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Comparison of load inverter topologies in a bipolar LVDC-distribution

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Abstract. Low voltage direct current (LVDC) distribution is a new low voltage distribution concept. Potential inverter topologies for a bipolar LVDC 1500 V distribution system are compared. Two- or three-level single-phase half or full bridges or three-phase load inverters can be used in LVDC distribution. Inverters can be connected to 750 V DC or 1500 V DC. The bases of comparison are the size of required LC-filters, voltage and current stresses of the components, capability to operate with reduced DC voltage and feed half-wave rectifying load. Two different LC-filter design methods are used.

According to the simulation results, the most suitable single-phase load inverter topologies connected to 750 V DC are two- and three-level full bridges. The structure of three-level inverters is more complex, but the size of the required passive filter components is just half of the size of the components with two-level inverters.

The difference between LC-filter sizes is not so significant when comparing with two-and three-level inverters connected to 1500 V DC. The maximum voltage stresses of the IGBT-components are $u_{dc}/2$ in three-level inverters but u_{dc} in two-level inverters. Smaller voltage stresses are a remarkable advantage especially at higher voltage levels.

Key words

LC-filter design, LVDC distribution, single-phase inverter, three-phase inverter, three-level inverter

1. Introduction

The structure of the electricity distribution network is changing. There will be more distributed generation and more energy reserves connected to the distribution network [1]. The good power quality is more important nowadays because people are dependent on undisturbed power supply [1]. The low voltage direct current (LVDC) distribution is a new voltage distribution concept which can fulfil these new requirements. Medium voltage is decreased to low voltage by a transformer and rectified to DC. The voltage is converted back to AC near the customer. The Low Voltage Directive 2006/95/EC enables the use of 1500 V DC in power transmission [2]. It is possible to increase the power transmission capacity with the use of DC [1]. Losses of the energy distribution are smaller, because all of the power is active power and there shouldn't be skin effect in DC cables. The target of the system is high cost-efficiency and reliability [1], [3]. The DC system makes it possible to compensate voltage sags and short interruptions in the medium voltage network, and thereby the DC voltage can decrease for example 25 % without any effects on the customer voltage [3].

The structure of the LVDC network is unipolar or bipolar. In the unipolar system, rectifiers and inverters are connected to 1500 V DC as presented in Fig. 1.

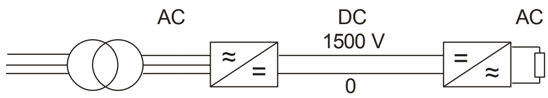


Fig. 1. A unipolar LVDC distribution network

The two voltage levels, ±750V DC, and the neutral are used in the bipolar system. The system can be fed by one rectifier which is connected as a bipolar connection as shown in Fig. 2 or by two rectifiers which are connected as a unipolar way between the positive or negative pole and the neutral. Customers are connected between the positive pole (customer A Fig. 2) or the negative pole (customer B) and the neutral as a unipolar connection, between the positive and the negative poles as a bipolar connection (customer C) or between the positive and negative poles with the neutral connection (customer D) in a bipolar way.

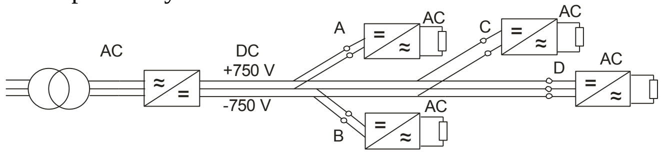


Fig. 2. A bipolar LVDC distribution network

It is possible to use two- or three-level single-phase half or full bridges or three-phase load inverters in both structures. The LVDC-distribution concept has been studied before, but the three-level NPC inverters are not used [1], [3]. Single-phase load inverters are presented in Fig. 3.

