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Optimal Interleaving Angle Determination In Multi Paralleled Converters Considering the DC Current Ripple and GRID Current THD

K.Arutselvan[1], John Denish C[2], Viravel P[2], Vignesh M2, Jeremm[2]
[1]Assistant Professor, Department of EEE, Narasu's Sarathy Institute of Technology, Tamil Nadu, India
[2]Students, Department of EEE, Narasu's Sarathy Institute of Technology, Tamil Nadu, India

ABSTRACT

Among different options available for wind energy system, this research is focused on directdriven Synchronous generator based variable speed wind turbines that are connected to powergrid via modular converter units. Compared to single full size power converter, modular designhas higher reliability/redundancy, better harmonic performance, lower developmental cost andhigher efficiency.Better harmonic performance of modular structure is possible through interleaving whicheffectively reduces ripple in the output current, enabling use of smaller sized filter components.Focus of this research is to design a controller that can perform automatic interleaving ofmodular three-phase converters used in above cited wind energy system. Developed controlalgorithm will have critical decisions carried out by local controllers. With minimumcommunication overhead the controller will ensure interleaved operation of parallel modulesunder all conditions.

Keywords— Interleaving, grid current, THD, converters

I. INTRODUCTION

Parallel converter configuration is widely used in telecommunication power supplies, renewable sources and so on. For the most of the renewable sources, for example photovoltaic, wind and fuel cells, they have relatively low voltage output compared with the voltage of dc bus or battery/ultra-capacitor storage. Even though the series connection is able to provide the high output voltage, it has the power limit because of the limited number of series connections in order to increase the nominal power. The parallel connection is realized as a more reliable and flexible configuration for multiple-input source applications. Boost converters are popularly employed in different applications to step up the line input voltage to the higher dc bus voltage, which will be considered in this paper. Based on the basic circuit theories, for parallel connection, the current at the load side is the sum of the current from each input branch. Hence, the current ripple is also added up at the load side to form a larger current ripple than that of each input.

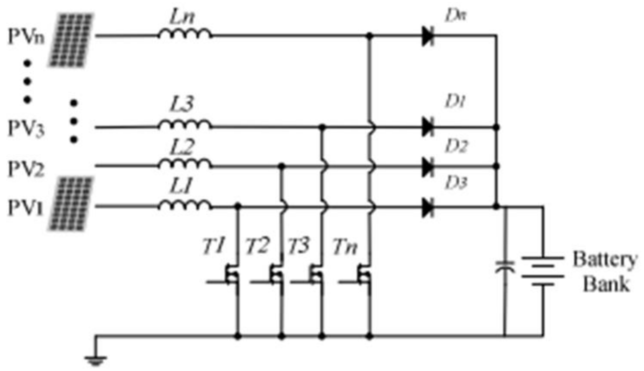

Fig.1. Parallel PV sources with boost converters

Interleaving based paralleled boost converter techniques with the features of high output power and low current ripple are proposed. Even though performance can be improved for parallel systems by using the interleaving technique, it is conventionally used for only one input source. For one input source, the output current ripple is reduced by paralleling boost converters with switching phase shift. The shift angle is determined by 2πN, where N is the number of converters. However, none of them takes the multiple inputs into consideration for the interleaving analysis. The main problem is that the conventional interleaved converters are implemented for only one input with the fixed phase shift offset (angles) between individual stages . As the development of the renewable energy in the current decade, the MPPT algorithms applied to each PV sources come to be a new challenge to the interleaving techniques, which requires the variable duty cycle operation of each converter for different source voltage

