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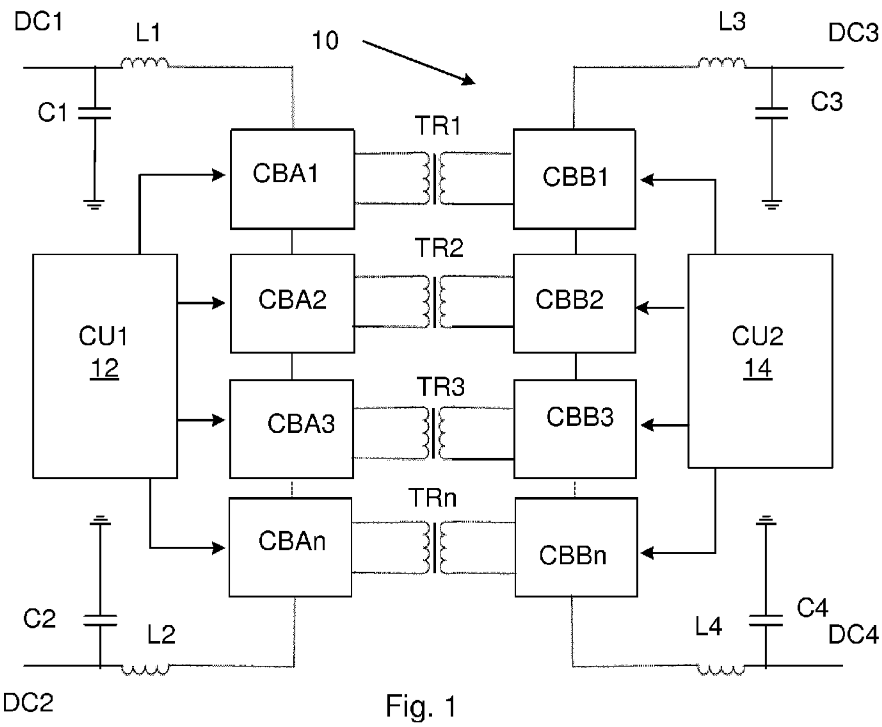

Fig. 1

(57) Abstract: A DC to DC converter (10) comprises n converter blocks (CBA1, CBA2, CBA3,... CBAn), each corresponding to an AC phase, connected in series in a first chain between a first and a second DC terminal DC1, DC2, n converter blocks CBB1, CBB2, CBB3, CBBn), each corresponding to an AC phase, connected in series in a second chain between a third and a fourth DC terminal (DC3, DC4) and n AC connections, each comprising a transformer (TR1, TR2, TR3, TRn) interconnecting two converter blocks, where $n \geq 3$. Each converter block comprises a wave-shaper branch connected in parallel with a switching arrangement. In each converter block of a chain the wave-shaper branch generates rectified wave shapes and the switching arrangement controls the application of rectified wave shapes across a winding of a corresponding transformer for generating an AC phase wave shape, while the sum of the rectified wave shapes of the chain contribute to the DC voltage between the two DC terminals.

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SERIES MODULAR DC TO DC CONVERTER

FIELD OF INVENTION

The present invention generally relates to voltage source converters. More particularly the present invention relates to a Direct Current to Direct Current converter.

BACKGROUND

The Modular multilevel converter (MMC) has become of interest to use in a number of different areas and topologies. One area of interest is the Direct Current - Direct Current (DC - DC) converter. One example of this is WO 2013/017160 where three parallel phase legs of one conversion unit are coupled to three parallel phase legs of a second conversion unit. In this topology each arm of the MMC has to be rated for pole to pole voltage and thus the overall submodule rating becomes large.

One of the research trends has been to propose new topologies to minimize the overall submodule rating and thus, significantly reduce the overall cost, losses, and converter footprint. The series connection of phases has been identified as one of the best solution to achieve this objective.

Series connected topologies have been proposed for DC/DC conversion; see for instance WO 2013/004282. However, these converters typically require bulky capacitors in addition to submodules to support the DC-link voltage.

There is in this regard room for improvement especially if using this topology in DC/DC conversion and with a view of making the converter less bulky along with a reduction of overall cost and losses.

SUMMARY OF THE INVENTION

The present invention is directed towards obtaining a DC - DC converter with reduced cost, size and losses.

This object is according to a first aspect of the present invention achieved through a Direct Current to Direct Current, DC to DC, converter comprising a first number n of converter blocks, each corresponding to an alternating current, AC, phase and connected in series in a first chain between a first and a second DC terminal forming a first DC link, a second number n of converter blocks, each corresponding to an alternating current, AC, phase and connected in series in a second chain between a third and a fourth DC terminal forming a second DC link and a number n of AC connections, each comprising a transformer interconnecting a converter block of the first chain with a corresponding converter block of the second chain, where $n \geq 3$, each converter block comprising:
a wave-shaper branch connected in parallel with a switching arrangement, the wave-shaper branch comprising a first wave-shaper arm formed as a chain-link of submodules and the switching arrangement comprising a first string of series-connected switches in parallel with the wave-shaper branch,
where in each converter block of a chain, the wave-shaper branch is configured to generate at least one rectified wave shape and the switching arrangement is configured to control the application of said at least one rectified wave shape across a winding of a corresponding transformer for generating an AC phase wave shape and the sum of the rectified wave shapes of the chain contribute to the DC voltage between the two DC terminals.

It is possible that the converter comprises at least one control unit configured to control each converter block. Such control of a converter block may comprise controlling all wave-shaper arms of the wave-shaper branch to generate rectified wave shapes and controlling the switching arrangement to apply rectified wave shapes across the winding of the corresponding transformer.

The AC wave shape is generated with a fundamental frequency. It is possible that this frequency is higher than 50/60 HZ, for instance higher than 100 Hz.

The present invention has a number of advantages. It has a low cost, low losses and a low rating. Furthermore the converter rating and the number of cells is lowered compared with previous converters of the same type.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will in the following be described with reference being made to the accompanying drawings, where

fig. 1 schematically shows one general series modular multilevel converter realization of a DC/DC converter with a first and second chain of converter blocks coupled to each other via transformers,
fig. 2 schematically shows a first realization of a converter block connected to one winding of a transformer,
fig. 3 schematically shows the generation of phase voltages by a chain of converter blocks in the first converter realization for forming sinusoidal AC wave shapes,
fig. 4 schematically shows pole-to-pole DC voltages provided by the converter with different numbers of converter blocks in the chains,
fig. 5 schematically shows the generation of voltages of a chain of converter blocks in the first converter realization for forming trapezoidal AC wave shapes,
fig. 6 schematically shows the first converter realization when there is a fault on an AC link between the two uppermost converter blocks of the two chains,

fig. 7 schematically shows a variation of the first converter realization for handling the fault on the AC link,
fig. 8 schematically shows a second realization of a converter block connected to one winding of a transformer,
fig. 9 schematically shows the generation of voltages of a chain of converter blocks in the second converter realization for forming sinusoidal AC wave shapes,
fig. 10 schematically shows the generation of voltages of a chain of converter blocks in the second converter realization for forming trapezoidal AC wave shapes, and
fig. 11 schematically shows a variation of the second converter realization for handling a fault on the AC link between the two uppermost converter blocks of the two chains.

DETAILED DESCRIPTION OF THE INVENTION

In the following, a detailed description of preferred embodiments of the invention will be given.

Fig. 1 shows one realization of a series modular multilevel converter (SMMC) 10 for converting between Direct Current (DC) and Direct Current (DC). Such a converter may find use in a number of different networks, for instance in a High Voltage Direct Current (HVDC) network, where the HVDC network may operate at voltage levels of 400 kV and above.

A first DC side of the converter 10 comprises a first and a second DC terminal DC1 and DC 2 and a second DC side of the converter comprises a third and a fourth DC terminal DC3 and DC4. The first and second DC terminals DC1 and DC2 may here form a first DC link, while the third and fourth DC terminals may form a second DC link. Here it may be mentioned that the first DC terminal DC1 typically has the highest electric potential of the first DC link, while the third DC terminal DC3 has the highest electric potential of the second DC link.

The first DC terminal DC1 is connected to a first inductor L1 and the second DC terminal DC2 is connected to a second inductor L2. A first capacitor C1 is connected between ground and a junction between the first DC terminal DC1 and the first inductor L1. A second capacitor C2 is connected between ground and a junction between the second DC terminal DC2 and the second inductor L2. There is also a first chain with a first number n of converter blocks connected in series between the first and second inductor L1 and L2. The first chain of converter blocks, which chain forms a first conversion unit, is thereby connected between the first and second DC terminals DC1 and DC2. The number of converter blocks n connected in series in this way correspond to a number of Alternative Current (AC) phase wave shapes that are to be generated by the converter blocks. As can be seen there is therefore a first converter block CBA1, a second converter block CBA2, a third converter block CBA3 and an nth converter block CBAn in the first chain.

In a similar manner the third DC terminal DC3 is connected to a third inductor L3 and the fourth DC terminal DC4 is connected to a fourth inductor L4. A third capacitor C3 is connected between ground and a junction between the third DC terminal DC3 and the third inductor L3. A fourth capacitor C4 is connected between ground and a junction between the fourth DC terminal DC4 and the fourth inductor L4. There is also a second chain with a second number n of converter blocks connected in series between the third and fourth inductor L3 and L4. The second chain of converter blocks, which chain forms a second conversion unit, is thereby connected between the third and fourth DC terminals DC3 and DC4. The number of converter blocks n connected in series in the second chain is the same as the number of AC phase wave shapes and the number of converter blocks in the first chain, which phases are to be generated by the converter blocks. Therefore, as can be seen in fig. 1 there is a first converter block

CBB1, a second converter block CBB2, a third converter block CBB3 and an nth converter block CBBn in the second chain. In many converter realizations n = 3. However, as can be seen in fig. 1, it is also possible that n > 3.

