Comparison of a Three and Four Phase Interleaved Bidirectional DC/DC-Converter for the Operation in an Energy Storage System in Wind Turbines

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Abstract—The increasing penetration of wind power to the electrical grid leads to the need of a stronger contribution of wind turbines to grid control, concerning quality and stability. For the purpose of controlling the active power injection, depending on the needs of the grid and not depending on the power generation, energy storage systems can be used. In this paper this kind of system with a bidirectional interleaved DC/DC-converter and electric double-layer capacitors as storage technology is investigated. The dimensioning of the converter’s main elements and its performance for three- and four-phase interleaved configurations is studied and compared. Simulations are carried out in MATLAB/Simulink/Plecs.

Keywords—Wind Energy, Energy Storage System (ESS), Interleaved Buck Converter, Bidirectional.

I. INTRODUCTION

The amount of power injection from regenerative energy sources like wind turbines (WT) to the mains is increasing steadily. The proportion of power attained from wind energy was growing with approximately 30% worldwide a year in the last couple of years [1]. It can be foreseen that in some parts of the electrical grid, especially in coastal regions, the main part of energy feed in will come from WT in the future. These decentralized feeders normally supply their energy by means of frequency converters to the grid. As a negative consequence, unwanted effects like high harmonics occur, also favorable ones, as for example the possibility to control the power feed in. Especially the reactive power can be controlled to stabilize the grid voltage and by using energy storage systems (ESS) the active power can be fed in independently from the fluctuations of the wind, as far as the ESS and the converter ratings allow. The grid codes (GC), like the German GC [2], contain the requirements for grid connection of WT. Because of the growth of wind energy it can be predicted that the GC will be expanded and sharpened in the future [3]. By means of ESS it is possible to smooth the active output power in order to reduce the unwanted grid effects, especially in weak grid regions. Sharpened GC requirements could lead to the necessity for WT to contribute to primary frequency control in the case of a low grid frequency. In this case the amount of active output power has to be increased. This amount could be supplied by an ESS. The converter system of a WT could be supported by an ESS in the case of a low voltage ride through (LVRT) at grid faults. The DC link voltage could be controlled constant in the case of an unsymmetrical voltage fault at the point of common coupling (PCC) in case of adapted power consumption ability of the ESS. If this PCC voltage collapses, the whole amount of generated power cannot be delivered to the mains. The ESS could buffer this power.

The foreseen need for storage technologies in WT leads to many investigations in this area. Storage technologies for wind power applications are investigated in [4], [5] and [6]. Electric double-layer capacitors (EDLC) are qualified but still too expensive as a storage solution for short term energy storage to smooth output power and to disburden the converter system in grid fault situations. But there is a trend of decreasing prices. In [1], [7] and [8] control strategies for constant output power for different generator types are investigated with ESS and EDLC and batteries. The authors of [9] and [10] use ESS to disburden WT systems during grid faults. In [11] and [12] DC/DC-converter topologies are investigated for this purpose. The authors conclude that interleaved buck converters are qualified topologies for ESS. In [13] a real time simulation of a WT with ESS is presented. Interleaved DC/DC-converters for electronic vehicle drives have been gained at the institute in former research work [14].

In this paper an ESS system is presented and investigated. It consists of a bidirectional n phase interleaved buck converter (BC) and is connected in parallel to the DC link of the full back-to-back converter system at its high voltage side, as shown in Fig. 1. On its low voltage side the storage unit which consists of EDLC is connected. This paper aims to dimension and to control such systems with three and four phase interleaved configurations (n = 3 and n = 4 respectively) of a bidirectional DC/DC-converter and to compare these configurations with respect to the systems performance and the effort of components used.

In section II the investigated topology of the interleaved bidirectional BC is presented and the main components of the ESS are dimensioned. Also the control strategy is described. BC configurations with n = 3 and n = 4 are compared in all chapters. A case study and simulations are presented in section III. This paper ends with a conclusion in section IV.

II. ENERGY STORAGE SYSTEM

There are two general concepts of combining wind power generation and ESS. First, an aggregated storage system can be installed at a specific point in the wind
power plant or in the grid. These ESSs typically have a large storage capacity and can be constructed for example as pumped hydro, compressed air or battery plants. These concepts tend to supply energy during peak loads and save energy during times of low energy consumption.