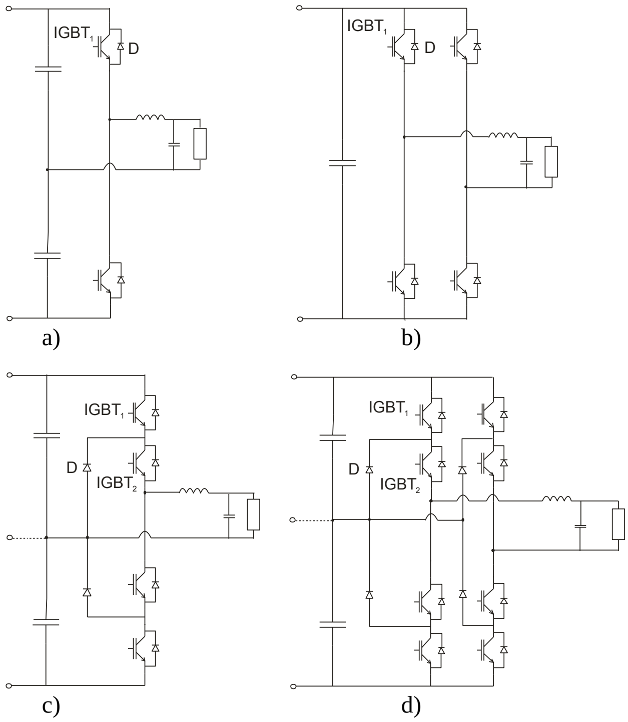


Fig. 3. Single-phase two-level a) half bridge, b) full bridge and three-level c) half bridge, d) full bridge

In most applications in a residential power supply there is no need for three-phase supply and in these situations the single-phase inverters are simpler than the three-phase inverters. The drawback is that the single-phase loads produce 2nd harmonic component to DC current.

The electrical network of the customer should be used isolated (IT) or with a galvanic isolation transformer if load inverters are unipolar connected to one voltage level or the single-phase full bridges are used. If load inverters are connected to the LVDC network in a bipolar way and single-phase half bridges or three-phase three-level inverters are used, it is technically possible to use operational grounding (TN) in the customer network without the galvanic isolation.

2. Inverter topologies and their LC-filter design

Two- and three-level single-phase half and full bridges and three-phase load inverters, which are suitable for LVDC distribution, are analysed in this study. LC-filters are designed for all these inverters according to the allowed current distortion of the filter inductor and the distortion of the load voltage. The overall physical filter size, produced power losses and costs should be minimized.

The size of the capacitor should be maximized if the size and losses of the inductor is wanted to be minimized. On the other hand, the capacitance value is not allowed to be too large because of large capacitive current losses [4]. The efficiency of the system would deteriorate because of reactive power flowing into the capacitor [4]. The capacitance relative value should be less than 5 % and the inductance relative value is not allowed to be larger than 10 % [5]. The large inductance causes the poor system dynamics because of the needed high voltage across the inductor [5].

The resonant frequency of the LC-filter (1) should be substantially below the inverter switching frequency to sufficiently attenuate the switching harmonics [5]. In addition the resonant frequency should be sufficiently above the frequencies of the most important harmonics to avoid resonance phenomena [5].

$$f_{res} = \frac{1}{2\pi\sqrt{LC}} \qquad (1)$$

Some base assumptions are done in the simulations. The inverters are fed by constant 1500 V or 750 V DC and they produce 230 V rms, 50 Hz AC-voltage. The 10 kW resistive load per phase is used to all inverters. The design parameters are presented in Table I. The inverter and filter losses are not taken into account. The carrier-based sinusoidal pulse width modulation method (PWM) is used and the switching frequency is 10 kHz. The constant sinusoidal modulation references are used with the modulators without any output voltage control. All simulations are done by Simplorer simulation software by the 0,1 µs simulation step.