The converter blocks in the first chain are coupled to the converter blocks in the second chain through AC connections, each comprising a transformer interconnecting a converter block of the first chain with a corresponding converter block of the second chain. There are more particularly n transformers in the converter 10. The first converter block CBA1 in the first chain is connected to a first winding, such as a primary winding, of a first transformer TR1, while a first converter block CBB1 of the second chain is connected to a second winding, such as a secondary winding, of the first transformer TR1. The second converter block CBA2 in the first chain is connected to a first winding of a second transformer TR2, while a second converter block CBB2 of the second chain is connected to a second winding of the second transformer TR2. The third converter block CBA3 in the first chain is connected to a first winding of a third transformer TR3, while a third converter block CBB3 of the second chain is connected to a second winding of the third transformer TR3. Finally, the nth converter block CBAn in the first chain is connected to a first winding of an nth transformer TRn, while an nth converter block CBBn of the second chain is connected to a second winding of the nth transformer TRn.

Each converter block forms an Alternating Current (AC) wave shape across the corresponding transformer winding. Thereby a pair of converter blocks in the first and second chains corresponds to an AC phase.

In order to form the different wave shapes there is a first control unit CU1 12 controlling the converter blocks in the first chain and a second control unit CU2 14 controlling the converter blocks in the second chain. The chains of converter blocks may be provided at the same location and therefore the first and second control units 12 and 14 may with advantage be combined into one control unit.

A control unit may be realized in the form of discrete components, such as one or more Field Programmable Gate Arrays (FPGAs), Application Specific Integrated Circuits (ASICs) or Digital Signal Processors (DSPs). However, it may also be implemented in the form of a processor with accompanying program memory comprising computer program code that performs the desired control functionality when being run on the processor.

As has been indicated earlier, it is possible that the converter 10 in fig. 1 may only comprise 3 phases. It should also be realized that it is possible to omit one or more of the first, second, third and fourth capacitors C1, C2, C3 and C4 as well as to remove one or more of the first, second, third and fourth inductors L1, L2, L3 and L4.

A converter block typically comprises a wave-shaper branch generating at least one rectified wave shape and comprising at least one wave-shaper arm, where the branch is connected in parallel with a switching arrangement comprising at least two switches, which two switches are placed in a first string of series-connected switches. The first string of series-connected switches is thereby also connected in parallel with the wave-shaper branch. A converter block is more particularly configured to generate an AC wave shape based on the at least one rectified wave shape, which AC wave shape forms an AC phase. On the DC side the voltages of the rectified wave shapes generated by the wave-shaper arms of the converter blocks are summed up to form the DC voltage between the two DC terminals between which the converter modules are connected. The DC terminals associated with a chain of converter blocks are often connected to two poles of a DC system and therefore the voltage between these two DC terminals is often called a pole-to-pole voltage or DC link voltage.

There are a number of ways in which the converter blocks may be formed.

A first variation of a converter block is shown in fig. 2. The converter block comprises a single wave-shaper arm. The wave-shaper branch thus comprises a single wave-shaper arm, in the figure shown as an AC voltage source 16, connected in parallel with the switching arrangement SA1, which switching arrangement SA1 comprises the previously mentioned first string of switches S1 and S3 and a second string of switches S4 and S2 in parallel with the first string, which two strings of switches are both connected in parallel with the voltage source 16. Thereby the switching arrangement SA1 is an H bridge switching arrangement. The transformer winding connected to the converter block has one end connected to a junction between the first and the third switch S1 and S3 in the first string of switches and the other connected to a junction between the fourth and the second switch S4 and S2 of the second string of switches. The voltage source 16 may here be formed as a chain-link of submodules with bipolar voltage contribution capability, such as full-bridge submodules SMA1 and SMA2, or as a chain-link of submodules with unipolar voltage contribution capability, such as half-bridge submodules SMB1 and SMB2. The switches may in turn be realized as a string of transistors, like Insulated Gate Bipolar Transistors (IGBTs), with anti-parallel diodes.

In fig. 2 the AC voltage V_{ac} across the transformer winding is also shown as well as the rectified phase voltage Vdc_ph generated by the wave-shaper arm 16.

It should here be realized that a wave-shaper arm may also be made up of a mixture of submodules with unipolar and bipolar voltage contribution capabilities.

The wave-shaper arm thus has series-connected half-bridge or full-bridge submodules, and an H-bridge switching arrangement connected in parallel with the wave-shaper arm. Each string in the H-bridge arrangement may comprise two series connected switches. In each converter block of a chain, the wave-shaper arm 16 generates at least one rectified wave shape, here in the form of a single rectified AC voltage, and the switches of the switching arrangement SA1 operate at a fundamental switching frequency to generate an AC voltage V_{ac} across the transformer winding, which fundamental frequencies may as an example be higher than 50/60 Hz, such as above 100 Hz. The switching arrangement thereby controls the application of the at least one wave shape across a winding of the corresponding transformer for generating an AC phase wave shape. The sum of the rectified wave shapes in a chain also contributes to the DC voltage between the DC terminals, i.e. contributes to the DC voltage on the DC link.

As a control unit is used to control a converter block, it is clear that a control unit controls the turning on and off of the switches in the submodules as well as the switches in the switching arrangement in order to perform the DC/DC conversion.

Fig. 3 shows one way of operating a chain of converter blocks in the first realization of the converter in order to form three rectified wave shapes or rectified phase voltages for forming three sinusoidal AC wave shapes as well as for forming a DC voltage.

Each wave-shaper arm 16 of a converter block forms a rectified AC wave shape, here in the form of a rectified sine wave, where three rectified sine waves Vdc_p1, Vdc_p2 and Vdc_p3 are separated or phase shifted from each other by 60 degrees, which through the control of the switching arrangement SA1 results in non-rectified phase voltages phase shifted from each other by 120 degrees. Here the first and the second switch S1 and S2 are jointly operated for applying one polarity of the rectified wave shape Vdc_ph across the corresponding transformer winding and the third and fourth switches S3 and S4 are operated for changing the polarity of the rectified wave shape across the transformer winding and thereby an AC wave shape is obtained. It can be seen that every other rectified wave shape has it is polarity reversed.

However, for forming the DC voltage, the rectified wave shapes Vdc_ph1, Vdc_ph2 and Vdc_ph3 of the phases are added to each other and thereby a pole-to-pole DC voltage Vpp or DC link voltage with ripple as shown in fig. 3 is obtained, which ripple is smoothed through suitable filtering, such as through using the capacitors and inductors connected to the DC terminals.

In the 3-phase operation shown in fig. 3, the pole to pole voltage will be equal to the sum of three rectified AC voltages having 60° phase shift, which will have 6N harmonic ripple, i.e. the ripple has sixth order harmonics.

This ripple can be significantly reduced through the addition of further phases. This is done through adding converter blocks in the chains coupled to each other via additional transformers. The reduction of ripple can be observed in fig. 4, which shows the pole-to-pole DC voltage or DC link voltage for three phases Vpp3, for 5 phases Vpp5, for nine phases Vpp9 and fifteen phases Vpp15, where each converter block is rated 1 per unit (p.u.). As can be clearly seen in fig. 4, the ripple decreases the more phases that are used and thereby the filtering requirements are relaxed the more phases that are used.

To reduce the ripple in the DC link, the number of phases may thus be increased. The total number of phases could as an example be an odd number to achieve minimum possible ripple. Thereby the number of converter blocks will also be odd. Utilizing higher number of phases is useful for very high-power applications. When the number phases are increased, the rating of each transformer used can be limited. The volume occupied by a transformer is thereby limited and it is therefore also more easily transported.

The comparison of voltage ripple with different number of phases is shown in Table 1. It can be observed that the voltage ripple reduces significantly as the number of phases increase.

	Min(multiple of AC peak)	Max(multiple of AC peak)	Ripple (pu)
3 phases	1.7320508	2	0.26794919
5 phases	3.0776835	3.236068	0.15838444
9 phases	5.6712818	5.7587705	0.08748866
15 phases	9.5143645	9.5667722	0.05240778

TABLE I

For DC to DC converter applications, the voltage wave shapes across transformer need not be sinusoidal. It is thus possible to use other wave shapes in order to reduce the ripple.

This is exemplified in fig. 5, which shows three phases Vdc_ph1, Vdc_ph2 and Vdc_ph3 of a rectified wave shape separated by sixty degrees from each other and obtained via the first converter realization. In this case the wave shape is a trapezoid wave shape having a cycle divided into six time intervals. In a first time interval, the voltage of the shape rises to a maximum level Vdc, which maximum level is then kept for a number of time intervals, in this example three. The maximum level is thereby kept during a second, third and fourth time interval. Then the voltage decreases to zero during a fifth time interval and remains at zero during a sixth time interval. The wave shape generation is then repeated. The rectified wave shape thus has a cycle where the voltage rises from zero to a maximum value during a first time interval, decreases from the maximum value to zero during a last time interval and remains at the maximum value during intermediate time intervals. It can be seen that through this type of rectified AC curve generation, a smooth DC link voltage Vpp is obtained requiring a minimum amount of filtering.

The ripple in the pole-to-pole voltage can thus be made almost zero with the trapezoidal modulation scheme. The basic idea is that one of the arm voltages should be ramped up while another is ramped down so that the pole-to-pole voltage is always maintained equal to 2Vdc (considering ripple in submodule capacitor voltages is negligible).

In the converter according to the first realization a fault may occur in the uppermost AC connection, i.e. in the connection between the first converter block CBA1 of the first chain and the first converter block CBB1 of the second chain. This connection may be termed an internal converter bus. An example of such a fault occurring in the first converter block CBA1 of the first chain adjacent the first transformer TR1 is schematically shown in fig. 6. It can be seen that the fault will lead to a fault current running from the first DC terminal DC1 through the first converter block CBA1 of the first chain to the fault on the AC connection. In the first converter block CBA1, the fault current more particularly runs through the first wave-shaper arm and the switching arrangement. One issue with series connected topologies is submodule capacitors of the upper-most arms in the uppermost converter blocks get over-charged during such an internal converter bus fault.