In this paper, a second concept of distributed ESS is considered where each WT contains its own ESS. It is connected to the DC link of the full power converter system and consists of a bidirectional DC/DC-converter and EDLC as storage. Such a system can be used for example to smooth the active output power, to let the WT contribute in frequency control or to enhance the behaviour during grid faults. To reach these targets the storage capacity has to be dimensioned.

The state of charge of an EDLC depends on its actual voltage. The maximum voltage $U_{\text{EDLC,max}}$ results from the number of the cells connected serially. Because the ESS should always be able to work at rated power, the minimal voltage $U_{\text{EDLC,min}}$ of the EDLC correlates with the maximum current load capacity $I_{\text{ESS,max}}$ of the DC/DC-converter and the EDLC. By (1) it can be seen, that the useable energy of the ESS depends on the voltage range.

$$E_{\text{ESS}} = \int_{t_{\text{min}}}^{t_{\text{max}}} P_{\text{ESS}}(t) \, dt = \frac{1}{2} C_{\text{EDLC}} \cdot (U_{\text{EDLC,min}}^2 - U_{\text{EDLC,max}}^2) \quad (1)$$

$I_{\text{ESS,max}}$ can be increased by paralleling IGBTs or using IGBTs with a higher maximum current on the one hand, on the other hand by paralleling single phase BC. The first way leads to less switching and measurement efforts. Parallel BC can be operated interleaved and so the total current ripple can be reduced.

The comparison in the following subsections refer to the dimensioning of the DC/DC-converter’s inductances for different interleaved configurations and to the EDLC capacitance.

A. Proposed Topology

The ESS consists of $n$ bidirectional interleaved BC connected in parallel. The control signals are phase shifted by $\frac{2\pi}{n}$ of a switching period ($T_s = 1/f_s$). The system’s rated power is $P_N$. IGBTs are used as switching devices with a maximum current of $I_{\text{max}}$. In this paper ESS systems with $n = 3$ and $n = 4$ will be investigated and compared. In Fig. 2 the proposed system is shown. The BC’s high voltage side is connected to the DC link of the back-to-back converter of the WT with $U_{\text{DC}}$, its low voltage side is connected to the energy storage unit, using EDLCs. Its voltage depends on its state of charge. Such EDLCs have a low energy density on the one hand, on the other hand they provide a large power density [15]. So they are able to buffer huge amounts of energy in short time periods and can be assembled for fast dynamic processes. In [13] und [16] EDLCs are also used as storage units in ESS for wind power applications. For the simulations an equivalent circuit from [1] with series resistances is used. The dimensioning of these EDLCs and the inductances is described in the next subchapters.

B. Dimensioning of EDL Capacitance

In this paper the ESS will be used and dimensioned to reach three main targets: to smooth the output power of a WT at fluctuating wind conditions, to contribute in primary frequency control and to enhance the behaviour at low voltage ride through (LVRT). For these single targets the capacities of the EDLCs have to be calculated. These calculations base on the required energy which has to be stored. To make universally valid statements the results are given as a factor $e$ with $J \text{ W} = s$ as unit. The number $e$ describes how many seconds the rated power $P_N$ can be stored or released.

1) Active Power Smoothing

In this operation, the ESS serves as a filter of the active power. The active power output depends on the fluctuating wind conditions. If primary WTs inject their power to the grid, as governments plan to increase the regenerative power injection steadily in the future, huge power oscillations could result. By means of the ESS a smoothing of the injected power could be necessary to avoid negative effects to the grid. It is obvious that the quality of this smoothing depends strongly on the size of the storage unit. The bigger the useable storage capacity, the higher oscillations in longer time periods can be smoothed [17] and power ramp rates can be implemented. The smoothing effect therefore also depends on the power...
management. For this purpose a fuzzy-controller could be used [4].

In the point of balanced operation (BO), the ESS must be able to save and to release power. In [16] it has been proposed that 20% of the WT’s rated power \( P_N \) should be buffered for approximately 1 minute for this purpose, this corresponds to \( e = 12 \) J. With such a big capacity good smoothing results could be reached. These investigations could not show how the smoothing capability changes with different storage sizes, i.e. with different \( e \). In this paper, it is approximated that the ESS should be able to save and release 5% of \( P_N \) for 30 seconds each, which corresponds to (2). But further investigations in this field are necessary.

\[
e_{\text{P-smooth}} = 3 \frac{J}{W} \quad (2)
\]

