The Effect of Converter Harmonics in Offshore High Voltage and Medium Voltage DC Networks

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The Effect of Converter Harmonics In Offshore High Voltage and Medium Voltage DC Networks

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***Abstract*-The outputs from turbines in current and planned offshore wind farms are generally interconnected using AC networks. However, there are significant potential advantages in using DC interconnection; in particular, the cable losses are greatly reduced. Such a system is likely to require the use of DC-DC converters to step up the rectified generator output voltage to an intermediate (collection) DC voltage, and then to a high DC voltage for transmission to the shore. These DC-DC converters will introduce harmonics into the DC network, and there is a strong possibility of significant circulating currents between the various converters, causing substantial losses.**

This paper presents the results of simulations studies of this system using Simulink. A model of a system comprising wind-powered permanent magnet generators, active rectifiers, high power DC-DC converters, appropriate filtering and submarine cables is described. The converter harmonics and their associated losses are presented, and possible methods for their reduction is discussed.

***Index Terms* — DC-DC Converter, Converter Harmonics, Multi-Terminal High Voltage Direct Current (MTHVDC).**

I. INTRODUCTION

As the world economy develops, fossil fuel sources of energy have been seriously depleted, and a large carbon footprint has reached deep into the earth. The pressures of increasing population, the human requirement for energy and the phenomenon stated above indicate that new energy resources, for example, wind power, are required.

Wind power is renewable energy source which has vast potential for further development as it has the advantages that it is pollution-free and plentiful [1]. However, wind power turbines also have negative consequences for the environment (in particular visual impact). Therefore, wind farms should be built away from centres of population, in particular offshore where the wind speeds are higher and more consistent. As is well known, most electrical energy is consumed in cities, so there is a need to transfer the energy over long distances efficiently [2]. HVDC transmission lines/cables are generally appropriate when wind farms are built more than about 80km from the shore. However, the maximum power rating for a wind turbine is about 5MW (steadily rising), while the power handling capability of a long HVDC cable can be in the gigawatt range, so is clear that single turbine connections to the shore are non-viable. Thus the requirement for Multi-Terminal DC connection technology is gradually emerging [3].

In 1963, the first parallel Multi-Terminal HVDC (MTHVDC) system was proposed [4], and Voltage Source Converter (VSC) was first commercially used in HVDC in 1999 [??]. Voltage source converters are always connected in parallel; one regulates the voltage while the other controls the power flow. One reason that MTHVDC systems are being developed is that the capacity of VSCs (and wind turbines) is limited, while a MTHVDC system can extract and deliver power to and from more than one connection point [4]. At present, most of the research on the subject has concentrated on the control of the VSC and the system, but few have studied the harmonics caused by the DC-DC converter, and their effects on voltage and current flow in the cable. In a multi-terminal system, tens (or even hundreds) of connections point may exist at the generating end, which means the current flow and voltage drop at each section between two connecting points may cause problems.

In this paper, the simulation results of a simplified Multi-Terminal system with eight wind turbines are presented, and the voltage and current waveforms monitored. While analysing the simulation results, any potential issues are discussed.

II. METHODOLOGY

Multi-Terminal HVDC systems with voltage source converters have not been used widely, as it is not a mature technology at present. There are different topologies for a MTHVDC network, and each of them has various problems during operation [5]. In a MTHVDC system, the voltage can be up to 500kV or even higher, so physical experiments are impossible in the lab, and all the research so far has been based on simulation.

In the simulation, a simplified model of the radial topology, as shown in Fig. 1, of a MTHVDC system with wind turbines was adopted. Matlab Simulink was selected as the simulation software.

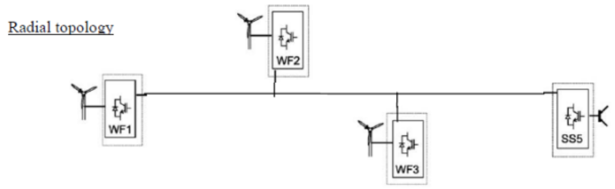


Fig. 1. Radial Topology for Multi-Terminal HVDC Network

A simplified model is chosen as there can be as many as 100 turbines in the whole system, each with a wind model, a permanent magnet synchronous generator (PMSG), and a voltage source converter (VSC), so the running time of a very detailed and accurate model can be extremely long.

