau = RC$, which equals the time it takes for the capacitor to discharge to 37% of its initial voltage. As long as the time constant is much longer than the time of one ripple cycle, a smoothed DC voltage will be produced. Due to the capacitor, the grid is to a large extent decoupled from the generator. This is beneficial for control purposes, also in case of faults.

5.2.3 Inverter operation

The DC voltage is converted to quasi-sinusoidal (a sinusoid with a slowly changing amplitude envelope, relative to the rate of change of phase of the sinusoid) AC voltage output using the inverter’s active switching elements. Insulated-gate bipolar transistors (IGBT) dominate as the inverter switching device. The inverters have diodes across them to take the reactive current and any regenerative energy.

The converter has three output ports, which can be clamped to either the positive (upper) DC-link bus or the negative (lower) DC-link bus, depending on which switch is turned on. The output of the inverter can achieve eight different possible switch combinations. By controlling the switches, known as modulation, the voltage source inverter can synthesize the desired output voltage.
5.2.3.1 PWM (switching)

Sinusoidal pulse-width modulation (PWM) is the most straightforward method used to vary inverters output voltage and frequency. The average value of voltage fed to the load is controlled by turning the switch between supply and load on and off at a fast pace. The duty cycle describes the portion of “on” time to the regular period, and the higher the duty cycle, the higher the power delivered to the load. Switching must be done fast enough as not to disturb the load, typically tens of kHz for a motor drive. Even though the output waveform is composed discrete values with fast transition, the fundamental component of the output behaves sinusoidal. The main advantage of PWM is that power loss in the switching devices is very low (practically no current during off-mode and hardly any voltage drop during on-mode). With a sufficiently high switching frequency and, when necessary, using additional passive electronic filters, the output waveform can be smoothed.

In order to produce a sinusoidal output voltage waveform at a desired frequency, three sinusoidal control signals that are $120^\circ$ shifted are compared with a triangular waveform, as shown in figure 6. It should be noted that an identical amount of average dc component is present in the output voltages of $v_{AN}$ and $v_{BN}$, which are measured with respect to the negative dc bus. In the inverter, the switches are controlled based on the comparison of $v_{control}$ and $v_{tri}$, and the following output voltage results.
5.3 Two-level vs. Three-level inverter

With a 3-level inverter the output voltage waveform is produced by using pulse-width modulation with three voltage levels rather than two. This causes the output voltage and current to be less distorted and have a lower THD (total harmonic distortion) compared to the 2-level inverter. Figure 7 is unfortunately unclear, but it is very apparent that the
harmonics decrease for the 3-level inverter.

Figure 7: Comparison of the 2-level and 3-level inverter output voltages and currents[4]

5.4 Main Advantages

The main advantages of a back-to-back voltage source converter are:

- Allows variable speed operation, which allows the power extraction from the wind to be optimized and can limit the power in case of high wind speeds. [6]
- Smaller & less expensive converters than full-scale converter topologies.
- Can transfer both active and reactive power in both directions. Can regulate reactive power exchanged between the wind turbine and the grid.
- Does not need neither a soft-starter nor a reactive power compensator.
- Generator is decoupled from grid by the DC link.

5.5 Main Drawbacks

The main drawbacks of a back-to-back voltage source converter are:

- Wound rotor is less rugged than squirrel cage induction generator.

6.0 Matrix Converter

The matrix converter might become a competitive alternative to the conventional back-to-back voltage source converter. An advantage of the matrix converter is the direct AC to AC conversion, by which the large energy storage element of conventional converters is
avoided. Due to the lack of energy storing element, the efficiency is expected to be higher and the design more compact.