Table I. – Design parameters

Phase voltage	$U_N = 230$ V
The base current	$I_B \approx 43{,}5$ A
Output power of the inverter 1-phase/ 3-phase inverter	$S_N = 10/30$ kVA
The base impedance	$Z_B \approx 5{,}3\ \Omega$
The base inductance	$L_B \approx 16{,}8$ mH
The base capacitance	$C_B \approx 601{,}6$ µF
The base frequency	$f_B = 50$ Hz
The switching frequency	$f_{sw} = 10$ kHz

The standard EN-50160 enables the maximum total harmonic distortion (THD) of the customer voltage to be 8 % up to the 40. harmonic component [6]. The maximum THD is defined according to equation 2, where *n* is the number of frequency components included in the calculation.

$$THD[\%] = \sqrt{\sum_{n=2}^{40}\left(\frac{U_{n,rms}}{U_{1,rms}}\right)^2} \times 100 \qquad (2)$$

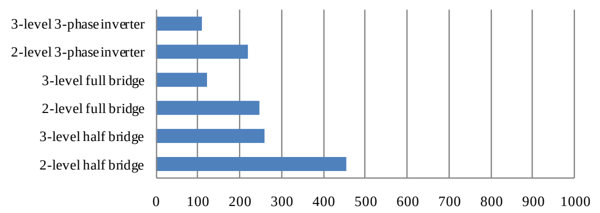
The losses in the inverters and filters should be minimized because the efficiency of the LVDC network should be at least as high as in the present AC network. Because of the high switching frequency, the THD calculation should not be limited up to 2 kHz as in the standard. Therefore the THD of the voltage is calculated according to equation 3 taking into consideration the whole frequency area because the high frequency harmonics also cause additional losses.

$$THD[\%] = \frac{\sqrt{U_{rms}^{2} - U_{1}^{2}}}{U_1} \times 100 \qquad (3)$$

The goal of the LVDC distribution is to ensure better voltage quality to the customers as at present. For this reason when using the first LC-filter design method the THD of the output voltage is limited to 5 % and when using the second design method it is limited to 2 %.

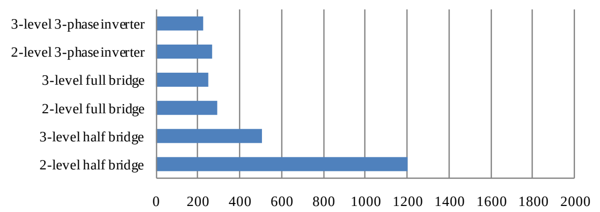
A. The first LC- filter design method

In the first case, the THD of the output voltage should not be over 5 % and the THD of the inductor current should not be more than 20 %. The results are presented in Fig. 4. The THD of the inductor current is usually limited to 10-30 % [7]. The inductor ripple current should be limited because otherwise the power losses, stresses and the temperature rise of the inductor would be too high. The amplitude of the inductor ripple current is not over 31-38 % of the amplitude of the current fundamental component, depending on the inverter topology, when inverters are connected to 750 V DC. The maximum amplitude of the ripple current is 26-40 % when inverters are connected to 1500 V DC. The largest ripple current exists with three-level inverters.



	2-level half bridge	3-level half bridge	2-level full bridge	3-level full bridge	2-level 3-phase inverter	3-level 3-phase inverter
L [µH]	455	260	248	123	220	110
C [µF]	11	12	6	6	11	10
fres [Hz]	2250	2849	4126	5859	3235	4799

a)



	2-level half bridge	3-level half bridge	2-level full bridge	3-level full bridge	2-level 3-phase inverter	3-level 3-phase inverter
L [µH]	1200	505	293	250	270	225
C [µF]	11	12	6	6	7	11
fres [Hz]	1385	2044	3796	4109	3661	3199

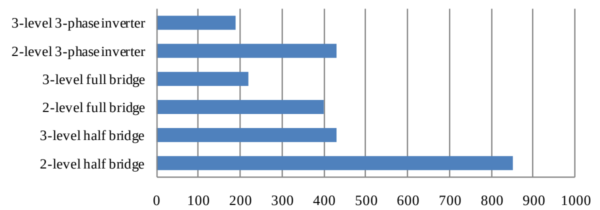
b)

Fig. 4. LC-filter sizes when inverters are connected a) to 750 V DC and b) to 1500 V DC, LC-filter design: THD_u is ≤ 5 % and THD_i is ≤ 20 %

The resonant frequencies of these filters are between 2250 Hz and 5859 Hz when inverters are connected to 750 V DC and between 1385 Hz and 4109 Hz when inverters are connected to 1500 V DC as seen in Fig 4. Three-level full bridge has the highest resonant frequency and two-level half bridge has the lowest. The inductance values are between 0,007 p.u. (three-level three-phase inverter connected to 750 V DC) and 0,071 p.u. (two-level half bridge connected to 1500 V DC) and the capacitance values are between 0,010 p.u. (full bridges) and 0,020 p.u. (three-level half bridge).