The main aim of simulation is to investigate the operation of Multi-Terminal-MVDC/HVDC networks, concentrating in particular on the harmonics in the current and voltage waveforms at sending end of the system. It is hoped to identify any challenges when building a MTHVDC network in the real world, and to discuss possible ways to solve the problems.

The circuit which was built in Simulink is detailed in Fig. 2, and the parameters used for this model are listed in Tables I to V.

Permanent Magnet Synchronous Generator (PMSG)		
Electrical Frequency	$V_{line\text{-}rms}$	Power
55Hz	2603V	5MW

TABLE I
PMSG PARAMETERS

The output (three phase) frequency of the generator is set to 55Hz in the simulation: the probability that the electrical frequency of the generator is the same as the system frequency, 50Hz, is extremely low.

TABLE II
PWM PARAMETERS

Pulse Width Modulation (PWM)			
Switch Type	Carrier Frequency	Fundamental Frequency	Modulation Index
IGBT	1155 Hz	55 Hz	0.85

In the three phase PWM circuit, a shared triangular carrier wave is used, and the carrier wave ratio is set to be an odd number and an integer multiple of 3, in order to achieve a symmetrical output waveform and to ensure that there are no even harmonics in the output [6].

TABLE III [7]
DC-DC CONVERTER

DC-DC Converter (Bridge) Duty ratio = 0.45					
Converter Type 1 (Single Phase)			Converter Type 2 (Three Phase)		
Switch Type and Frequency	Transformer turns ratio	Power	Switch Type and Frequency	Transformer turns ratio	Power
IGBT 10kHz	1:10	5MW	IGBT 1kHz	1:8	20MW

In Fig. 2, all the 5MW DC-DC converters belong to the converter type 1 (single phase, shown in Fig. 4) in Table III, and the 40MW DC-DC converter is the only three phase DC-DC converter (shown in Fig. 5) in the system.

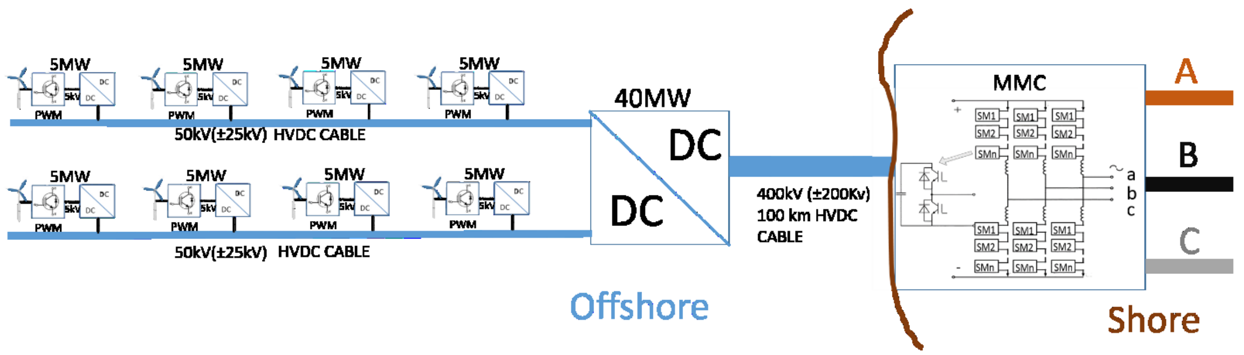


Fig. 2. Offshore MTHVDC Network Simulation Model

TABLE IV [8] [9] [10]
HVDC PARAMETERS

HVDC Cable π Model				
Frequency for RLC Specification	Resistance /km	Inductance /km	Capacitance /km	Number of π Section (variable)
50 Hz	0.013 Ω	0.466 mH	0.28 µF	2

The start-up time of a 5MW turbine is about 3 minutes, as observed at the Dunhuang (China) Wind Farm in 2012 by the researcher [11]. During the startup time, the next turbine is started only when the previous one is running in the steady state. However, as this paper concentrates on the steady state operation of the system, so at the beginning of the simulation, all the turbines are assumed to be running at their steady state speed.

III. Results

Fig. 3-5 show the detailed circuits of the PWM rectifier, 5MW single phase DC-DC converter and 40MW three phase DC-DC converter blocks in Fig. 6, while the sending end part of the model is as illustrated by Fig. 6.