Whether or not the matrix converter is competitive to the two-level back-to-back voltage source converter with regards to efficiency especially when considered in the specific application of a wind turbine based on the doubly-fed induction generator, will be investigated. The matrix converter has several advantages over traditional rectifier-inverter type power frequency converters. It provides sinusoidal input and output waveforms, with minimal higher order harmonics and no sub harmonics; it has inherent bi-directional energy flow capability; the input power factor can be fully controlled. Last but not least, it has minimal energy storage requirements, which allows to get rid of bulky and lifetime-limited energy-storing capacitors. But the matrix converter has also some disadvantages. First of all it has a maximum input output voltage transfer ratio limited to 87 % for sinusoidal input and output waveforms. It requires more semiconductor devices than a conventional AC-AC indirect power frequency converter, since no monolithic bi-directional switches exist and consequently discrete unidirectional devices, variously arranged, have to be used for each bi-directional switch. Finally, it is particularly sensitive to the disturbances of the input voltage system.[11][12]

6.1 Principle of Operation

The matrix converter consists of 9 bi-directional switches that allow any output phase to be connected to any input phase. The circuit scheme is shown in figure 8. The input terminals of the converter are connected to a three phase voltage-fed system, usually the grid, while the output terminals are connected to a three phase current-fed system. The capacitive filter on the voltage-fed side and the inductive filter on the current-fed side represented in the scheme of figure 8 are necessary. Their size is inversely proportional to the matrix converter switching frequency.

![Diagram of a three phase to three phase matrix converter.](Figure 8: Circuit of a three phase to three phase matrix converter. a,b,c are at the input terminals. A, B, C are at the output terminals.)
It is worth noting that due to its inherent bi-directionality and symmetry a dual connection might be also feasible for the matrix converter: a current-fed system at the input and a voltage-fed system at the output.

With nine bi-directional switches the matrix converter can be assumed to have theoretically $2^9$ different switching state combinations. But not all of them can be usefully employed. Regardless of the control method used, the choice of the matrix converter switching state combinations (from now on simply matrix converter configurations) to be used must comply with two basic rules. Taking into account that the converter is supplied by a voltage source and usually feeds an inductive load, the input phases should never be short-circuited and the output currents should not be interrupted. From a practical point of view these rules imply that one and only one bi-directional switch per output phase must be switched on at any instant. By this constraint, in a three phase to three phase matrix converter, there are 27 permitted switching combinations.[2][7]

Since no internal energy storage is present, the relation between input quantities and output quantities is clear. From figure 8 the transfer matrix can be obtained like below

\[
\begin{bmatrix}
v_A \\
v_B \\
v_C \\
\end{bmatrix} =
\begin{bmatrix}
m_{Aa} & m_{Ab} & m_{Ac} \\
m_{Ba} & m_{Bb} & m_{Bc} \\
m_{Ca} & m_{Cb} & m_{Cc} \\
\end{bmatrix}
\begin{bmatrix}
v_a \\
v_b \\
v_c \\
\end{bmatrix}
\text{ and }

\begin{bmatrix}
i_A \\
i_B \\
i_C \\
\end{bmatrix} =
\begin{bmatrix}
m_{Aa} & m_{Ba} & m_{Ca} \\
m_{Ab} & m_{Bb} & m_{Cb} \\
m_{Ac} & m_{Bc} & m_{Cc} \\
\end{bmatrix}
\begin{bmatrix}
v_a \\
v_b \\
v_c \\
\end{bmatrix}
\]
6.2.2 Input Current

Likewise to the output voltages, the input currents are directly generated by the output currents, synthesized by sequential piecewise sampling of the output current waveforms. If the switching frequency of the matrix converter is set to a value that is much higher than the input and output frequency, the input currents drawn by the converter are sinusoidal: their harmonic spectrum consists only of the fundamental desired component plus a harmonic content around the switching frequency.

In figure 10 the input current drawn by a matrix converter for a 2 kHz switching frequency is shown. It can be noted that the amplitude of the switching harmonic components is comparable to the fundamental amplitude. It is then obvious that an input filter is needed in order to reduce the harmonic distortion of the input line current to an acceptable level.