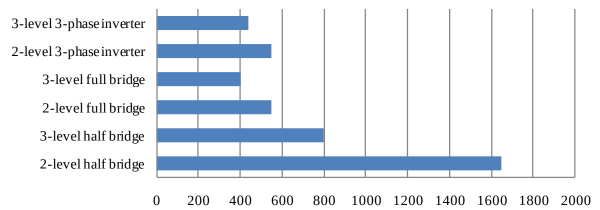
B. The second LC- filter design method

In the second case, the THD of the output voltage should not be over 2 % and the maximum amplitude of the inductor ripple current should not be over 20 % of the amplitude of the current fundamental component. The inductor ripple current is usually limited to 15-25 % [4]. The results, where the second LC-filter design method is used, are given in Fig. 5.



	2-level half bridge	3-level half bridge	2-level full bridge	3-level full bridge	2-level 3-phase inverter	3-level 3-phase inverter
L [µH]	850	430	400	220	430	190
C [µF]	15	16	9	8	13	13
fres [Hz]	1409	1919	2653	3794	2129	3202

a)



	2-level half bridge	3-level half bridge	2-level full bridge	3-level full bridge	2-level 3-phase inverter	3-level 3-phase inverter
L [µH]	1650	800	550	400	550	440
C [µF]	20	18	8	9	8.5	13
fres [Hz]	876	1326	2399	2653	2328	2104

b)

Fig. 5. LC-filter sizes when inverters are connected a) to 750 V DC and b) to 1500 V DC, LC-filter design: THD_u is ≤ 2 % and $\hat{\imath}_{ripple}$ is ≤ 20 %

The THD of the inductor current is smaller than in the previous case, it is 9,4 -13,8 % depending on the inverter topology. The losses of the inductor are smaller than in the previous case because of the smaller ripple current [4]. The current stresses, switching and conduction losses in the IGBTs of the inverters are smaller because of the smaller ripple current [4]. The resonant frequencies of the filters are lower than in the previous case. The resonant frequencies are between 1409 Hz and 3794 Hz when inverters are connected to 750 V DC and between 876 Hz and 2653 Hz when inverters are connected to 1500 V DC as seen in Fig 5. The inductance values are between 0,011 p.u. (three-level three-phase inverter connected to 750 V DC) and 0,098 p.u. (two-level half bridge connected to 1500 V DC) and the capacitance values are between 0,013 p.u. (three-level full bridge connected to 750 V DC and two-level full bridge connected to 1500 V DC) and 0,033 p.u. (two-level half bridge connected to 1500 V DC).

C. Discussion

The waveform of the inductor current is changed when different inverter topologies are used. The largest ripple current is located in different places depending on the inverter topology. The inductor currents and output voltages of three-level full bridge connected to 750 V DC are presented in Fig.6 when both of the LC-filter design methods are used.

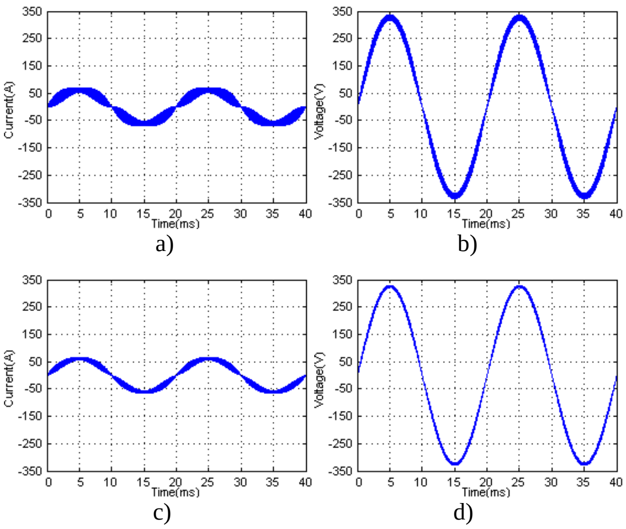


Fig. 6. a) Inductor current and b) output voltage when three-level full bridge is connected to 750 V DC and THD_u is ≤ 5 %, c) inductor current and d) output voltage when three-level full bridge is connected to 750 V DC and THD_u is ≤ 2 %