Today, a doubly fed induction generator (DFIG) with a partially rated rotor-side converter is the mainstream technology in the market for large wind turbines. Meanwhile, a permanent magnet generator (PMG) interfaced to the grid through a full power converter is increasingly being adopted due to its higher power density, better controllability, and reliability, especially so during grid faults. The voltage level of a wind power converter is usually in the range of 380 690 V due to generator voltage rating and voltage limitation of power electronics devices. Therefore, the power converter is connected to the grid via a step-up transformer to match the grid voltage level (10.5 35 kV) in the wind farm collection system. In the low voltage (690 V) system, when wind turbine power is larger than 500 kVA, several power converters are connected in parallel to handle the increasing current. The large current transfer also results in a parallel connection of multiple cables and causes substantial losses , voltage drop as well as high cost of cables and connections. This disadvantage can be avoided by placing the step-up transformer into the nacelle. However, the bulky and heavy transformer significantly increases the mechanical stress of the tower. Instead of paralleling converters and cables, another alternative to transfer high power is to use medium voltage transmission, where the current is reduced and the step-up transformer may not be needed if the converter output voltage level can reach the grid voltage (10.5 kV 35 kV). Hence, a transformer-less, medium voltage high power converter system would be an attractive technology for large wind turbines, especially when today's wind turbine power rating is approaching 5 MW. Since the system current rating can be a good indicator for the cable and connection cost and losses. As can be seen, the increase of voltage level to 10 or 35 kV can significantly reduce the current ratings. Medium-voltage high-power converters have been widely used for motor drive applications, such as neutral point clamped (NPC) converters and cascaded H-bridge converters, which benefit from multilevel voltage output, less voltage stress, and better harmonic spectrums. The cascaded H-bridge converter is recognized as more suitable for industrial product in the sense of modular structure, high reliability, and fault-tolerant ability. In addition, it is the only available and practical multilevel converter topology that may meet the voltage level of more than 10 kV subject to the voltage rating of power electronic devices. For motor drive applications, the cascaded H-bridge converter needs several independent power sources for the inputs, which are usually provided by an input transformer with multiple secondary windings. Whereas, in a wind power conversion system, the multiple generator coils can be used as the independent sources for the converter modules.

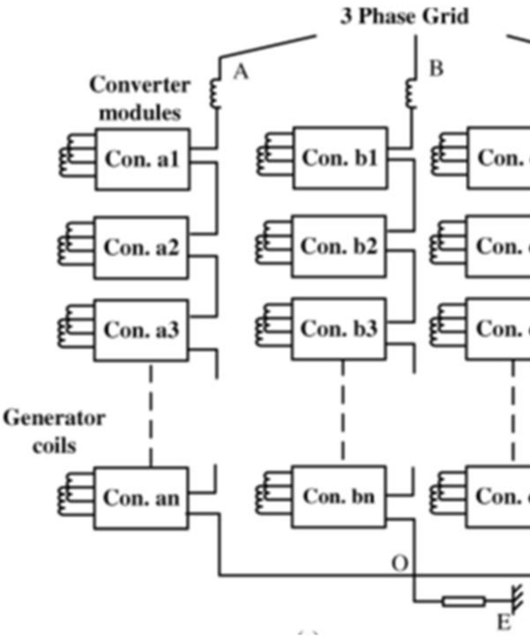

Fig.2. Parallel converter for wind turbine.

Power Electronics Converters forWind Turbine Systems

The paper has given an overview of different power electronic converters in WTSs with special attention paid to the many possible topologies at low voltage and medium voltage. An important trend is that the technology is moving toward a higher power level, and it is inevitable that it goes for higher voltage and as a consequence into multilevel single cell structures or to multicell modular structures that can even use standard low voltage power converter modules. One current concern beyond being able to upscale the power is being better able to predict reliability of power electronic converters and control, as it has been a major failure cause in WTS, and better lifetime prediction and condition monitoring methods in the future will be important to improve the technology. The use of a multicell approach in the power converter design can also lead to transformer less high-power converters which are directly connected to aMV grid with reduction of power losses, weight, and volume. Research is ongoing in this direction. Further, as the wind turbines are aggregated into wind power stations—configurations most useful for single-turbine operation are perhaps not the most feasible solution for a large-scale off-shore wind farm needing a large power transmission system.

II. CONVENTIONAL METHOD

The Voltage Source Converters (VSCs) are often connected in parallel in a Wind Energy Conversion System (WECS) to match the high power rating of the modern wind turbines. The effect of the interleaved carriers on the harmonic performance of the parallel connected VSCs is analyzed in this paper. In order to achieve low switching losses, the 60◦ clamp Discontinuous PulseWidth Modulation (DPWM1) is used to modulate the VSCs. A step-by-step design procedure of the line filter, which ensures the desired harmonic performance under all operating conditions, is presented. The analytical harmonic solution for the two parallel interleaved VSCs is derived in order to obtain the worst case voltage magnitude of the individual harmonic components. The required value of the filter admittance for the specific harmonic component is obtained by using the worst case voltage magnitude and the allowable harmonic injection limit. In order to achieve the desired filter performance with optimal values of the filter parameters, the use of a LC trap branch with the conventional LCL filter is proposed. The expressions for the resonant frequencies of the proposed line filter are derived and used in the design to selectively choose the values of the line filter components. The analysis and design methodology are also verified experimentally.