Consider a 3-phase system, if there is converter bus fault between the first converter blocks of the first and second chains, then the pole-to-pole voltage will appear across the wave-shaper arm of the first converter block CBA1 in the first chain, as shown in Figure 6. Even if the converter is blocked, the sum of the submodule voltages Vdc of the upper-arm Vdc is less than pole to pole voltage and thus, the submodule capacitors get charged via diodes up to 2Vdc.

In order to handle such a fault and protect the submodules, it may be necessary to bypass one or more wave-shaper arms. One variation of the first converter realization of the converter that achieves this is schematically shown in fig. 7. As can be seen in this figure there is a first string of bypass switches BPSS1 connected in parallel with the first converter block of the first chain and a second string of bypass switches BPSS2 connected in parallel with the first converter block of the second chain, where such a string of bypass switches is connected in parallel with the wave-shaper arm of the corresponding converter block. The string of bypass switches is thus connected in parallel with the wave-shaper arm of the converter block that is closest to the DC terminal of the DC link having the highest electric potential. The bypass switches may in this case be realized as thyristors, which are jointly being turned on in the case of detection of fault on the AC connection. The thyristors may be oriented downwards. Their direction of conductivity may thus be from the first and third DC terminals DC1 and DC3 towards the second and fourth DC terminals DC2 and DC3, respectively.

During converter bus fault at the top-most phase, the thyristors should thus be fired so that a fault current will be bypassed from the submodules of the top-most wave-shaper arm. It should be noted that, more thyristor bypass strings may be required if the number of phases increase. For example, consider a 9-phase system with each wave-shaper arm rated for Vdc/3 such that the pole-to-pole voltage obtained is 2Vdc. If it is assumed that a sinusoidal modulation scheme is utilized, then the bypass thyristors are required for all those top-most arms whose sum of submodule voltages reach up to 2Ud to prevent the overcharging of submodule capacitors due to the fault current. The faulty AC connection will block up to Vdc/3 and hence it is necessary to bypass 2Vdc-(Vdc/3) submodules that is equal to 5Vdc/3, i.e., top five phase valve arms need to be bypassed. It can thereby be seen that the number of wave-shaper arms being bypassed is a number that together have a rating that is the difference between the DC link voltage and the rating of one wave-shaper arm.

A second variation of a converter block is shown in fig. 8. The converter block comprises two wave-shaper arms. The wave-shaper branch thus comprises two wave-shaper arms, a first and a second wave-shaper arm, in the figure shown as a first and second AC voltage source 16A and 16B, with the branch being connected in parallel with a switching arrangement SA2, which switching arrangement SA2 only comprises a first string of switches S1, comprising a first and a second switch S1 and S2. Thereby the string of switches S1 and S2 is also connected in parallel with the two voltage sources 16A and 16B. The transformer winding connected to the converter block has one end connected to a junction between the first and the second switches S1 and S2 in the first string of switches and the other connected to a junction between the two voltage sources 16A and 16B. Also in this case the voltage sources 16A and 16B may be formed as chain-links made up of submodules with bipolar voltage contribution capability, such as full-bridge submodules SMA1 and SMA2 or as a chain-link of submodules with unipolar voltage contribution capability, such as half-bridge submodules SMB1 and SMB2. The switches may in turn be realized as a string of transistors, like anti-parallel thyristors or IGBTs, with anti-parallel diodes or as a string of anti-parallel thyristors. Also in this case a wave-shaper arm may be made up of a mixture of submodules with unipolar and bipolar voltage contribution capabilities. The first voltage source 16A in this case generates a first voltage or rectified wave shape Vdc_phU f or an upper or positive half of an AC wave shape and the second voltage source 16B generates a second voltage or rectified wave shape Vdc_phL for a lower or negative half of the AC wave shape.

The converter block may thus comprise two wave-shaper valve arms which comprise series-connected half-bridge or full-bridge submodules, and a switching arrangement or two director valve arms that comprise series-connected switches that may be IGBTs with anti-parallel diodes or series-connected anti-parallel thyristors. If anti-parallel thyristors are utilized in the switching arrangement SA2, the wave-shaper arm requires 100% full-bridge submodules in order to provide commutation voltage and most importantly to sustain transient operating conditions. On the other hand, the state-of-the-art DC/DC converters utilize higher fundamental frequency to reduce the transformer size and cost. However, thyristor commutation will be difficult at higher fundamental frequency due to time limitations in each fundamental cycle. The switching arrangement (director valve arm) may thereby need to be realized as series connected IGBTs for higher fundamental switching frequency operation.

The operation may generally be performed in the following way.

In a converter block, one of the wave-shaper arms, denoted an active or AC arm, generates the rectified AC voltage and the corresponding director valve or switch of the switching arrangement connects this active arm and applies the generated rectified wave shape to the transformer. At any instance in time, three out of six wave-shaper arms are utilized for generating AC voltages and the other three arms, which may be denoted DC arms or inactive, are available for compensating the voltage ripple in the pole-to-pole DC voltage. For example, during a positive half-cycle, the upper arm of each phase will be connected to the transformer winding of the AC connection, while the lower arm compensates the DC voltage ripple. The AC voltage wave shape across the transformer can be trapezoidal or sinusoidal.

The first wave-shaper arm 16A thus generates a first rectified wave shape Vdc_phU and the second wave-shaper arm 16B generates a second rectified wave shape Vdc_phL. Moreover, the first switch S1 of the first string in the switching arrangement SA2 applies the wave shape Vdc_phU of the first wave-shaper arm 16A across the connected transformer winding for generating a positive half cycle of the AC wave shape Vac_ph and the second switch S2 of the first string in the switching arrangement SA2 applies the wave shape Vdc_phL of the second wave-shaper arm 16B across the connected transformer winding for generating the negative half cycle of the AC wave shape Vac_ph.

Thereby a wave-shaper arm has a half cycle when it is active in contributing to forming of an AC wave shape and a half cycle when it is inactive in such forming. An inactive wave-shaper arm of at least one converter block in a chain may then be used for countering voltage ripple in the DC link voltage caused by the rectified wave shapes of the active wave-shaper arms.

Fig. 9 shows one way of operating a chain of three converter blocks in the second realization of the converter in order to form a number of phase voltages that are to be used for forming three sinusoidal AC wave shapes as well as for forming a DC voltage.

Each wave-shaper arm of a converter block forms one half cycle of the AC wave shape of the phase. Thereby, in the first or upper wave-shaper arms 16A of the converter blocks are used for forming the voltages Vdc_phU1, Vdc_phU2 and Vdc_phU3 of the positive half cycle and the second or lower wave-shaper arms 16B of the converter blocks are used for forming the voltages Vdc_phL1, Vdc_phL2 and Vdc_phL3 of the negative half cycle. However, as can be seen both wave-shaper arms generate positive wave shapes. The switching arrangement SA2 controls which of the generated voltages is to be applied across the transformer winding as well as the polarity, where the first switch S1 connects the first upper wave-shaper arm 16A across the transformer winding with one polarity and the second switch S2 connects the second lower wave-shaper arm 16B across the winding with an opposite polarity.

The three rectified sine waves provided by the wave-shaper branches (upper and lower wave-shaper arms) of the converter blocks are separated or phase shifted from each other by a phase shift of 60 degrees, which through the control of the switching arrangement SA2 results in a non-rectified phase voltage separated from the other phase voltages by of 120 degrees.

In order to form the DC voltage, the rectified wave shapes are added to each other and thereby a DC voltage Vdc_sum with ripple as shown in fig.

9 is obtained. However, this ripple is avoided through the inactive wave-shaper arms being used to compensate the ripple, where inactive in this case means inactive in relation to the forming of an AC wave shape on the AC connection. The inactive or DC wave-shaper arms are thus used to form a compensating voltage Vdc_comp in order to counteract the ripple, resulting in the pole-to-pole DC voltage Vpp shown in fig. 9. This provides a significant relaxation of the filtering requirements. This compensation thus reduces the ripple on the DC voltage. However, it does not influence the AC voltage.

Put differently, for a 3-phase system, each AC arm will generate the rectified AC voltage as commanded by the corresponding control unit. The sum of the active arm voltages will have 6N harmonic ripple and the other three DC arms are utilized to compensate the ripple as shown in Figure 9. If each arm rating is considered one p.u., then the pole-to-pole voltage will be equal to two p.u.

Also in this second variation of the converter it is possible to use a trapezoidal wave shape, which is schematically shown in fig. 10. Fig. 10 shows the operation of the upper and lower wave-shaper arms of three converter blocks together with the generation of the DC voltage and the three AC voltages. In this case a cycle of the wave-shaper branch comprises a first half made up of six time intervals. The cycle of the rectified wave shape thereby comprises twelve time intervals. As can be seen the upper wave-shaper arm of a converter block forms a voltage or rectified wave shape Vdc_phU1 to be used for forming a positive half of a trapezoid AC wave shape, where during a first time interval the voltage of the shape rises to a maximum level 2Vdc/3, which maximum level is then kept for a number of time intervals, in this example four, which are in a second, third, fourth and fifth time interval. Then the voltage decreases to zero during a further sixth time interval, whereupon the lower wave-shaper arm performs the same operation, i.e. forms a voltage Vdc_phL1 comprising the same shape during an equal number of following time intervals to be used for the negative half-cycle of the AC wave shape. It can also be seen that when the upper wave-shaper arm forms the positive half-cycle of the AC wave shape, the lower phase arm is used to compensate DC ripple. It can more particularly be seen that at the maximum level of the formed wave shape, the voltage Vdc_phL1 of the lower wave-shaper arm rises to half the maximum level in the second time interval and then goes back to zero in the third time interval, again rises to half the maximum level during the fourth time interval followed by a return to zero during the fifth time interval. The upper wave-shaper arm has the same type of operation when the lower wave-shaper arm generates the rectified wave shape that is to be used for the negative half- cycle of the trapezoidal shape. Thereby in the second half of the cycle of the wave-shaper branch the rectified wave shape Vdc_phU1 stays at zero in a seventh time interval, rises to half the maximum level in an eighth time interval, goes back to zero in a ninth time interval, again rises to half the maximum level during a tenth time interval, returns to zero during an eleventh time interval and then stays at zero in the twelfth time interval.