According to the results presented in Fig. 4 and in Fig. 5, the filter inductors required with three-level inverters are almost half the size of those with the comparable two-level inverters when the inverters are connected to 750 V DC. The reason for the difference is lower modulated voltage harmonics produced by three-level inverters. The harmonic content of the output voltage with the three-level inverters is small, because there are more voltage levels in the output voltage than with two-level inverters. The reduced size of filter inductors is an important advantage because the passive filter components are substantial causes to the weight, cost and loss of inverters [8].

When the supply voltage of the inverters is raised up to 1500 V DC, the filter inductance value required with three-level half bridge is furthermore half the inductance value needed with the two-level half bridge. The difference between the inductance values is smaller when full bridges or three-level inverters are used because of the smaller modulation index. All potential three-level inverter output voltage levels are not used when modulation index is under 0,5.

3. Voltage and current stresses of the inverters

The voltage and current stresses of IGBTs and diodes are calculated to all inverter topologies when they are connected to 750 V DC or to 1500 V DC. The results, when the inverters are connected to 750V DC, are shown in Table II. The upper peak or the average current values in the tables are calculated when the first LC-filter design method is used and the lower values are calculated when the second LC-filter design method is used. The results are presented in Table III when the inverters are connected to 1500 V DC. The modulation index of inverters is also shown. The IGBTs and diodes of the inverters, which voltage and current values are presented in Tables II and III, are marked in Fig. 3.

The theoretical maximum voltage stress of power semiconductor switches and diodes is $u_{dc}/2$ when three-level inverters are used, which is half of the voltage stress on two-level inverters [8]. This is shown in Tables II and III.

Table II. – Voltage and current stresses when inverters are connected to 750 V DC

Inverter	Mod Ind	$\hat{u}$ [V]	$\hat{i}_{IGBT(1,2)}$ [A]	$\hat{i}_D$ [A]	$i_{IGBT\,1,av}$ [A]	$i_{IGBT\,2,av}$ [A]	$i_{D,av}$ [A]
2-level half bridge	0,87	750	66,5 64,2	66,5 64,2	16,2 16,5		3,4 3,2
3-level half bridge	0,87	375	69,5 66,6	69,5 66,6	13,9 13,3	20,4 19,6	6,5 6,2
2-level full bridge	0,43	750	80,8 73,2	80,7 73,2	13,1 13,1		6,5 6,4
3-level full bridge	0,43	375	70,5 66,4	70,4 66,4	6,7 6,7	19,6 19,6	12,9 12,9
2-level 3-phase inverter	0,87	750	83,2 79,2	66,5 65,8	15,5 15,5		3,1 3,0
3-level 3-phase inverter	0,87	375	84,4 73,5	72,6 64,2	14,2 14,2	23,4 21,0	6,9 6,8

The maximum current stresses of IGBTs and diodes are the same as the maximum current of the filter inductor in one-phase load inverters. The peak current of IGBTs and diodes differs from each other in three-phase inverters, the maximum current stresses of IGBTs are the as the maximum current of the filter inductor but the peak current of the diodes is smaller. The IGBTs and diodes of two-level full bridge and three-phase inverters has the largest peak current in Table II because the maximum ripple current of the inductor is located at the same place than the peak of the fundamental current. The maximum and average current stresses of all IGBTs are the same in two-level inverters. The lower the modulation index, the bigger the average current of the diodes.

The maximum current which flows through the outer IGBT ($IGBT_1$) and the inner IGBT ($IGBT_2$) in three-level inverters is the same, but average currents differ from each other. The lower the modulation index, the smaller the average current of the outer IGBT. The flowing current though the antiparallel diodes in three-level inverters is almost zero. The currents of clamping-diodes are presented in Tables II and III in the case of three-level inverters. The lower the modulation index, the bigger the average current of clamping diodes.