The matrix converter performance in terms of input currents represent a significant improvement with respect to the input currents drawn by a traditional VSI converters with a diode bridge rectifier, whose harmonic spectrum shows a high content of low-order harmonics. By the light of the standards related to power quality and harmonic distortion of the power supply this is a very attractive feature of matrix converter.\[2][13]
6.2.3 Input Power Factor

The input power factor is another attractive feature of matrix converters, which holds for most of the control algorithms. Despite this common capability, it is worth noting that a basic difference exists with respect to the load displacement angle dependency. For instance, the algorithm does not require the knowledge of the load displacement angle in order to fully control the input power factor. On the contrary, the algorithm requires the knowledge of the load displacement angle whenever the reference input power factor is different from unity. From an algorithm computational burden point of view this is a drawback, since it implies additional quite heavy calculations. In figure 11 the input power factor drawn by a matrix converter for a 2 kHz switching frequency is shown.
6.3 Control Technology

With the matrix converter, simultaneous control of the output voltage and input current is possible, but simultaneous and independent control is not easy to implement. The control method becomes complicated because switching one bi-directional switch in order to output a certain voltage causes the change of the input current condition. The higher speed, higher performance and lower cost of control devices in recent years, however, have made it possible to realize even complicated control with ease. In the conventional control method for a matrix converter, the pulse pattern for each bi-directional switch is calculated directly from the condition for obtaining the desired AC output voltage and the condition in which the input current becomes a sinusoidal wave. The control method is unique for the matrix converter and is capable of outputting various pulse patterns. However, since the pulse pattern is calculated directly, it is difficult to control the input current and the output voltage independently. [5]

6.4 Commutation and Protection

Figure 12 shows the commutation and protection circuit of the matrix converter. Commutation is the process wherein the current flowing to a switch $S_a$ for example, is transferred by turning on a switch $S_b$ and turning off a switch $S_a$ to transfer that current to switch $S_b$.

The switch must be controlled, so that there is no short circuit and the load current is not interrupted. If the load current is interrupted, a large surge voltage is impressed upon the semiconductor switch and the switch is damaged. Therefore, similar to conventional PWM inverter, dead time is provided to prevent a short circuit condition and surge voltage generated during this dead time interval is absorbed by a protection circuit. As a result, loss increases and the protection circuit grow in size, as it requires a large electrolytic capacitor to absorb energy. This reduces the advantage of the matrix converter. [7]
The commutation problem is solved by controlling the two RB-IGBTs (reversed biased insulated gate bipolar transistors) that compose a bi-directional switch independently. In other words, by keeping a reverse biased switch constantly in its on state, the device is made to behave the same as the freewheeling diode in the conventional PWM inverter, and the load current is not interrupted.

6.5 Main Advantages

The main advantages of a matrix converter are:

- Sinusoidal input and output waves with minimum harmonics.
- Input power can be fully controlled.
- Minimum energy storage requirements.
- Compact design.
- Adjustable (including unity) power factor.
- Bidirectional power flow.
- High quality waveform.
- More stability and fewer fluctuations.

6.6 Main Drawbacks

The main drawbacks of a matrix converter are:

- Higher complexity in modulation and analysis effort.
- Requires more semiconductor devices.
- Sensitive to disturbances of the input voltage.

7.0 Converter Comparison

In this section, the back-to-back voltage source converter and the matrix converter will be compared.

7.1 Component Count

In the back-to-back voltage source converter, two power converters are used whose instantaneous operation is decoupled by a capacitor, as an energy storage element. In the matrix converter, the multiple conversion stages and the intermediate energy storage element are replaced by a single power conversion stage. Both converters use IGBTs as bi-directional switches.

Turbine reliability is a major issue in wind turbine design. A prediction of the system reliability requires a detailed investigation. However, taking a simple approach, assuming reliability to some extent is related to the number of involved semiconductor components, the two converter topologies are easily compared. The component count presented in the table represents the ideal component count, while in practical applications more
components are often used to withstand for example high voltage ratings. The proportions can still be compared, and evaluating the component count, it appears that the back-to-back converter is clearly the best choice.