This type of operation is performed by the three converter blocks with a separation of 120 degrees in relation to each other, which as can be seen leads to the forming of trapezoidally shaped AC voltages separated by 120 degrees from each other and a smooth DC voltage Vpp. Thereby a smooth DC voltage is also here obtained requiring a minimum amount of filtering.

The submodule utilization is further improved by the use of the trapezoidal modulation scheme. It should be observed that the pole-to-pole voltage equal to 2Vdc is obtained with a valve rating of 2Vdc/3 instead of Vdc with sinusoidal modulation scheme. Thereby it is possible to also lower the voltage rating and consequently also the number of components used, compared with the sinusoidal scheme.

Also in the converter according to the second realization a fault may occur in the uppermost AC connection, i.e. in the connection between the first converter block CBA1 of the first chain and the first converter block CBB1 of the second chain.

In order to handle such a fault and protect the submodules, it may be necessary to bypass one or more of the wave-shaper arms. One variation of the second realization of the converter that achieves this is schematically shown in fig. 11. As can be seen in this figure there is a first string of bypass switches BPSS1 connected in parallel with the first or upper wave-shaper arm UA of the wave-shaper branch in the first converter block CBA1 in the first chain and a second string of bypass switches BPSS2 connected in parallel with the first or upper wave-shaper arm UA of the wave-shaper branch in the first converter block CBB1 in the second chain. The bypass switches may also in this case be realized as thyristors, which are jointly being turned on in the case of a detection of a fault on the AC connection.

Also in this case the thyristors are oriented downwards. Their direction of conductivity is thus towards the second and fourth DC terminals, respectively.

The submodule capacitors of upper-most arms are thereby protected from getting over-charged during internal converter bus fault at the upper-most phases. The pole to pole voltage will appear across the upper-arm of the first converter block CBA1 if there is converter bus fault at the corresponding AC connection and thus in the case of a fault, the submodule capacitors get charged via diodes up to 2Vdc. This is avoided through firing all the downward oriented thyristors in the director valve arm. If IGBTs are used in the switching arrangement (director valve arms), then the bypass thyristors may be required across upper-most arms as shown in Figure 11. It should be noted that, more thyristor bypass arms may be required if the number of phases increase. Basically, the bypass thyristors are required for all those top-most arms whose sum of submodule voltages reach up to 2Vdc, i.e. the pole to pole or DC-link voltage, to prevent the overcharging of submodule capacitors due to fault current.

As can be seen above, the invention has a number of advantages. It provides reduced cost, size, and losses compared to front-to-front converters with parallel wave-shaper arms. It also provides bypass of submodules during internal converter bus fault. If submodules with bipolar voltage contribution capability are used, then the converter also has a DC link fault blocking capability.

In table II there is a comparison between submodule rating of the topologies and a front to front DC /DC converter using parallel wave-shaper arms.

Topology	Overall submodule rating
Front-to-front	24*Vdc
First realization	6*Vdc
Second realization (sinusoidal)	12*Vdc
Second realization (trapezoidal)	8*Vdc

TABLE II

The invention can be varied in a multitude of ways. There are a number of ways in which switches may be implemented. They may be implemented as anti-parallel self-commutated components, such as two transistors, like Insulated Gate Bipolar Transistors (IGBTs) or Metal–Oxide–Semiconductor Field-Effect Transistor (MOSFETs), or Integrated Gate-Commutated Thyristors (IGCTS), using a self-commutated circuits with anti-parallel circuit-commutated circuits, such as an IGBT or IGCT together with a diode or thyristor, or as anti-parallel circuit commutated components, such as two anti-parallel thyristors or a thyristor with anti-parallel diode. A self-commutated component is here a component that may be directly turned off through receiving a control signal in order to stop conducting current, while a circuit-commutated component is a component needing an applied negative voltage to stop conducting current, for instance through the use of a dedicated circuit. As a thyristor is an example of one type of circuit commutated component, it can be seen that this type of circuit commutated component also has the ability of being directly turned on through receiving a control signal in addition to requiring an applied external negative voltage for being turned off. Such circuit-commutated turn off may with advantage be achieved through applying a negative voltage across the circuit-commutated component, for instance using a submodule with bipolar voltage contribution capability.

Moreover, a valve may be realized through a number of series-connected component combinations of the types described above.

From the foregoing discussion it is evident that the present invention can be varied in a multitude of ways. It shall consequently be realized that the present invention is only to be limited by the following claims.

CLAIMS

1. A Direct Current to Direct Current, DC to DC, converter (10) comprising a first number n of converter blocks (CBA1, CBA2, CBA3, ... CBAn), each corresponding to an alternating current, AC, phase and connected in series in a first chain between a first and a second DC terminal (DC1, DC2) forming a first DC link, a second number n of converter blocks (CBB1, CBB2, CBB3, CBBn), each corresponding to an alternating current, AC, phase and connected in series in a second chain between a third and a fourth DC terminal (DC3, DC4) forming a second DC link and a number n of AC connections, each comprising a transformer (TR1, TR2, TR3, TRn) interconnecting a converter block of the first chain with a corresponding converter block of the second chain, where $n \geq 3$, each converter block comprising:
a wave-shaper branch connected in parallel with a switching arrangement (SA1; SA2), said wave-shaper branch comprising a first wave-shaper arm (16; 16A) formed as a chain-link of submodules and said switching arrangement comprising a first string of series-connected switches (S1, S3; S1, S2) in parallel with the wave-shaper branch,
where in each converter block of a chain, the wave-shaper branch is configured to generate at least one rectified wave shape (Vdc_ph; Vdc_phU, Vdc_phL) and the switching arrangement (SA1; SA2) is configured to control the application of said at least one rectified wave shape across a winding of a corresponding transformer for generating an AC phase wave shape (Vac; Vac_ph) and the sum (Vdc_sum) of the rectified wave shapes of the chain contribute to the DC voltage between the two DC terminals.

2. The converter (10) according to claim 1, wherein the number $n > 3$.

3. The voltage source converter according to claim 2, wherein the number n is an odd number.

4. The converter (10) according to any previous claim, further comprising a string of bypass switches (BPSS1, BPSS2) in parallel with the first wave-shaper arm of at least one converter block (CBA1, CBB1) of each chain, which converter block is the converter block of the chain closest to the DC terminal of the corresponding DC link with the highest potential.

5. The converter (10) according to claim 4, where the strings of bypass switches are provided for a number of wave-shaper arms, which number has a rating that is the difference between the DC link voltage and the rating of one wave-shaper arm.

6. The converter (10) according to previous claim, wherein the switching arrangement of each converter block comprises a second string of switches (S2, S4) in parallel with the first string (S1, S3), where the first wave-shaper arm (16) is configured to generate said rectified wave shape as a rectified AC wave shape (Vdc_ph) and the switching arrangement is configured to provide the AC wave shape (Vac) through changing the polarity of the rectified AC wave shape.

7. The converter (10) according to claim 6, wherein one end of said transformer winding is connected to a junction between the switches of the first string and the other end is connected to a junction between the switches of the second string.

8. The converter according to any of claims 1 - 5, wherein the wave-shaper branch of each converter block comprises a second wave-shaper arm (16B), where the first wave-shaper arm (16A) is configured to generate a first rectified wave shape (Vdc_phU), the second wave-shaper arm (16B) is configured to generate a second rectified wave shape (Vdc_phL), a first switch (S1) of the first string in the switching arrangement (SA2) is configured to apply the wave shape (Vdc_phU) of the first wave-shaper arm (16A) across the connected transformer winding for generating a

positive half cycle of the AC wave shape (Vac_ph) and a second switch (S2) of the first string in the switching arrangement (SA2) is configured to apply the wave shape (Vdc_phL) of the second wave-shaper arm (16B) across the connected transformer winding for generating the negative half cycle of the AC wave shape (Vac_ph).

9. The converter (10) according to claim 8, wherein one end of the transformer winding is connected to a junction between the switches (S1, S2) of the first string and the other end is connected to a junction between the two wave-shaper arms (16A, 16B).

10. The converter (10) according to claim 8 or 9, wherein each wave-shaper arm has a half cycle when it is active in contributing to a forming of an AC wave shape and a half cycle when it is inactive in such forming and an inactive wave-shaper arm of at least one converter block in a chain is configured to counter voltage ripple in the DC link voltage caused by the rectified wave shapes of the active wave-shaper arms.

11. The converter according to any previous claim, wherein the AC wave shape is a sinusoidal wave shape.

12. The converter according to any of claims 1 - 10, wherein the AC wave shape is a trapezoidal wave shape.

13. The converter according to claim 12, wherein the rectified wave shape has a cycle where the voltage rises from zero to maximum value during a first time interval, decreases from the maximum value to zero during a last time interval and remains at the maximum value during intermediate time intervals.

14. The converter according to any previous claim, wherein a chain-link of submodules comprises submodules with a unipolar voltage contribution capability.

15. The converter according to any previous claim, wherein a chain-link of submodules comprises submodules with a bipolar voltage contribution capability.

