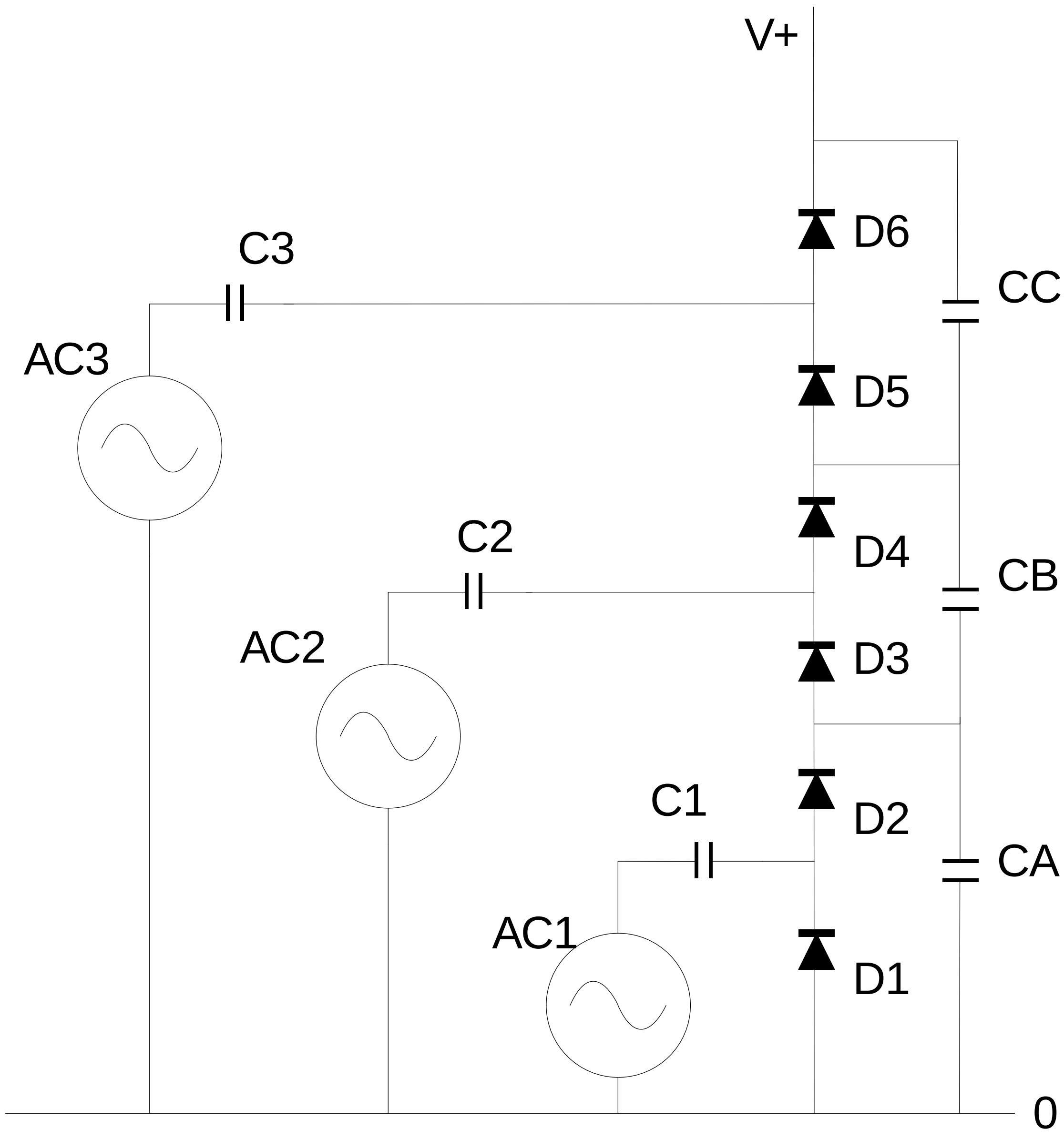
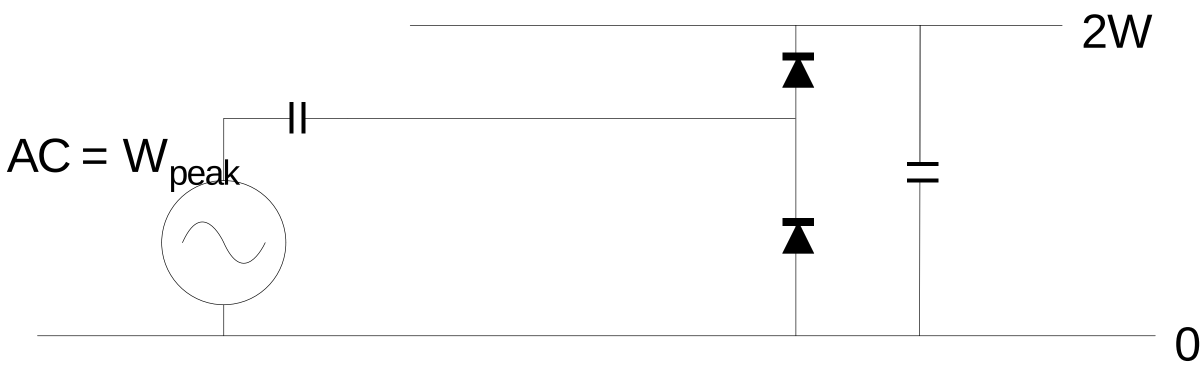
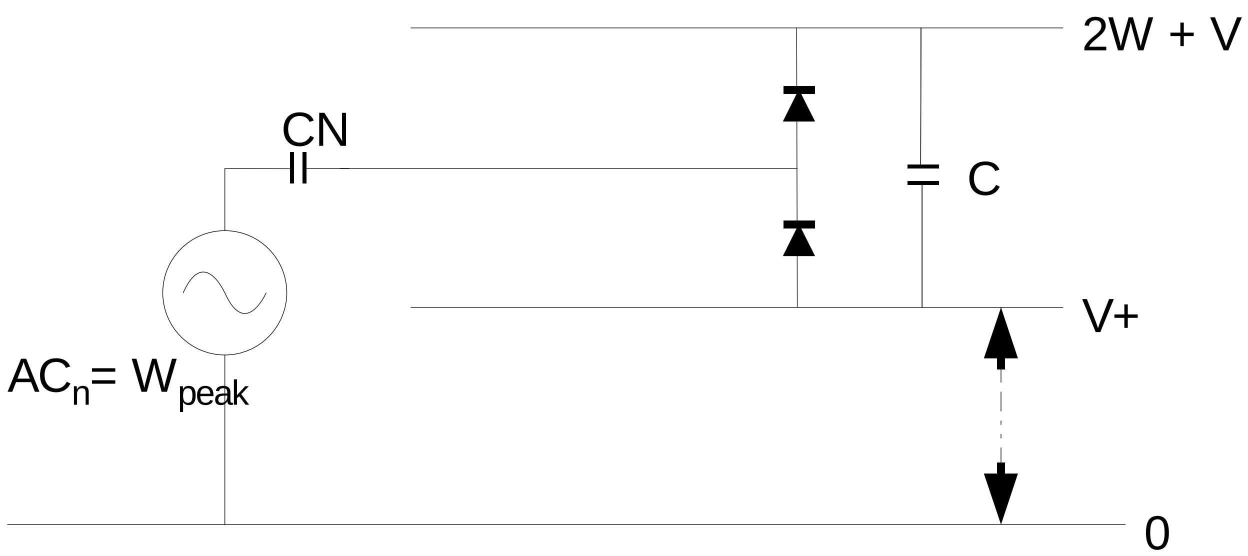