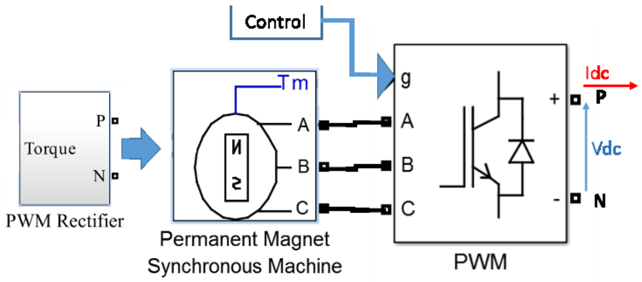


Fig 3. PMSG and PWM Rectifier

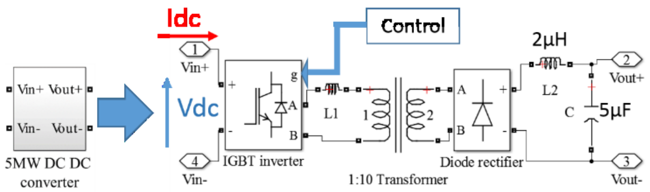


Fig. 4. Single Phase 5MW DC-DC Converter

All the values of inductors and capacitors in Fig. 4 and Fig. 5 are less than 5 µH/µF, as it can be very expensive to have high values of inductance/capacitance in the high voltage side of the offshore system.

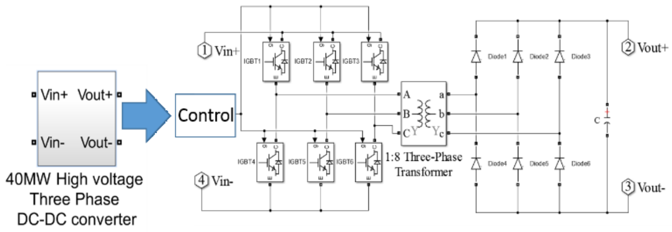


Fig. 5. Three Phase 40MW DC-DC Converter.

A. *Harmonics Caused by the 5MW DC-DC converter*

During the simulation the 20MW three phase DC-DC converter was removed temporarily, as only the effect of 5MW converter was monitored.

1) *Waveform of V_{dc1} and I_{dc1} in Fig. 6 when 5MW DC-DC converter L_1 =0, L_2 =2µH (detailed in Fig. 4).*

Fig. 7 illustrates the steady state waveform of V_{dc1} and I_{dc1}.