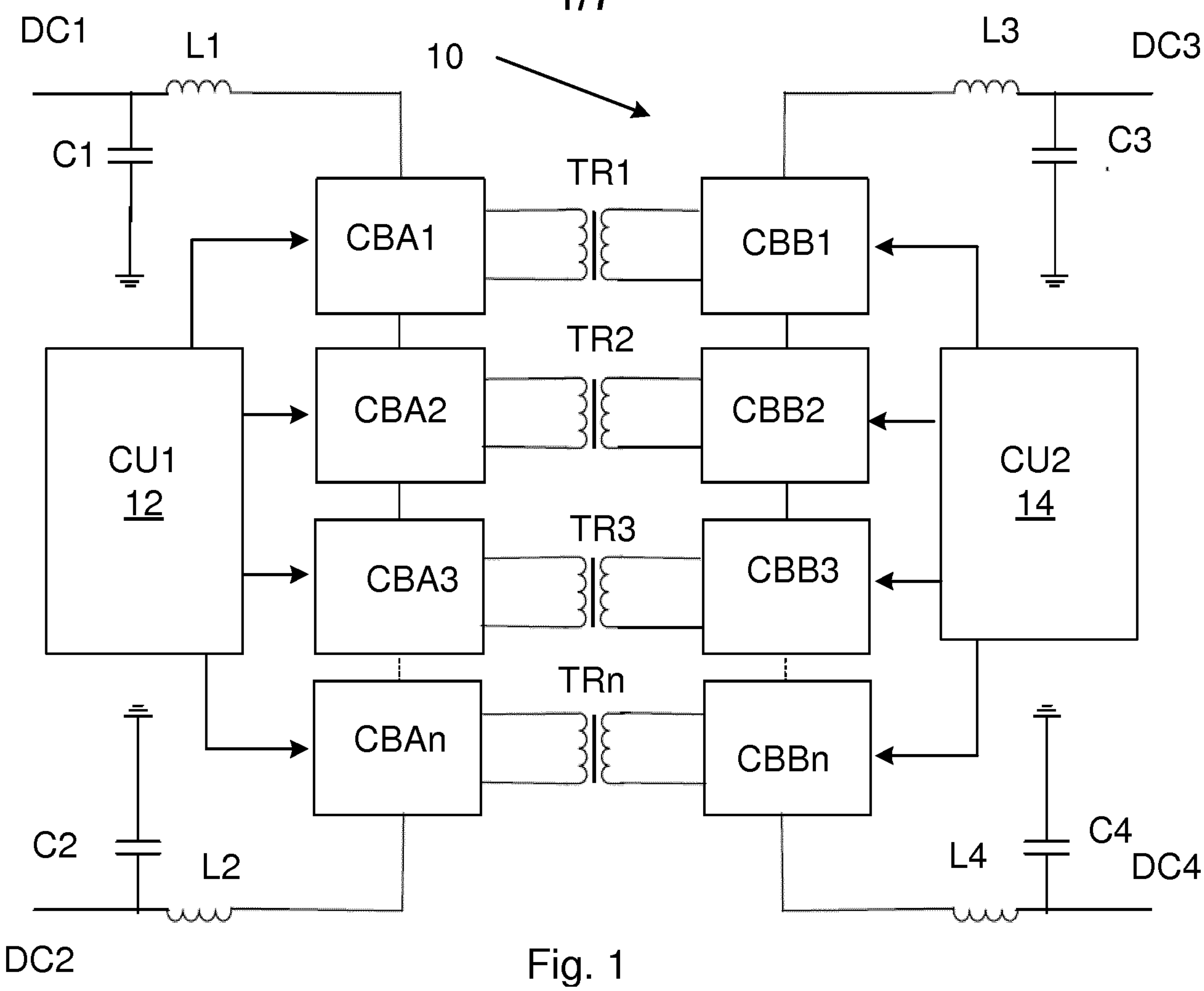

DC1
L1
10
L3
DC3
C1
C3
TR1
CBA1
CBB1
TR2
CBA2
CBB2
CU1
12
CU2
14
TR3
CBA3
CBB3
TRn
CBAn
CBBn
C2
L2
L4
C4
DC4
DC2

Fig. 1

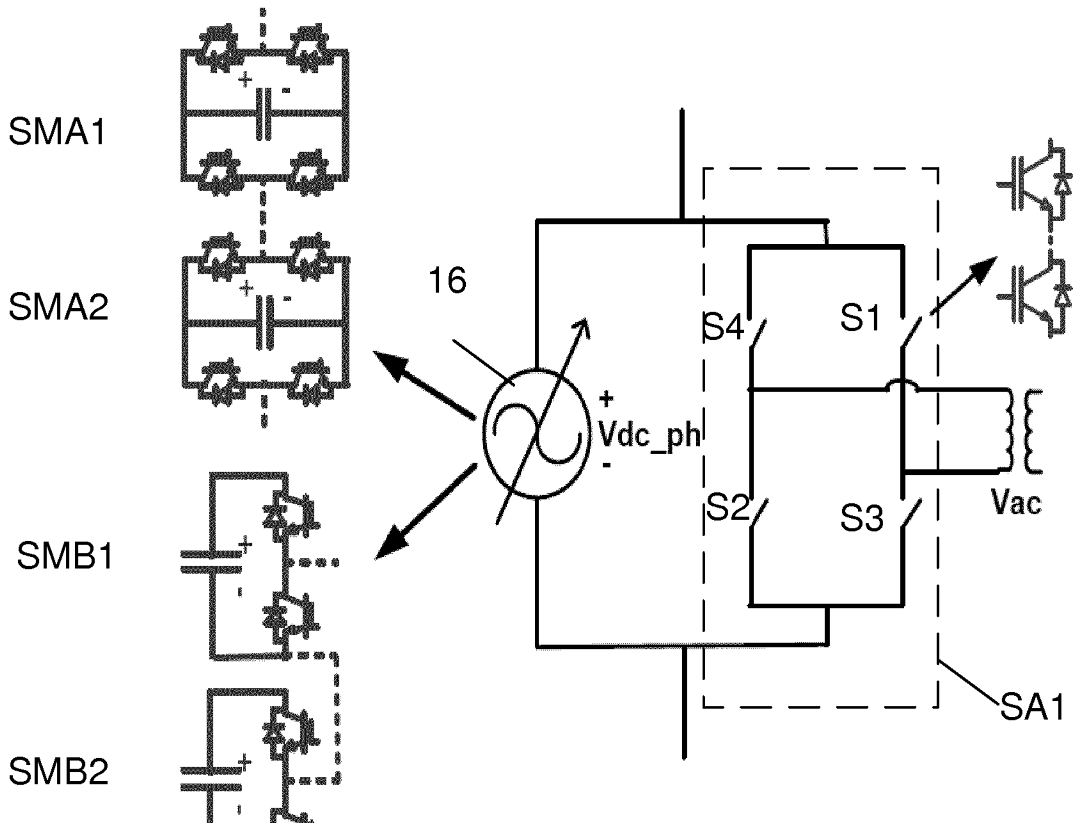

SMA1
SMA2
16
S4
S1
+
Vdc_ph
-
S2
S3
Vac
SMB1
SMB2
SA1

Fig. 2

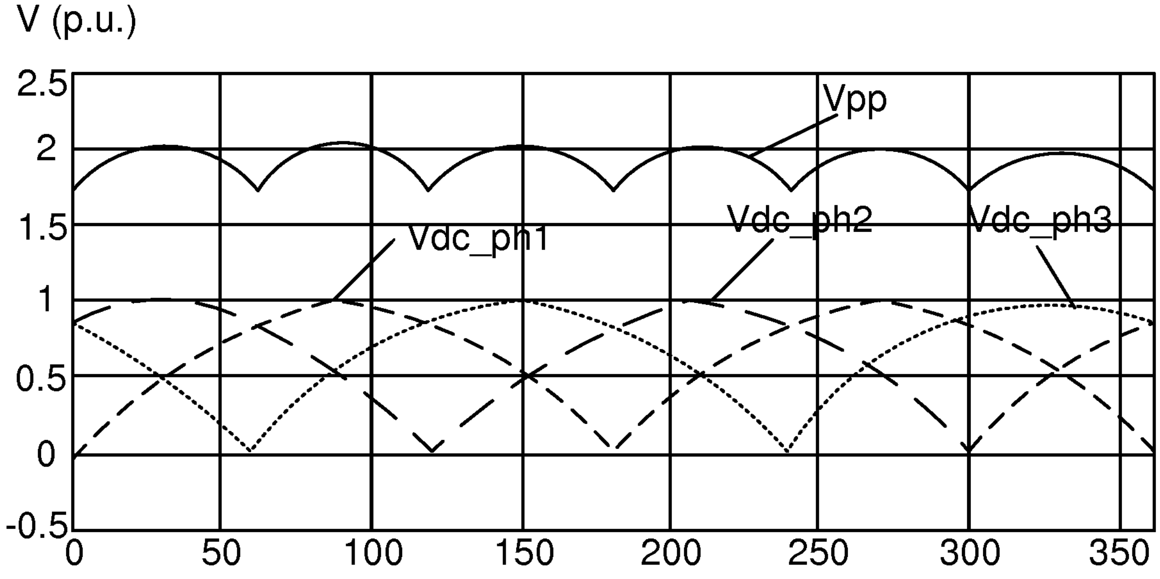

V (p.u.)
2.5
2
1.5
1
0.5
0
-0.5
Vpp
Vdc_ph1
Vdc_ph2
Vdc_ph3
0
50
100
150
200
250
300
350
Angle(Deg)