2) Frequency Control Contribution

Actually, the European network of transmission is using an amount of 3000 MW for frequency primary control purposes. This is about 1% of the peak load of 300 GW [18]. For a frequency deviation of \( \pm 200 \) mHz this reserve must be activated for at last 15 min. Generally WTs are operated by a maximum power point tracking (MPPT) algorithm to harvest the maximum power from the wind. In this operation mode they can not provide primary control reserve without an ESS. If the whole primary control was provided by wind energy power plants, the necessary storage capacity would be 750 MWh (3).

\[
E = 3000 \text{ MW} \cdot 900 \text{ s} = 750 \text{ MWh} \quad (3)
\]

Today the primary control reserve is provided by big power stations. [18] defines that 2% of the nominal power has to be reserved for primary control by each power station with a nominal power above 100 MW. Fewer resources, reducing the global \( CO_2 \) emission and nuclear phase-out, will certainly result in a new situation. Smaller power stations and suppliers of renewable energies will take part in the control market. In Germany, for example, there is no regulation defining the minimal size of power stations for frequency control contribution. But all contributing power stations need to reserve a minimum power of 1 MW for primary control purposes [19]. A primary control with WTs or rather wind parks will cause a permanent reserve by reducing the general active power output by a few percent or a storage of the additionally required power by ESS. In this case the necessarily stored energy for primary control contribution would be 1 MW \( \cdot 900 \text{ s} = 250 \text{ kWh} \).

By using a wind park with 10 WT the energy stored by one WT would have to be 25 kWh.

If the main part of the generated energy is produced by renewable fluctuating sources, the grid codes need to be adapted to the future development of the energy market. For an economic optimization, a change of requirements for primary control reserve could be one option. The additional reserves of the secondary control need be put into effect faster. In [18] it is defined that secondary control will only be activated if there is an (ACE) “Area Control Error”. In this case, secondary control needs to be adapted after 15 min since fault occurrence.

The regulation for the secondary control demand requires a full availability of secondary reserve after 5 min. If pumped storage power plants and other fast active power stations could bring in their power within \( t_{\text{sec}} = x \) min as secondary power reserve and WT contribute with 2% of \( P_N \), the time gap in between could be buffered by WT with ESS with a capacity of \( e = 1.2 \cdot x \) J.

For the construction of the energy storage system considering \( t_{\text{sec}} = 2.5 \) min, the stored energy could be calculated with (4).

\[
e_{\text{control}} = 3 \frac{J}{W} \quad (4)
\]

3) LVRT Enhancement

In the case of a voltage breakdown only a part of the generated power can still be injected into the grid due to limited power rating of the LSC. If WTs disconnected in such a case from the grid, the loss of power injection could even enforce the grid fault. So WTs have to provide a LVRT capability [20]. To strengthen the grid a reactive current injection is also required [2] in the fault case. The amount of injected reactive current \( I_r \) depends on the voltage sag depth \( \Delta U \) (p.u.) and a factor \( k \) which is set up by the grid provider and differs within 0 and 10.

In [2] it is defined as (5), taking a voltage dead band of \( \pm 10\% \) around the nominal voltage without the need of injection into account.

\[
k = \frac{I_r}{I_N} \frac{\Delta U}{U} \quad (5)
\]

By means of the ESS, the generated power \( P_{\text{gen}} \) which can not be fed into the grid in case of an LVRT, should be stored and released after fault clearance. To calculate the storage size for this purpose the worst case should be considered, if there was a three phase breakdown to 0 for 150 ms and a fault clearance described by the worst case line in the LVRT characteristic [2] and shown in Fig. 3 (black line). Calculations about this were done in [4] and [10], but the need of reactive current injection was not considered, which is done in this paper. In Fig. 3, three areas are defined: Area I reaches from \( t_0 \) to \( t_1 \). In this time span the voltage sag is 100% and no energy can be injected into the grid. The whole amount of \( P_{\text{gen}} \) has to be stored in the ESS. Between \( t_1 \) and \( t_2 \) area II can be defined. The grid voltage rises linearly. Depending on \( k \) full reactive current \( I_r \) has to be injected until \( t_2 \). During this time the LSC has no capacity to feed in active power as well, so \( P_{\text{gen}} \) still needs to be stored in the ESS. \( t_2 \) can be calculated by (6).