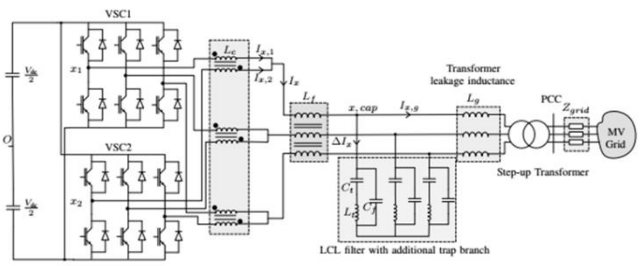

Fig .3. Block Diagram

The carrier signals, of the parallel connected VSCs in WECS (shown in the Fig 3.1), are interleaved to reduce the value of the filter components. The effect of the interleaved carriers on the operation of the parallel VSCs is analyzed in this section. The interleaved operation of the parallel VSCs: 1) improves the line current quality. 2) Reduces the switch current ripple of each VSC, provided the circulating current is suppressed effectively. Therefore, the value of the filter components can be reduced. However, additional inductive filter is required to suppress the circulating current. A CI is used as a circulating current filter due to its effectiveness in suppressing the circulating current. Multiple parallel interleaved VSCs with magnetic coupling between the parallel interleaved legs of the corresponding phase can be realized using the following configurations: 1) Whiffletree configuration. 2) Cyclic cascade configuration. 3) Using a magnetic structure with multiple parallel magnetic limbs. In addition to suppress the circulating current, the CI also performs the function of averaging the switched output voltage of the parallel interleaved legs. The values of the line filter components depend on the magnitude of the individual harmonic component in the average output voltage, which is the same in all of the above mentioned CI configurations. Therefore, the line filter design can be carried out independently, without considering the circulating current filter arrangement. In this paper, the WECS with two parallel interleaved VSCs is considered. However, the line filter design approach, presented in this paper, can be used for any number of parallel interleaved VSCs. The use of the LC trap branch with the conventional LCL filter is proposed. The converter side inductor Lf , the grid side inductor Lg, and the capacitor Cf forms the LCL filter. The series connection of the Lt and Ct forms the LC trap branch. The WECS is connected to a medium voltage network by using a step-up transformer. The leakage inductance of a step-up transformer often ranges from 0.04-0.06 pu, and it is considered as a part of the grid side inductance Lg. The interleaving angle of 180◦ is used as it results in optimal harmonic performance at high modulation indices. The closed form analytical solution to determine the individual voltage harmonic components of the pulse width modulated voltage is derived. Moreover, the relationship between the maximum value of the switch current ripple and the converter side inductor is also obtained. Conventional Disadvantages: DPWM as the modulation scheme is used to eliminate the harmonic components. Large dc link capacitor is used to mitigate the THD. More number of switches is used which increases the switching loss.

Operation of Paralleled Dc-Dc Converters Taking Into Account Cable Resistances For Load Sharing Applications: In this paper two DC-DC converters connected in parallel with the purpose of load sharing by applying droop method is considered. This method requires no communication interconnection and compensates for converter parameter variations and imbalances in line impedance. The DC-DC converter input source can be any DC source such as photovoltaic module and wind turbine or fuel cell and it is a closed loop system. In this work proportional-integral (PI) controller, will have their performance evaluated to control the paralleled converters connected to DC micro-grid. The PI controller is tuned by particle swarm optimization (PSO) method. The designing of stable DC-DC converter with primary droop current-sharing control, the stability of the interconnected parallel DC-DC converter system was studied. When the cable resistance of the paralleled DC converters differs, the interconnected system might be unstable and due to this the uneven load sharing occurs. To resolve this issue to some extent without the use of communication lines, a novel technique is applied to parallel DC boost converter in order to optimize the large uneven current sharing. The parallel converter must provide an even load sharing and secondly redundancy. Simulation results are presented in the paper using Mat lab/Simulink to confirm the concept.

As the power generation using solar power had increased dramatically because it is pollution free as compare to power generation using fossil fuel. Therefore, in standalone systems, these kind of paralleled DC converters will play a vital role if the proper control strategy (PSO tuned PI controller) taking cable resistances into account for power generation along with maximum power point tracking for the solar and wind will be applied. The medium to low voltage DC applications for residential use will be more reliable and efficient in future. These medium to low voltage network can later be reconstructed which may results in formation Medium range DC power micro-grids.