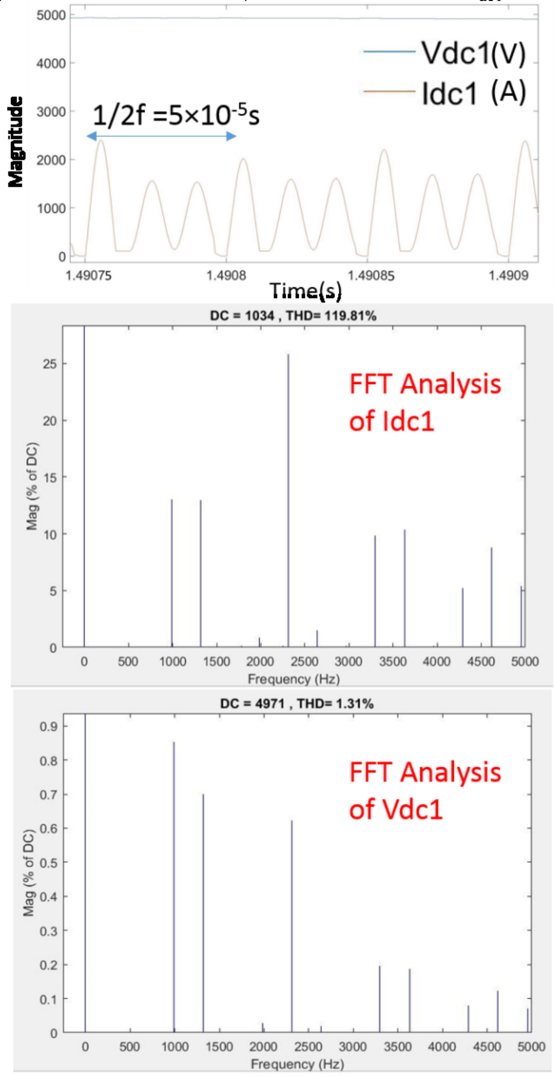
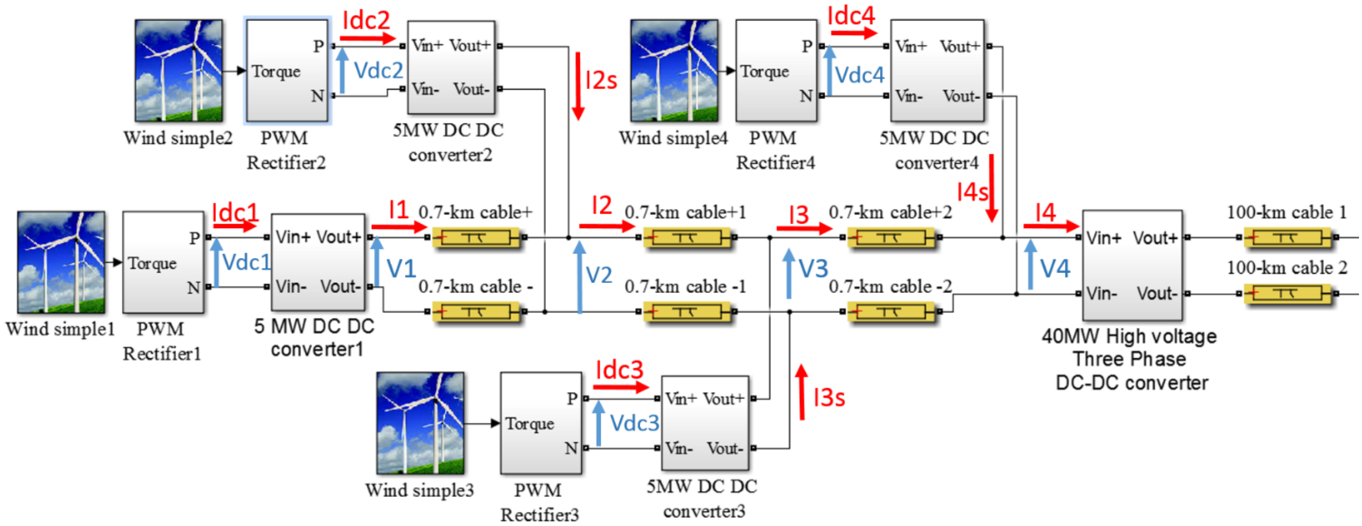


Fig. 7. V_{dc1} I_{dc1} Waveform and Harmonics



[redacted]

Fig. 6. Sending End of the Simulation Model

It is clear that the single phase DC-DC converter leads to high harmonics on the PWM output dc current, as the THD of V_{dc1} is only 1.31%, but for I_{dc1} it is 119.8%. The reason is the value of the inductor of the DC-DC converter is small, and the relatively ideal transformer has a low equivalent series inductor, so the circuit can only work in the discontinuous mode. In each period the value of the inductor current should start to increase from zero when two of the IGBTs are switched on, and decrease rapidly when all the switches are off. The input current waveform is the same during t_{on} and back to zero even more quickly due to the characteristics of the bridge converter.

The current waveform in Fig. 7 also shows the resonance between the inductor and capacitor, so it seems more like three sin waves during 1/2f, where f is the switching frequency of the IGBT switch, rather than triangular wave.

Converter Efficiency:
5MW DC-DC converter input power = 5.31774MW
5MW DC-DC converter output power = 4.66522MW
Efficiency= 87.7%

2) *Waveform of I_{dc1} in Fig. 6 when 5MW DC-DC converter L_1 =2μH L_2 =0.02μH (detailed in Fig. 4)*

As discussed previously, if there is only a small inductor at the output side of the converter, the converter input dc current has high harmonics and relatively low efficiency. Increasing the value of the inductor on the output side is not easy in a high voltage system.

By looking at the equivalent circuit of a transformer, it is apparent that adding a small inductor L_1 on the primary (low voltage) side of the transformer has same effect as increasing the output side inductor L_2. Increasing the value of inductance on the low voltage side is easier than on the high voltage side, and when referring the primary side inductor to the secondary side, the value can be regarded as rising n^2 times, where n is the transformer turns ratio.