\[
t_2 = 0.9 - \frac{1}{k} \cdot \frac{0.9}{t_3 - t_1} + t_1 \quad (6)
\]
From $t_2$ on, in area $III$, up to $t_3$, the reactive current is linearly decreased with the voltage regeneration and the total injectable power $S_{grid}$ of the LSC increases again. In all areas, $P_{ESS}$ can be calculated by (7). In regions $I$ and $II$ $S_{grid}$ is equal to $Q_{grid}$, the injected reactive power.

$$P_{ESS}(t) = P_{gen}(t) - \sqrt{S_{grid}(t)^2 - Q_{grid}(t)^2}$$ (7)

As a worst case consideration, $k$ is assumed as 10 and $P_{gen} = P_N$. By means of these equations $E_{ESS}$ and $e$ can be calculated as shown in (9).

$$E_{ESS} = \int_{t_3}^{t_4} P_{ESS}(t) \, dt$$ (8)

$$e_{LVRT} = \frac{E_{ESS}}{P_N} = 1.399 \frac{J}{W}$$ (9)

4) Discussion of Results

In the three previous subsections the required relative storage capacity $e$ for the different ESS applications has been calculated. These applications require to feed in active power (f-control), to store active power (LVRT) or both (P-smoothing). So a point of balanced operation can be increased by paralleling IGBTs, by the utilization of DC/DC-converter was calculated. This volume can be found for different $n$, different areas and different $U_L$ combinations in the phases can be defined. They can be numbered from $l = 0$ to $l = n - 1$. The variables $a$ and $t$ are related by (12).

$$\frac{1}{n} < a \leq \frac{l + 1}{n}$$ (12)

For each area the current fluctuation range can be calculated. By means of $l$, (13) can be derived to calculate $\Delta I_L$ depending on $a$.

$$\Delta I_L = \frac{U_{DC} \cdot T_s}{L_n} \cdot (1 - l \cdot a) \left( a - \frac{l}{n} \right)$$ (13)

To determine the maximum current fluctuation range $\Delta I_{L,max}$, (13) has to be derived by $a$. A maximum can be found for $a_{max} = \frac{1 + 2l}{2n}$. By means of (14) $\Delta I_{L,max}$ can be calculated for different $n$.

$$\Delta I_{L,max} = \frac{U_{DC} \cdot T_s}{L_n} \cdot \frac{4l}{n}$$ (14)

To receive an equal current fluctuation range for all $n$ at the output of the DC/DC-converter, a necessary inductance $L_n$ can be calculated by (15), using (14).

$$L_n = \frac{L_n}{n}$$ (15)

In [14] the inductor volume for a three-phase interleaved DC/DC-converter was calculated. This volume can be predicted by the energy of the $n$ inductors $E_{ind}$. For its calculation the square of the maximum current amplitude of each phase $I_{L,max}$ has to be used. The branch current fluctuation range is maximum for $a = \frac{1}{2}$. For a given maximum duty ratio $a_{max} = \frac{U_{ESS}}{U_{DC}}$, smaller than $\frac{1}{2}$, $\Delta I_{L,max}$ can be calculated by means of (11). In (16) the dependence of $\Delta I_{L,max}$ and the maximum possible branch current ripple (for $a = \frac{1}{2}$) is shown, which is $n$-times the value of $\Delta I_{L,max}$.

$$\Delta I_{L,max} = n \cdot 4 \cdot (a_{max} - a_{max}^2) \cdot \Delta I_{L,max}$$ (16)

By defining an output current ripple percentage $x$ in (17), the maximum phase current amplitude in (18) can be
calculated by the currents in (19) and (20).

\[
\Delta I_{L,max} = x \cdot T_{L,max}
\]

\[
\dot{I}_{L,i,max} = \frac{T_{L,i,max} + \Delta I_{L,i,max}}{2}
\]

\[
T_{L,i,max} = \frac{I_{L,max}}{n}
\]

\[
\Delta I_{L,i,max} = n \cdot x \cdot 4 \cdot \left( a_{max} - a_{max}^2 \right) \cdot T_{L,max}
\]

Hence \( E_{L,n} \) can be calculated by (21).

\[
E_{L,n} = n \cdot \frac{1}{2} \cdot L_n \cdot \dot{I}_{L,i,max}^2
\]

The relation of \( E_{L,3}/E_{L,4} \) can be plotted for different \( a_{max} \) in Fig. 5. To receive a small output current ripple, the volume of the inductors can be reduced using a higher interleaved level, especially if \( U_{EDLC,max} \) is smaller than half of the DC link voltage \( (a_{max} < \frac{1}{2}) \).