Table III. - Voltage and current stresses when inverters are connected to 1500 V DC

Inverter	Mod Ind	$\hat{u}$ [V]	$\hat{i}_{IGBT(1,2)}$ [A]	$\hat{i}_D$ [A]	$i_{IGBT\ 1,av}$ [A]	$i_{IGBT\ 2,av}$ [A]	$i_{D,av}$ [A]
2-level half bridge	0,43	1500	73,6 70,8	73,6 70,8	12,6 13,2		6,2 6,5
3-level half bridge	0,43	750	79,6 73,1	79,6 73,1	6,6 6,7	19,4 19,6	12,8 12,8
2-level full bridge	0,22	1500	84,3 73,6	84,2 73,5	11,5 11,5		8,1 8,1
3-level full bridge	0,22	750	80,6 73,2	80,6 73,2	3,3 3,3	19,6 19,6	16,2 16,2
2-level 3-phase inverter	0,43	1500	86,0 73,2	78,6 69,7	13,2 13,1		6,5 6,4
3-level 3-phase inverter	0,43	750	79,3 70,3	79,1 70,2	7,1 6,7	21,3 19,7	14,2 13,0

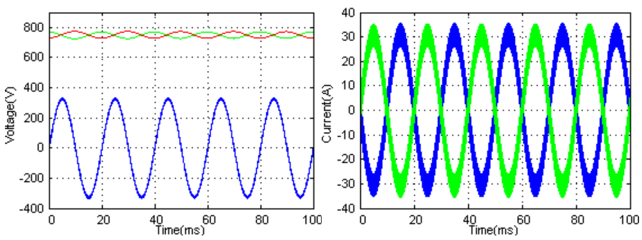
It can be concluded from Tables II and III that there are not very remarkable differences in the current stresses of IGBTs and diodes when the size of the LC-filter is changed. The maximum currents of IGBTs and diodes are smaller when the second LC-filter design method is used because of smaller ripple current in the inductor. The average currents of the IGBTs and diodes are almost the same as in the previous case.

4. Functional requirements of the inverters

The inverters are suitable to the bipolar LVDC distribution only if they fulfil certain functional requirements. The inverters should be capable of producing the wanted sinusoidal 230 V rms AC voltage with the minimum DC voltage and the inverters should withstand half-wave rectifying loads.

A. The half bridges

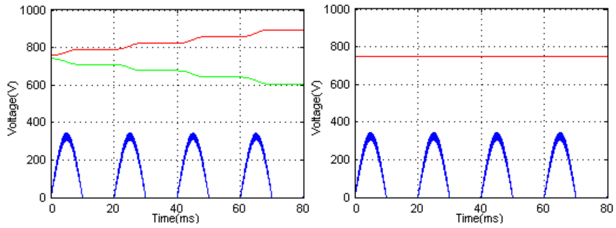
The half bridges are simple, low-cost and easy to control. Because of fundamental frequency current which circulates though the DC link capacitors and the connection of half bridge, the mutual voltages of capacitors fluctuate by 50 Hz base frequency. This is shown in Fig. 7.



a) b)

Fig. 7. a) Output voltage, voltages of the DC link capacitors and b) currents of the DC link capacitors when two-level half bridge is connected to 1500 V DC

DC link capacitors need to be large to balance the voltage fluctuation. It is not even possible to supply half-wave rectifying load because the voltage balance of the capacitors doesn't persist without a balancing circuit, as shown in Fig. 8 a. The balancing circuit consists of the two IGBTs, and the inductor which is connected to the midpoint of the DC link [9].



a) b)

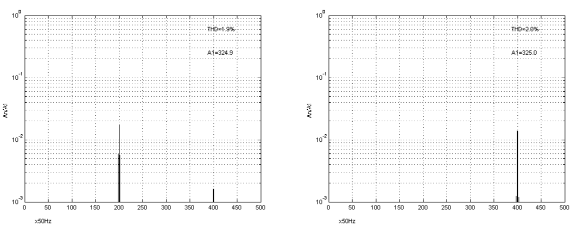
Fig. 8. Load voltage and voltages of the DC-capacitors when a) three-level half-bridge and b) three-level full bridge supplies half-wave rectifying load