Fig. 3

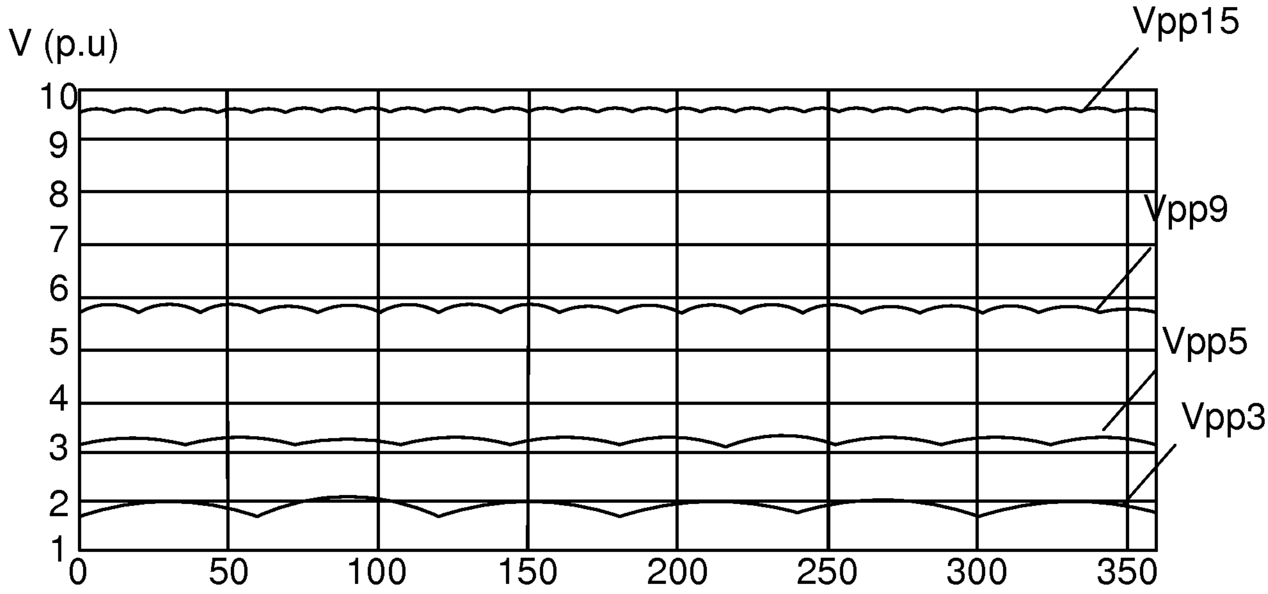
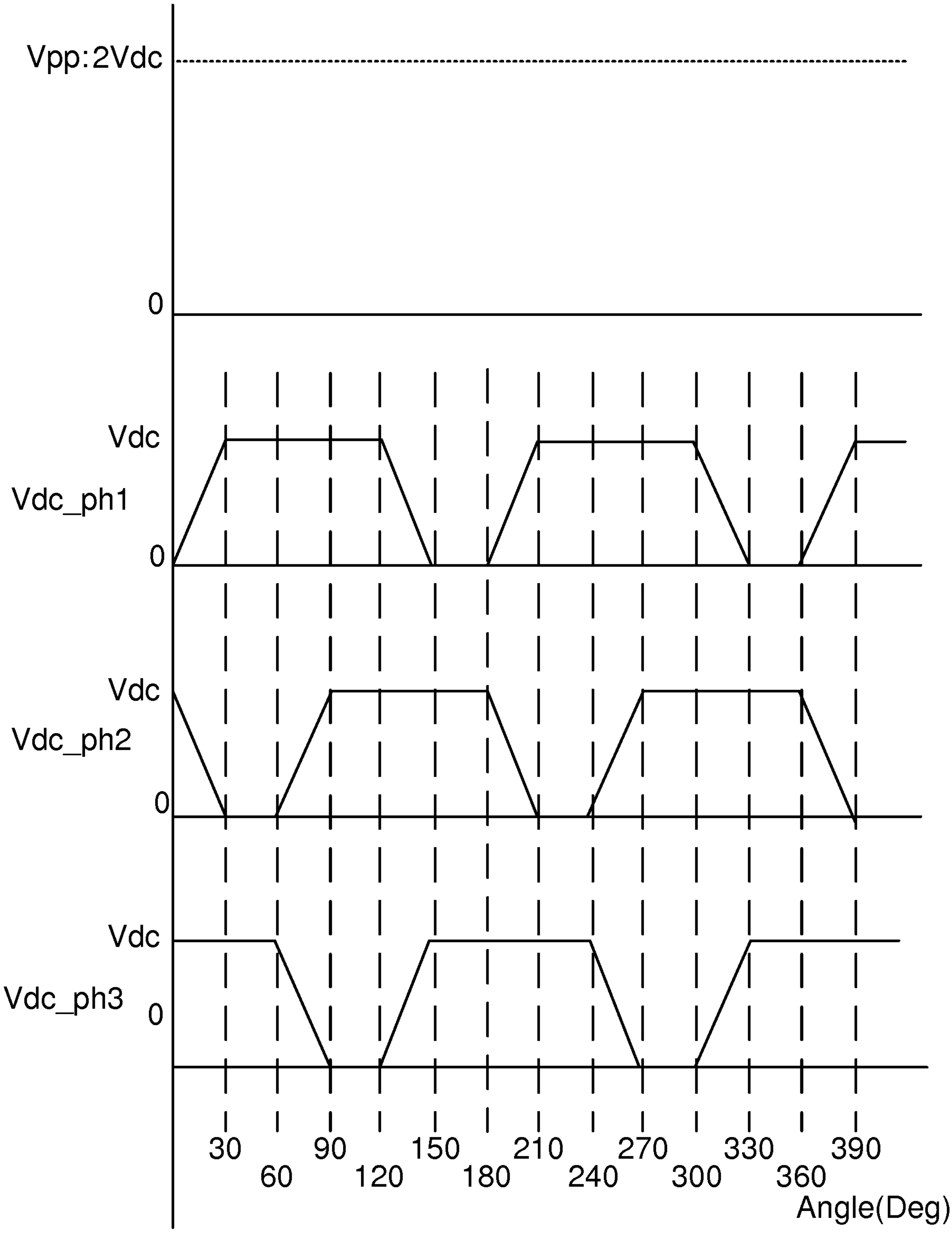

V (p.u)
10
9
8
7
6
5
4
3
2
1
Vpp15
Vpp9
Vpp5
Vpp3
0
50
100
150
200
250
300
350
Angle(Deg)

Fig. 4


Vpp: 2Vdc
0
Vdc
Vdc_ph1
0
Vdc
Vdc_ph2
0
Vdc
Vdc_ph3
0
30
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90
120
150
180
210
240
270
300
330
360
390
Angle(Deg)

Fig. 5

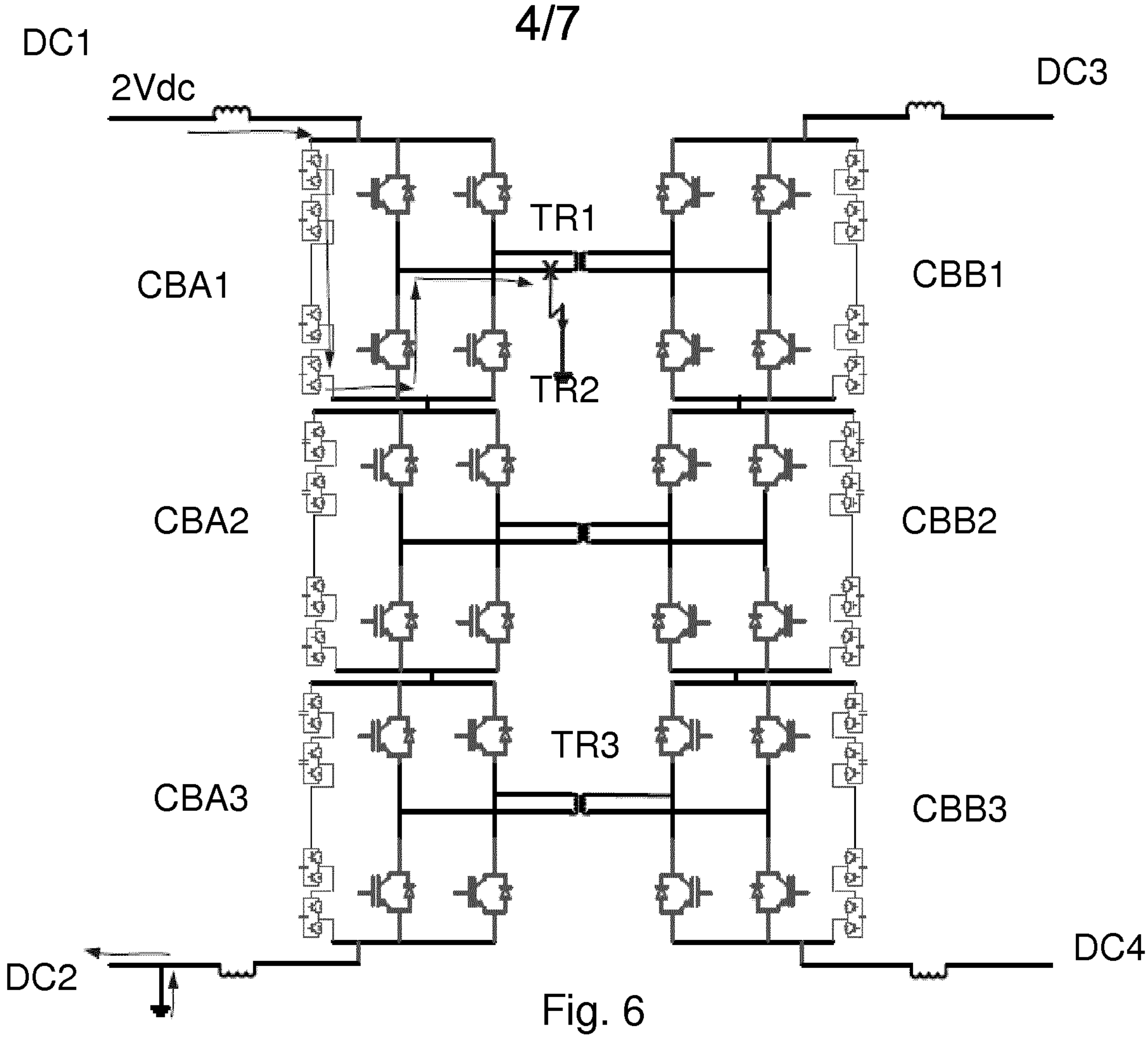
DC1
2Vdc
DC3
TR1
CBA1
CBB1
TR2
CBA2
CBB2
TR3
CBA3
CBB3
DC2
DC4