D. Control

The IGBTs are switched by push-pull operation and receive the switching signals by a pulse width modulation (PWM). So there are only two switching states \([0, 1] \) for each branch, as shown in Fig. 6. Because of the antiparallel diodes the current can flow in both directions. So no discontinuous operation can take place. A cascaded control with an inner current-control loop and an outer voltage-control loop is implemented. Similar control structures are presented in [10] and [21]. For control design purposes the bidirectional interleaved BC can be treated as a conventional buck converter with one branch. PI-controllers, as shown in Fig. 7, are used to control the currents in the inductances by generating the duty cycle \( a \) as actuating variable for the PWM. This signal is compared to a sawtooth signal and the switching times for the IGBTs result. At interleaved operation there is one PI-controller for each BC-branch and the sawtooth signals are shifted by \( \pi / n \) of one switching period to one another. The current is equally divided to all branches resulting in an equal stress for all devices. This control structure requires a measurement of all branch currents. There are also advanced strategies, for example current sharing, in which fewer measurement sensors are necessary [22]. The inner loop controller is limited between \([a_{min}, a_{max}]\) depending on the minimal switch-on times of the IGBTs. In high dynamic processes the controller operates at these boundaries.

The controller of the outer loop generates the reference value for the controller of the inner loop, \( I_{L,n} \), with the target to maintain the DC link voltage \( U_{DC} \) constant. For controller design purposes the behaviour of the closed inner loop can be described as a PI delay-element. Its settling time is estimated by the current dynamics. Here a PI-controller is also implemented, as shown in Fig. 8. The current reference is limited up to \( n \cdot I_{L,i,max} \). Because the actuating variables of the controllers are limited, an anti-windup is used for each PI-controller. This is necessary but challenging for the design process, because the plant loses its linear characteristics in high dynamic processes.

III. CASE STUDY AND SIMULATION

A. Model Description

A Simulation model was built and components were dimensioned in a laboratory setup scale with the properties shown in table I. This parameter setup is used for simulations, which are done with MATLAB/Simulink/Plecs.

For the dimensioning of the storage, EDLC-modules, each with a capacity of \( C_{EDLC} = 50 \text{ F} \), capacitive voltage of \( U_C = 56 \text{ V} \), internal series resistance of \( R_i = 12 \text{ m}\Omega \) and a maximum steady state current of \( I_C = 650 \text{ A} \), are considered [23]. In order to maintain always full power \( P_N \) transfer capability and considering \( R_i \) and \( m \) EDLC modules serially connected, the minimum useable EDLC voltage is given by (22), the maximum useable EDLC voltage can be calculated by (23).

\[
U_{EDLC,\text{min}} = \frac{P_N}{I_{L,max}} - I_{L,max} \cdot m \cdot R_i
\]

\[
U_{EDLC,\text{max}} = m \cdot U_C - R_i \cdot \frac{P_N}{U_C}
\]

By means of (10) the dependence of \( e \) on \( I_{L,max} \) can be plotted in Fig. 9. It can be seen that \( e \) increases with a
Fig. 9. Useable storage capacities $e$ depending on $I_{L,\text{max}}$ for the same EDLC stack configuration (3 EDLC modules, in total with $C_{\text{ESS}}$ and $R_{\text{i,ESS}}$, connected in series) and a constant maximum power of $P_N$.

higher current load capability of the DC/DC-converter for the same EDLC configuration. To fulfill the requirement of $e_{\text{min}} = 4.5 \text{s}$, at least a maximum current $I_{L,\text{max}} = 275 \text{ A}$ is necessary. Here, it is important to mention that $e$ refers to $P_N$ and not to the maximum power $S_{\text{conv,max}}$ of the DC/DC-converter. $P_N$ remains constant, $S_{\text{conv,max}}$ increases with an increasing $I_{L,\text{max}}$. If $e$ was related to $S_{\text{conv,max}}$, the curve in Fig. 9 would fall for high $I_{L,\text{max}}$.