Fig. 8 indicates the steady state waveform of I_{dc1}. V_{dc1} is not shown again as it does not change significantly.

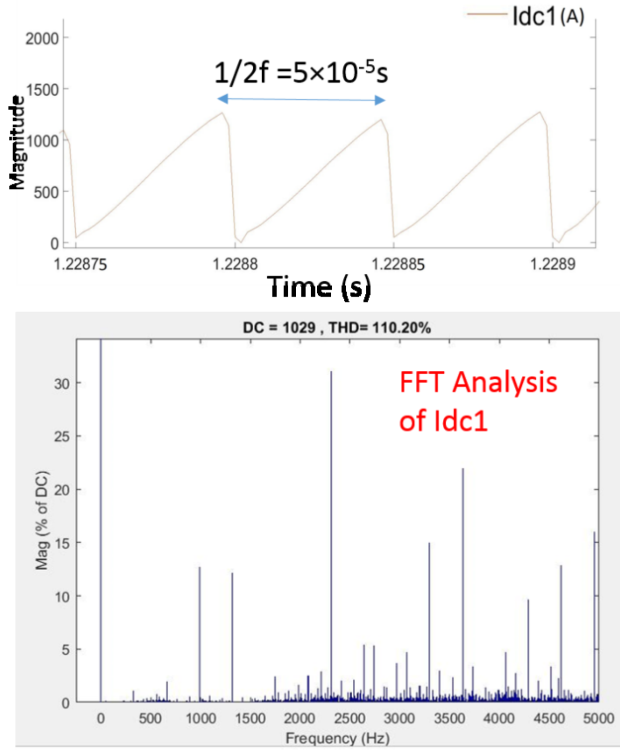


Fig. 8. I_{dc1} Waveform and FFT with Primary Side Inductor

Generally speaking, the effect of having a 2μH inductor on the primary side is preferable to having an inductor on the secondary side. Firstly, it is easier to manufacture. Secondly, resonance does not exist anymore and the waveform is triangular wave as expected. In this situation, the performance of the triangular wave is easier to predict, and the peak current value is lower than that in 1). Finally, the efficiency is increased.

Converter Efficiency:
5MW DC-DC converter input power = 5.172783MW
5MW DC-DC converter output power = 4.631055MW
Efficiency = 90%

In this part, only the performance of one 5MW DC-DC converter is discussed, as the simulation results of all converters are very similar.

B. Harmonics Caused by the Three Phase 40 MW DC-DC converter

In contrast to the effect of single phase DC-DC converters, the distance between different single phase converters and the three phase DC-DC converter are not the same. In order to monitor the effect of the three phase DC-DC converter on different section, I_1, I_{2s}- I_{4s}, V1 - V_4 (the output current and voltage waveform single phase DC-DC converter) in Fig. 6 are compared and discussed together. $V_{dc1}\rightarrow V_{dc4}$ are treated as being identical, as are $I_{dc1}\rightarrow I_{dc4}$.

1) Current waveforms in Fig. 6.

The waveforms of I_1, I_{2s}, I_{3s} and I_{4s} are shown in Fig. 9. It can be observed that the ripples/THD increase from I_1 to I_{4s}, which means the further the turbine is from the three phase DC-DC converter, the better the current waveform will be. The reason is that the 0.7km cables connected between each 5MW converter work as filters in the network. Another issue is that the shape of the waveform of I_4 (the dc output current from the 5MW converter connected directly to the 20MW DC-DC converter) is very different from the currents from the other three converters. It resembles the superposition of a square wave with a positive dc component. In order to explain the phenomenon, the waveforms of I_{4s}, I_3 and I_4 need to be monitored, which are shown in Fig. 10.