A Transformer-Less High-Power Converter for Large Permanent Magnet Wind Generator Systems: Unlike the conventional cascaded H-bridge converter used in motor drive applications, the wind power converter serves as the interface between the wind generator and the grid. At the generator side, each converter module requires a stable voltage source input, where a pair of generator coils with 90 phase shift is connected either in parallel or in series to reduce the low frequency power ripple. This will require a special winding arrangement of the generator as well as a control strategy for the generator-side rectifier. A single-switch boost-type power factor correction (PFC) circuit is used as the rectifier, enabling the generator unity power factor operation and also maintaining the converter cell dc-link voltage under different wind speeds. At the grid side, the cascaded H-bridge converter is facing the grid instead of the motor. Then, the control scheme should allow active power and reactive power transferred to the grid as well as dealing with different grid conditions such as grid faults. The voltage oriented vector-control strategy is used to achieve independent control of active power and reactive power fed into the grid and phase-shifted PWM is used for modulating the cascaded converter. The proposed topology and control method is verified by a 2-MW 11-kV grid simulation system and also by a 3-kW experimental system.

Current Ripple Cancellation of Multiple Paralleled Boost Converters for PV/Battery Charging System with MPPT: A novel multi-input boost-converter based interleaving technique is proposed, analyzed and verified by simulation and experiments. The proposed interleaving technique is also validated through the well-known P & O MPPT algorithm to each boost converter with different voltages of input PV sources. The organization of this paper is listed as follows presents the operation principle interleaved boost converters for multiple input sources, then, the proposed current ripple cancellation technique for parallel boost converters is proved by the simulation results. The most favorable advantages are 1) the input sources can be many, 2) the voltages and duty cycles can be different from each other for the proposed technique, 3) the proposed technique can be applied to different control for the multiple input configuration. The proposed switching technique for boost converters will be extended to other types of converters in parallel configurations with different current and voltage controllers in the future papers. Previous studies showed that the grid codes can be met, even with reduced impedance of the output filter, by optimizing the interleaving angle between the Pulse Width Modulated (PWM) carrier waves. The interleaving angle refers to the phase shift between the carriers of each converter module. When carrier interleaving is applied to a parallel converter system, it affects both the AC and DC side of the converter. Furthermore, if carrier interleaving is used, a high frequency circulating current will appear between the modules of the converters. The circulating current occurs because of the opposite zero vector generation, caused by the modulation and the interleaving. To suppress this high frequency circulating current additional Common Mode (CM) impedance is required. Objective of this Project is to Optimal Interleaving Angle Determination. Manipulating the interleaving angle between the

Pulse Width Modulated (PWM) carrier waves of each converter. In order to maintain a THD of the grid current in a level that complies while in the DC link the current ripple is reduced

III. PROPOSED SYSTEM

The wind turbine converter has two converters connected in a back-to-back configuration. One side of the converter is connected to the grid, another side is connected to the generator. Typically, to be able to push energy to the grid, the DC link voltage level is kept constant. The grid side converter is operated with a modulation index of around 1. On the other hand, the modulation index of the generator side converter depends on the power coming from the wind, thus having a huge fluctuation.