Fig. 6

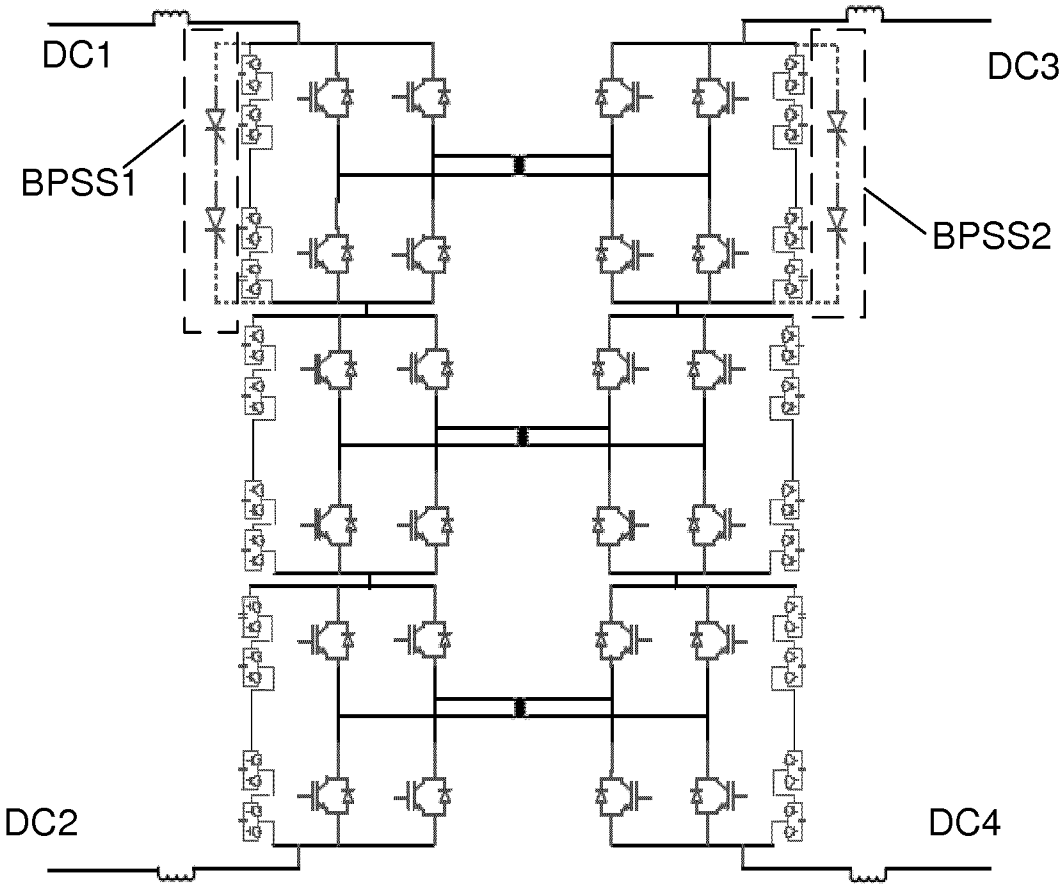
DC1
DC3
BPSS1
BPSS2
DC2
DC4

Fig. 7

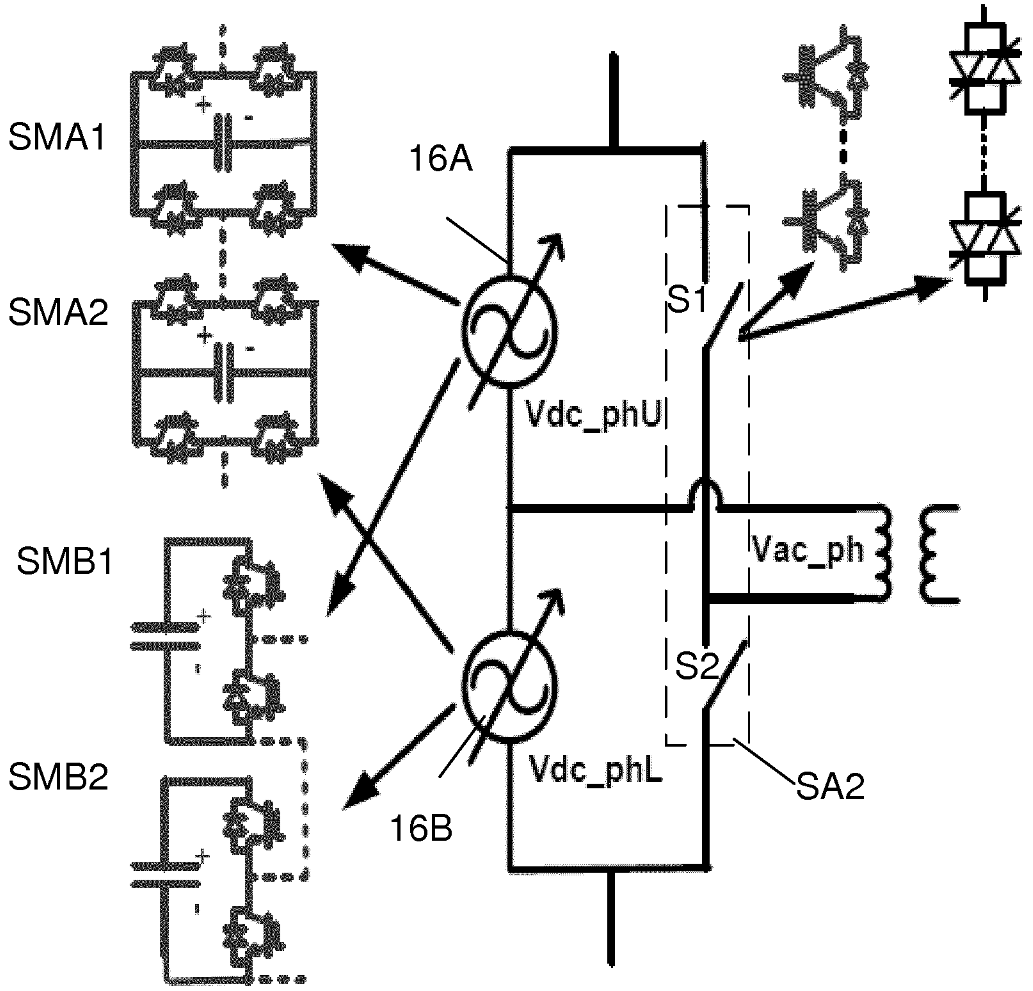
SMA1
SMA2
SMB1
SMB2
16A
16B
S1
S2
Vdc_phU
Vdc_phL
Vac_ph
SA2

Fig. 8

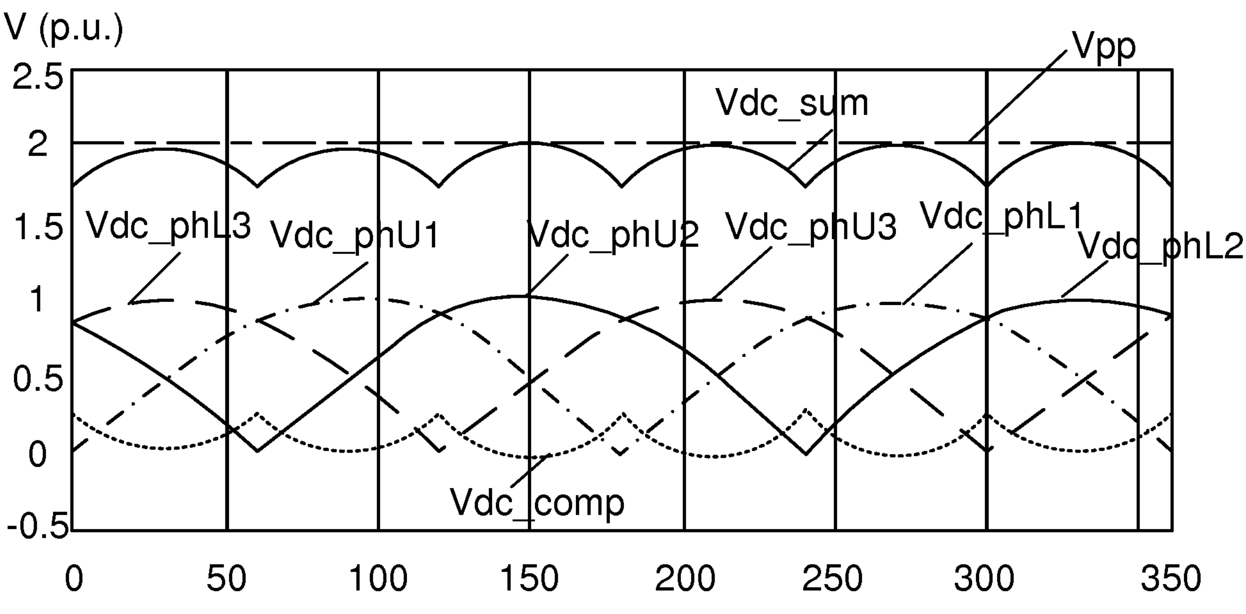
V (p.u.)
2.5
2
1.5
1
0.5
0
-0.5
0
50
100
150
200
250
300
350
Vpp
Vdc_sum
Vdc_phL3
Vdc_phU1
Vdc_phU2
Vdc_phU3
Vdc_phL1
Vdc_phL2
Vdc_comp
Angle(Deg)