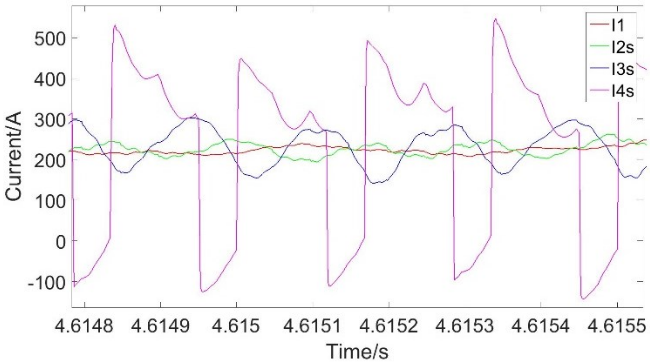


Fig. 9. Waveform of I_1, I_{2s}, I_{3s}, I_{4s}

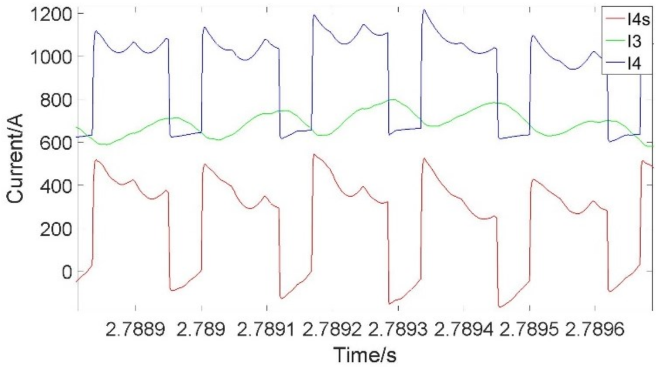


Fig. 9. Waveform of I_{4s}, I_3, I_4

I_4 is the input current of the three phase DC-DC converter in Fig. 5. The waveform of I_4 can be considered as a square wave with two (positive) levels when the transformer is relatively ideal (with small leakage inductance). This is because the current loop on the primary side of the transformer will only have two positive voltage levels:

1. V_{dc} -- when one upper IGBT on ($V_{dc}/2$) and one lower IGBT on ($-V_{dc}/2$)
2. $V_{dc}/2$ -- when one upper IGBT on ($V_{dc}/2$) and one lower IGBT off (0)

According to Kirchhoff current law, $I_3+I_{4s} = I_4$, so I_{4s} will be negative when $I_3>I_4$. This means in each period, 0.001s in this simulation, there will be 0.0003s (30%) when the current is circulating from the last section of cable to the last 5MW DC-DC converter, increasing the losses.

2) THD Comparison

The Total Harmonic Distortion of V_1-V_4, I_1, I_{2s}-I_{4s} and $I_1 - I_4$ will be compared in Tables V, VI and VII.

TABLE V
THD of V_1, V_2, V_3, V_4 in Fig. 6

	V1	V2	V3	V4
DC component	47.69kV	47.68kV	47.67kV	47.66kV
THD	2.93%	2.81%	2.67%	3.63%

From Table V, the influences from the three phase DC-DC converter on the single phase converter are very small. Even for the direct connected converter 4, the THD of V_4 is just a little bit higher than others, but still within an acceptable range. Due to the high voltage transmission, the relatively low current will not cause a high voltage drop on the 0.7km connection cable, and the values of V_1-V_4 can be regarded as the almost the same.

TABLE VI
THD of I_1, I_{2s}, I_{3s} and I_{4s} in Fig. 6

	I_1	I_{2s}	I_{3s}	I_{4s}
DC component	228.9A	228.9A	229.7A	234.6A
THD	10.1%	11.48%	31.47%	130%

TABLE VII
THD of I_1, I_2, I_3 and I_4 in Fig. 6

	I_1	I_2	I_3	I_4
DC component	228.9A	475.7A	678.4A	992A
THD	10.1%	11.48%	10.36%	29.97%

From Table V and VI, it is clear that the three phase converter causes high current harmonics on the 5MW converter connected directly to it. This time, adding inductors at the primary side or increase the primary leakage inductance can increase the harmonics of the current, so the best way to solve this problem can be have a filter at the input of the three phase DC-DC converter. Finally, in this simulation, the efficiency of the three phase DC-DC converter is very low and will be examined further.

IV. CONCLUSION AND FUTURE WORK

In multi-terminal HVDC networks, the DC-DC converter is necessary in each stage. However, the results in this paper evidence that both the single phase DC-DC converter and three phase DC-DC converter will cause high current harmonics on DC current components, which will not only increase the rating of the power electronic devices, but will also increase the losses. In future work, both the single phase converter and the three phase DC-DC converter will be analyzed in detailed and all the issues presented in this paper will be discussed, especially concentrating on the very low efficiency of the three phase DC-DC converter.

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