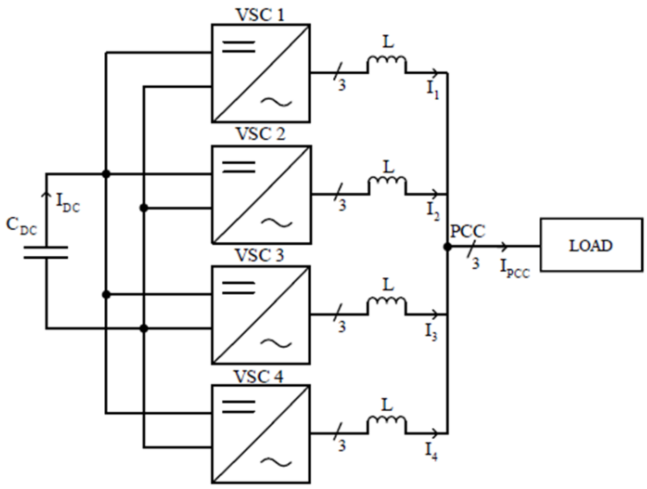

Fig.4. 4 level modular converter

The topology of 4 parallel connected converters is depicted by Fig. 4.1. In this topology the VSCs are sharing the same DC link. For filtering purposes at the output of each converter a single phase inductor is connected. The single phase inductor offers both differential and common mode filtering. The differential mode filter is used to reduce the harmonic components of the differential mode current caused by the modulation, while the common mode filter is used to suppress the circulating current between the modules, which appears due to interleaving. Several other methods exist for suppressing the circulating current. The first method is to use a three phase differential mode inductor and a three phase common mode inductor at the output of each converter. Another method is to use coupled inductors (CI) between the corresponding phases of every converter. However, by using the CI the modularity of the system is compromised, since the CI is only effective if both of the converters are operated with the same power. In the case of the CM the modularity can be maintained because the filtering does not depend on the other converter. In this article, since the modularity is a driving factor the solution with the CM is used. In this paper the authors, investigate the effect of the modulation index and the interleaving angle on the total current Total Harmonic Distortion (THD) and on the Root Mean Square (RMS) value of the DC link current. Moreover, a graphical explanation is presented for different interleaving angles, which will explain the findings of the study.

where, Vphis the RMS value of the phase voltage and Iphisthe RMS value of the individual converters' phase current,fundis the fundamental frequency, in this case 50 Hz. Theinductance value is specified in percentage, in this way theanalysis can be applied for different power levels by usingthe same inductance value in percentage.In the study the authors would like to evaluate the effectof the interleaving for the full modulation range, thus theconverters are connected to a load resistor. Anothermethod would be to connect the converter to the grid, butif the modulation index has to be varied from 0.1 to 1.15then the DC link voltage has to be changed. For very smallmodulation indices it may happen that the DC link voltagewould be too high and it would not be a feasible solution.The interleaving angle (θ) refers to the shift between thecarriers and its maximum can be calculated as:

$$\theta = \frac{2\pi}{n}\left[rad\right]$$

Where, n refers to the number of paralleled converters.

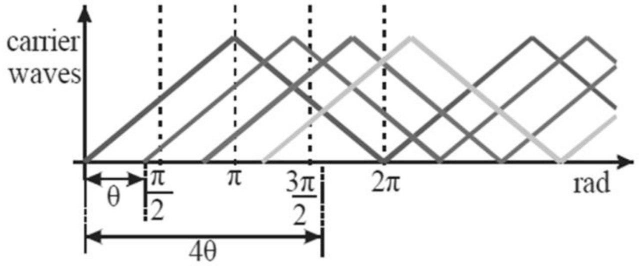

Fig .5. Carrier Wave Form

For the simulation study a 6.9kVA converter with 4parallel modules sharing the same DC link was considered fig4.1. To avoid additional harmonics the DC power wassupplied by a DC power source. Three single phaseinductors (L) have been used as an output filter for each ofthe converter modules. The use of single phase inductorsis justified, because it offers both common mode anddifferential mode filtering. As mentioned previously, thecommon mode inductance is required to limit thecirculating current, while the differential mode inductanceis used for shaping the current flowing out from theconverter. The value of the inductors was considered to be7.1%. The value can be calculated as follows:

$$L = \frac{V_{ph} \bullet \frac{7.1}{100}}{I_{ph} \bullet 2\pi \bullet f_{fund}} [H]$$

When the carrier of each converter is in phase theharmonics caused by the modulation are also going to bein phase, thus at the PCC the amplitude of these harmonicswill be n times larger.The interleaving of the carrier signals helps to eliminatecertain harmonics from the resultant current. This dependson the number of modules and on the interleaving angle. On the other hand, due to interleaving the currentdrawn from the DC link will occur at different timeintervals. Because the stress on the DC link capacitor isdependent on the current drawn from it, using interleavingthis stress can be reduced.There are different modulation strategies used inparallel converters such as Space Vector Modulation (SVM), Sine PWM, and several Discontinuous PWMmethods (DPWM). In this study formodulation the SVM technique will be used.By using SVM 6 active (v100 –v101) and 2 zero vectors(v00, v111) can be generated. During one modulation periodany arbitrary voltage vector can be generated by the sumof two active and two zero vectors. Φdenotesthe angle between the generated voltage vector (V) and theα axis, while d1 and d2 are the duty cycles. For the specificcase illustrated.V will be generated byapplying v100 and v110 for the times specified by d1 and d2.One can observe that the generation of these activevectors is done in the following order: zero vector, activevector 1, active vector 2, zero vector, active vector 2,active vector 1 and zero vector. The ripple current is aconsequence of this switching sequence. When no carrier interleaving is used, the same voltagevectors are applied to all converter at any given time. Onthe other hand, when carrier interleaving is applied, thegenerated voltage vectors will be shifted compared to theother converters. In other words, if the carriers of twoconverters are phase shifted by 180o, the applied voltagevectors will be in opposition. This means that i.e. the topswitch of the first converter could be connected to thepositive DC bus, and the bottom switch of the same phasecould be connected to the negative DC bus. Doing so, thepositive and negative terminals of the DC link will be shortcircuited through the single phase inductors, thus Acirculating current appears between the modules. Thefrequency of this circulating current is equal to theswitching frequency. The modulation indexand the interleaving angle has been swapped and the totalcurrent THD (IPCC) and the RMS value of the DC linkcapacitor current (IDC) have been observed. For a faircomparison the output current was maintained constant forall the modulation indices. This is required in order toensure that the filter (L) offers the same filtering for all thecases. To ensure the constant output current, the loadresistance was changed for every modulation index. Thevalue of the load resistance can be calculated as follows:

$$R_{Load} = \frac{mV_{dc}}{2I_{PCC,p}}$$

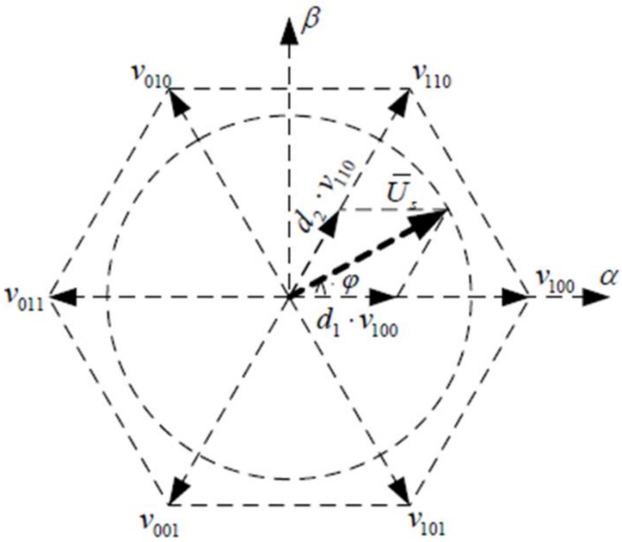

Fig.6.Vector diagram

where, Rloadis the load resistance, Vdcis the DC linkvoltage and IPCC,pis the peak value of the total current andm is the modulation index.

The interleaving angle has been swept from 0 to 90.This range was selected due to the fact that in the range of90 to 180 the results are in reflection symmetry, while inthe case of the modulation index a sweep between 0.1 and1.15 has been made with steps of 0.05.

The variation of the RMS value of the DC link currentripple, in function of modulation index and interleaving angle, is depicted. It can be observed that theRMS value changes in function of the modulation indexand interleaving angle. Even though the IPCC current isconsidered to be more or less constant, the reason why theRMS value of the DC link current is changing is becausethe output voltage of the converter is dependent on themodulation index hence, the delivered is constant for allthe modulation indices.In the case of total current THD, just like for theprevious case, the value depends both on the interleavingangle and on the modulation index. However, in this casethe effect of the interleaving angle is more predominant. Ithas to be noted that the total current THD has multiple local minimum points.

Proposed Advantages: SVPWM modulation is used to eliminate the THD.Due to interleaved structure the system has several advantages,In case of failure of a converter module this can be easily disconnected and the other converters can remain in operation, but reducing the overall power rating. Another advantage is that when the produced instantaneous power is below a certain level, not all converters need to be connected; therefore the lifetime of the whole system can be increased and the losses may be reduced.

IV. EXPECTED OUTPUT

The concept has been validated for 4 parallel connected converters. Measurement results for multiple interleaving angles from 0 to 90 degree with a step of 15 degree for an output current of 10 A, where the modulation index was varied between 0.15 and 1.1 was presented. For the presented cases the total current THD has decreased from 9.45% to 1.65%.

V. CONCLUSION

This article analyzed the effect of the carrierinterleaving angle on the total current and the RMS valueof the DC link current of 4 parallel converters. In case ofparallel converters the amplitude of the current ripple fromthe DC link and the total current depends on theinterleaving angle between the carriers of the PWMsignals. Several simulations have been carried out, fromwhere the trend of the current ripple vs. interleaving anglefor the DC link and total current was analyzed. It can beconcluded that the minimum for the total THD and DC linkcurrent ripple can be found at different interleaving angles.Moreover, for different modulation indices the optimalinterleaving angle differs. The interleaved modulationschemes were illustrated graphically, thus the cause of thecurrent ripples during a modulation period can be tracked.Depending on the hardware configuration, with an optimalinterleaving angle the size of the DC link capacitor can bereduced while the total current can comply with thestandards.

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