The inductances can be calculated by (14) to $L_{n=3} = 0.519 \text{ mH}$ and $L_{n=4} = 0.389 \text{ mH}$. Fig. 10 shows the current fluctuation range $\Delta I_L$ for three and four times interleaved operation with the calculated inductances depending on the duty cycle. The area of operation is marked in red. The point of balanced operation is marked by the vertical red line. It is important that $\Delta I_L$ is small for small $a$, because in such operation points the highest currents $I_L$ can flow and the total effective current should not exceed the IGBT’s current limitation. In Fig. 11 the regions of steady state operation are shown. For the simulation model a maximum converter current of 450 A is chosen which may not be exceeded. Because of the power invariance and the fact that $U_{\text{DC}}$ always remains constant, the current at the DC link side $I_{\text{DC}}$ also remains constant for all states of charge of the EDLC when $P_{\text{ESS}} = P_N$. The duty cycle $a$ is proportional to $U_{\text{ESS}}$ in steady state, $U_{\text{EDLC}}$ can be calculated considering $R_{\text{i,ESS}}$. During dynamic operations it can temporarily leave this marked area.

B. Simulation Results

Due to complexity the wind turbine converter system is not simulated. The generator of the wind turbine system produces an unsteady current flow due to fluctuating wind conditions but the LSC should deliver a constant power to the grid. So the ESS has to maintain the DC link voltage constant by absorbing the resulting current difference $I_{\text{diff}} = I_{\text{gen}} - I_{\text{grid}}$ with $I_{\text{gen}}$ as the DC current from the GSC and $I_{\text{grid}}$ as the DC current flowing into the LSC, as shown in Fig. 12.

Fig. 12. Simulation model (black) of the ESS, connected to the DC link of the WT

1) General behaviour

To simulate different conditions of WT and failures, the simulation is taken out for three different $I_{\text{diff}}$ set points, as shown in Fig. 13. The EDLC module has a state of charge $U_{\text{ESS}} = 123 \text{ V}$. Firstly a positive difference current of $I_{\text{diff}} = 20 \text{ A}$ ($\approx 0.5 \cdot I_{\text{DC,nom}}$) arises, simulating a very strong rise of the wind speed or a grid fault, starting at $t = 0.01 \text{s}$. The DC link controller reacts fast due to its small time constant. The DC link voltage maintains almost constant, it has an overshoot of less than 0.15% and is controlled to its nominal value within a few milliseconds. At $t = 0.02 \text{s}$ the difference current changes abruptly to $I_{\text{diff}} = -20 \text{ A}$. Nearly the same behaviour of the controller could be achieved again. Due to different dynamics this process needs more time and a higher overshoot, as well...
as a longer transient state occurs. In section II it was shown that voltage at the BC inductances $U_{L}$ changes with each switching state. Because of the big difference of primary voltage $U_{DC}$ and secondary voltage $U_{ESS}$ the absolute value of $U_{L}$ and so the inverter dynamics for current falling situations is slower than for current rising situations. 20ms later, $I_{diff}$ changes to an alternating current with an amplitude of 10 A and an offset of 25 A at a frequency of 200 Hz. In the case of unsymmetrical grid faults at the DC link voltage of a converter system an oscillation of 100 Hz typically arises [24]. As shown in the simulation the ESS is capable to stabilize the DC link voltage at even higher frequencies. Also, oscillations due to wind fluctuations can be controlled.

2) LVRT

In Fig. 14 the simulation shows the behaviour of a condition similar to a grid fault. From $t = 0.01$ s, the total rated current of the WT can not be supplied to the grid and flows into the storage unit. The DC link voltage can be kept nearly constant the whole time.

![Fig. 14. LVRT-Simulation with $n = 3$, green: actual value, red: reference value](image)

**IV. CONCLUSION**

In this paper, a multi interleaved buck converter for the use in an ESS connected to the DC link of a WT converter system, is investigated. The main components of this system are dimensioned for the purpose of stabilizing the wind turbine system during grid fault, to achieve a constant output power at fluctuating wind conditions and to contribute to frequency control of the grid. Current ripple and total inductor volume can be reduced by increasing the interleaved level $n$, on the other hand the measurement and switching effort rise. Within a case study the components could be determined for an ESS with rated power $P_{N} = 30$ kW. A comparison of this setup for different maximum currents $I_{L,max}$ shows that available storage capacity increases with increasing $I_{L,max}$. Especially in the case of high investment costs for storage components this should be taken into account. A control strategy of this DC/DC-converter is shown. In simulations the functionality of the use in WT to reach the proposed targets could be shown by using test signals representing grid fault conditions and fluctuating wind conditions.

**REFERENCES**