Fig. 9

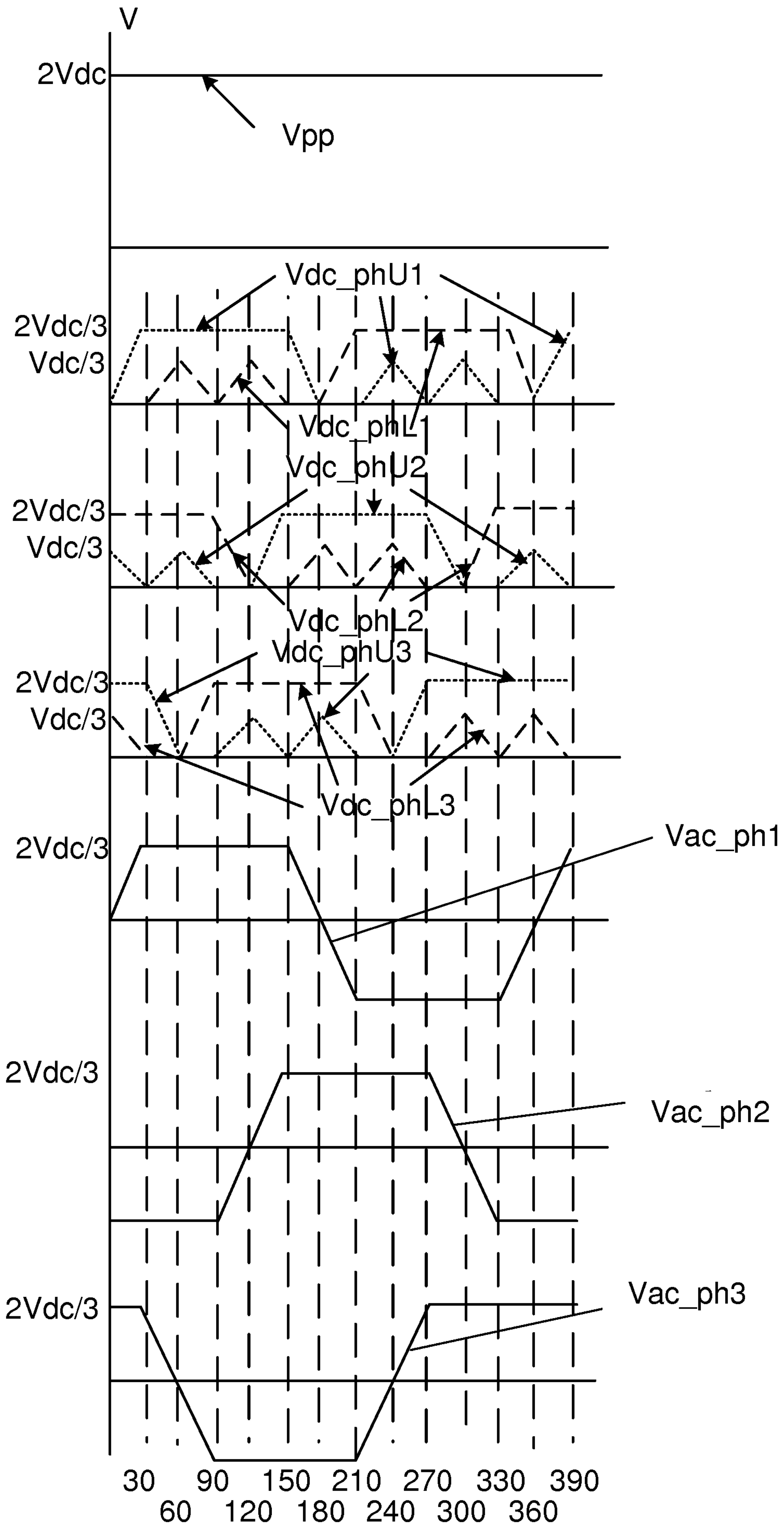
V
2Vdc
Vpp
Vdc_phU1
2Vdc/3
Vdc/3
Vdc_phL1
Vdc_phU2
2Vdc/3
Vdc/3
Vdc_phL2
Vdc_phU3
2Vdc/3
Vdc/3
Vdc_phL3
2Vdc/3
Vac_ph1
2Vdc/3
Vac_ph2
2Vdc/3
Vac_ph3
30 90 150 210 270 330 390
60 120 180 240 300 360
Angle(Deg)

Fig. 10

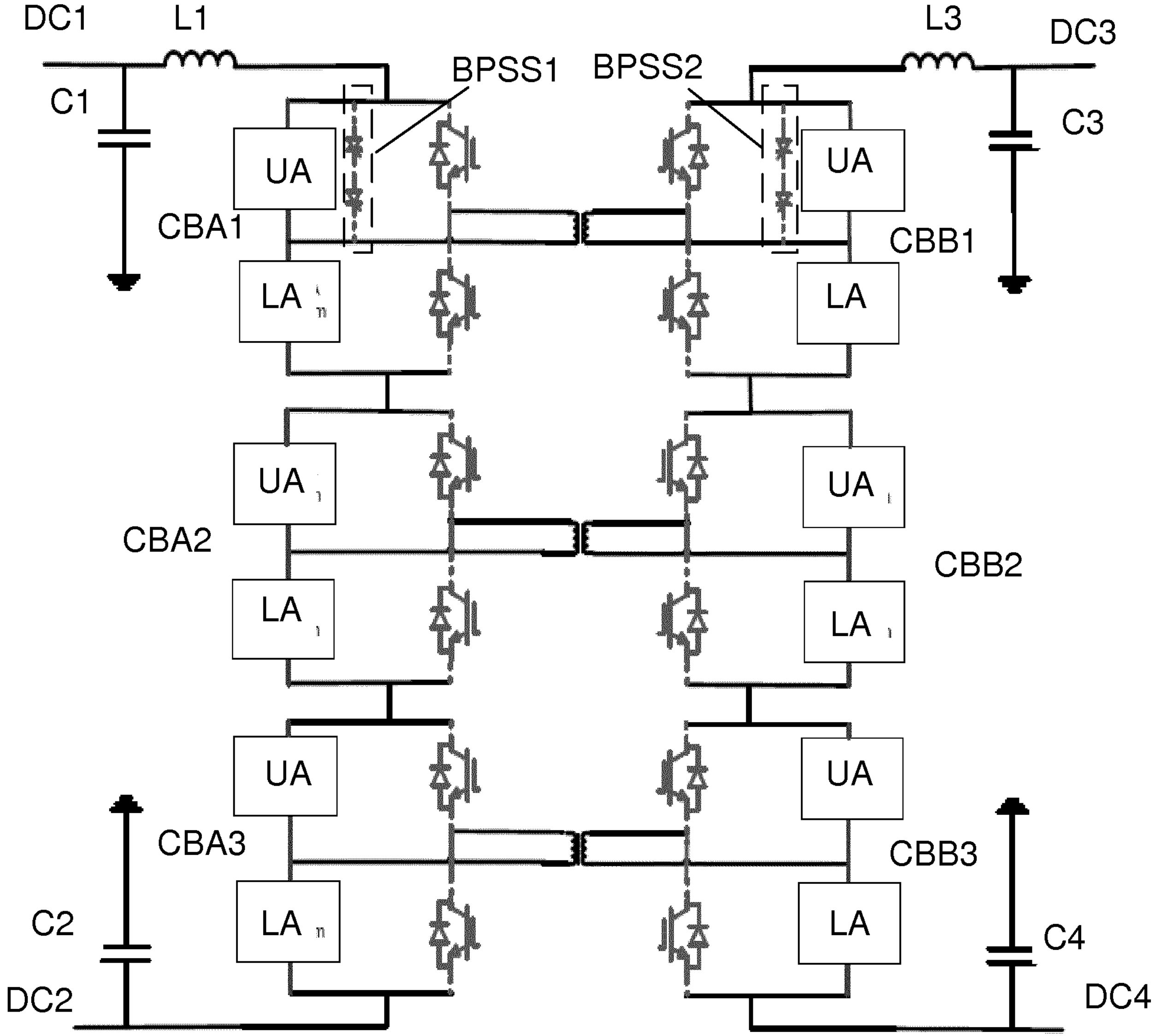
DC1
L1
C1
BPSS1
BPSS2
L3
DC3
C3
UA
LA
CBA1
CBB1
CBA2
CBB2
CBA3
CBB3
C2
DC2
C4
DC4

Fig. 11

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2018/065940

A. CLASSIFICATION OF SUBJECT MATTER
INV. H02M1/32 H02M3/335
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H02M

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	TRAINER D R ET AL: "B4-111 A new Hybrid Voltage-Sourced Converter for HVDC Power Transmission", CIGRE SESSION, CIGRE, PARIS, FR, 23 August 2010 (2010-08-23), pages 1-12, XP008134692,	1-3,6-15
A	figure 4 paragraph [0003] -----	4,5
Y	CN 104 283 436 A (UNIV HUAZHONG SCIENCE TECH) 14 January 2015 (2015-01-14) figure 1 -----	1-3,6,7, 11-15
	-/--	

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
12 March 2019	20/03/2019

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Gotzig, Bernhard

1

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	M TOMASINI ET AL: "DC-Link voltage ripple minimization in a modular multilevel voltage source converter for HVDC power transmission", PROCEEDINGS OF THE 2011-14TH EUROPEAN CONFERENCE ON POWER ELECTRONICS AND APPLICATIONS (EPE 2011), 1 January 2011 (2011-01-01), pages 1-10, XP055212884, ISBN: 978-1-61-284167-0 figure 1 paragraph [0004] -----	1-3
Y	US 2018/091038 A1 (SUBRAMANIAN SASITHARAN [SE]) 29 March 2018 (2018-03-29) figure 9 paragraph [0088] -----	1-3,8-10

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2018/065940

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US 2018091038 A1	29-03-2018	CN 107580751 A	12-01-2018
		EP 3292624 A1	14-03-2018
		US 2018091038 A1	29-03-2018
		WO 2016177398 A1	10-11-2016