It is not possible to produce the required sinusoidal 230 V rms AC voltage with half bridges connected to 750 V DC if the DC voltage is reduced by 25 % because the modulation index would increase to be over one. Half bridges are also problematic from the electrical protection point of view, because an active limiting of short-circuit current, which flows through the DC link capacitors, is difficult. The currents of the DC link capacitors are presented in Fig. 7.

Operational grounding can be used with half bridges when these are connected to 1500 V DC. Asymmetrical loads can also be supplied, because the possible balancing circuit of the DC link in the case of a bipolar connected rectifier or the control of an active rectifier in the case of unipolar connection can keep the voltage balance between the two DC link capacitors.

B. The full bridges

The structure of the full bridge is more complex than the structure of the half bridge, but the passive components, which are needed both on the DC and AC side, are smaller. Small capacitors in the DC link are sufficient and components of the LC-filter are smaller. Full-bridges don't produce harmonic currents at the switching frequency as the half bridges do. The first group of switching harmonics is located at twice the switching frequency as seen in Fig. 9.



a) b)

Fig. 9. Spectrum of the output voltage when two-level a) half bridge and b) full bridge is connected to 750 V DC and the second LC-filter design method is used

It is possible to supply half-wave rectifying loads by full bridges as shown in Fig 8 b. The modulation index of full bridge inverters is always under 0,5 both at the 750V and 1500 V DC voltage level, so it is possible to produce 230 V rms AC voltage to the customer in spite of the reduced

DC voltage level. The drawback of the low modulation index is that all potential three-level inverter output voltage levels are not used.

C. The three-level inverters

The modulation index of three-phase inverters connected to 750 V DC is high (0,87). The required size of the filter inductor connected with three-level three-phase inverter is half the size of an inductor connected with the two-level three-phase inverter. It is possible to produce 230 V rms AC voltage with three-phase inverters connected to 750 V DC nevertheless DC voltage reduces 25 % if the modulation index is boosted 15 % by the injection of a third harmonic component to the sinusoidal modulation references or by using the vector modulation.

5. Conclusion

The suitability of different inverter topologies for LVDC distribution is analyzed. Two- and three-level single-phase half and full bridges and three-phase load inverters are compared when they are connected to 750 V DC or 1500 V DC. The bases of the comparison were the size of required LC-filters, voltage and current stresses of the components, capability to operate with reduced DC voltage and feed half-wave rectifying load. Two different design methods for LC-filters were used.

According to the results, the most suitable single-phase load inverter topologies connected to 750 V DC are two- and three-level full bridges. Full bridges are able to supply half-wave rectifying loads and these are capable of producing 230 V rms AC to the customer in spite of the reduced DC voltage level. The size of the required passive filter components with three-level inverters is just half of the size of the components with two-level inverters. The drawback is that the structures of the three-level inverters are more complex. When load inverters are fed with 750 V DC in a unipolar way, the electrical network of the customer should be used isolated or the galvanic isolation transformer has to be used.

The difference between LC-filter sizes is not so significant when comparing with two-and three-level inverters connected to 1500 V DC. Because of the low modulation index, all potential three-level inverter output voltage levels cannot be used. The maximum voltage stresses of the IGBT-components are $u_{dc}/2$ in three-level inverters but u_{dc} in two-level inverters. Smaller voltage stresses are a remarkable advantage especially at higher voltage levels. The most suitable load inverter topologies connected to 1500 V DC are three-level inverters. Operational grounding of the customer network can be used with half bridges and three-phase load inverters.

The future work within the topic will include the power loss calculations, simulations and measurements in the laboratory with the inverters and filters, which are the most suitable for the bipolar LVDC distribution. Future work will provide answers to questions related to the total lifecycle costs and efficiency of different inverter topologies in the LVDC distribution network.

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