<table>
<thead>
<tr>
<th></th>
<th># of diodes</th>
<th># of transistors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back-to-back</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Matrix</td>
<td>18</td>
<td>18</td>
</tr>
</tbody>
</table>

*Table 1: Comparison of component counts*

### 7.2 Efficiency

Figure 13 shows how the efficiency of the two converts varies with increasing transformer frequency. As seen from the figure, the efficiency for a matrix converter decreases less with increasing frequency than a back-to-back converter. In high frequency applications, this may be an argument to use a matrix converter.

![Converter efficiency vs. transformer frequency](image)

*Figure 13: Converter efficiency vs. transformer frequency [3]*

### 7.3 Switch Utilization

Together with the number of switching devices, the switch utilization can provide an indirect measure of the converter cost. An approach applied for calculating the switch utilization factor simply gives a measure of the ratio between turbine nominal power and installed converter volt-amperes [1]:

$$\nu = \frac{P_{tur}}{\sum V_T \cdot I_T + V_D \cdot I_D}$$

A more sophisticated approach can be applied by using the actual turbine power capability in relation to the totally installed volt-amperes [1]:

...
\[ \nu = \frac{\hat{P}_{\text{tur}}}{\sum V_T \cdot I_T + V_D \cdot I_D} \]

Where \( P_{\text{tur}} \) is the turbine power to be generated in order to reach the thermal limits of the converter, \( V_T \cdot I_T \) is the VA-rating for the individual transistors and \( V_D \cdot I_D \) is the VA-rating for the individual diodes.

Figure 14 shows the utilization factor \( \nu \). The dashed lines refer to the utilization factor calculated by the first equation, while the solid lines are calculated from the second equation. As seen from the figure, the matrix converter has a higher utilization factor for every speed.

![Utilization factor \( \nu \) with two-level, matrix, three-level (DC), and three-level (DC) graphs.](image)

**Figure 14: The switch utilization factor for the converter topologies [1].**

### 7.4 Output Voltage Waveforms

In figure 15 the output voltage waveform of a matrix converter is shown and compared to the output waveform of a traditional voltage source inverter (VSI). The output voltage of a VSI can assume only two discrete fixed potential values, those of the positive and negative DC-bus. In the case of the matrix converter the output voltages can assume either input voltage a, b or c and their values are not time-invariant: the effect is a reduction of the switching harmonics.
The converter losses when operating in the normal operating range are shown in figure 16. The blue curve represents the calculated losses for the back-to-back voltage source converter, while the green curve represents the losses for the matrix converter. From this evaluation, the back-to-back voltage source converter seems to be the best choice.

Although the losses seem to be significantly larger for the matrix converter, the system based on the doubly-fed system does not “reward” the gained converter efficiency. This is due to the fact that only about a third (or even less) of the generated power is actually processed by the power converter.
8.0 Conclusions

This report has looked at power converts in modern wind turbines. The focus has been on the conventional back-to-back voltage source converter and the less used matrix converter.

Taking a simple approach and assuming reliability is related to the number of involved semiconductor components, the two converter topologies are easily compared. Evaluating the component count, it appears that the back-to-back converter is clearly the best choice.

The efficiency for a matrix converter decreases less with increasing frequency than a back-to-back converter. In high frequency applications, this may be an argument to use a matrix converter. Following the evaluation of converter losses, the back-to-back voltage source converter seems to be the best choice.

Cost is very often an important deciding factor in choosing whether or not to use power converters and which ones to choose. The matrix converter has a higher component count than the voltage source converter, and it can therefore be assumed that it also has a higher cost.

The output voltage of a voltage source converter can assume only two discrete fixed potential values, while the output voltages of a matrix converter can assume more values. The effect is a reduction of the switching harmonics, giving a more sinusoidal output voltage.

In spite of the mentioned advantages compared to the more conventional back-to-back voltage source converter, the matrix converter is still not widely used in practice. It still requires more investigation and optimization, to gain a significant share in the industry applications.
9.0 References