Figure 1



(i) Prior Art



(ii)

Figure 2

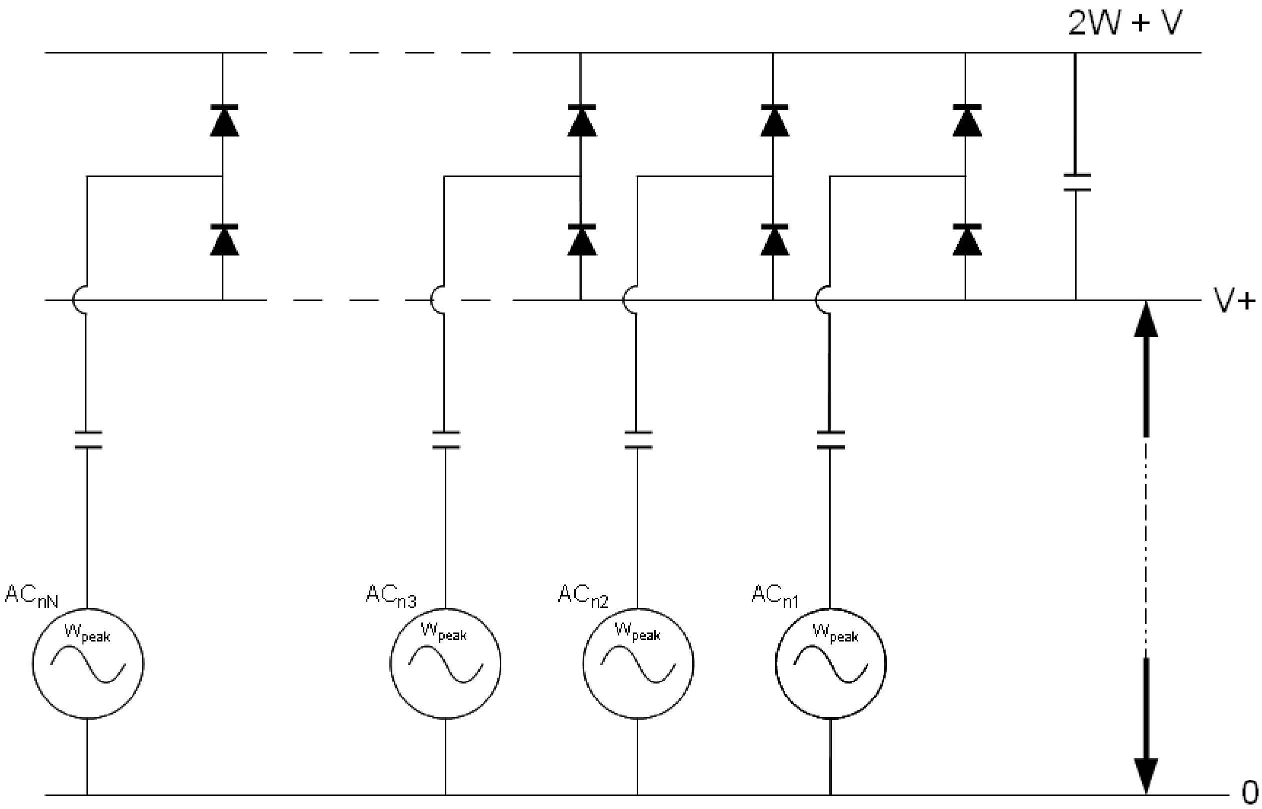


Figure 3

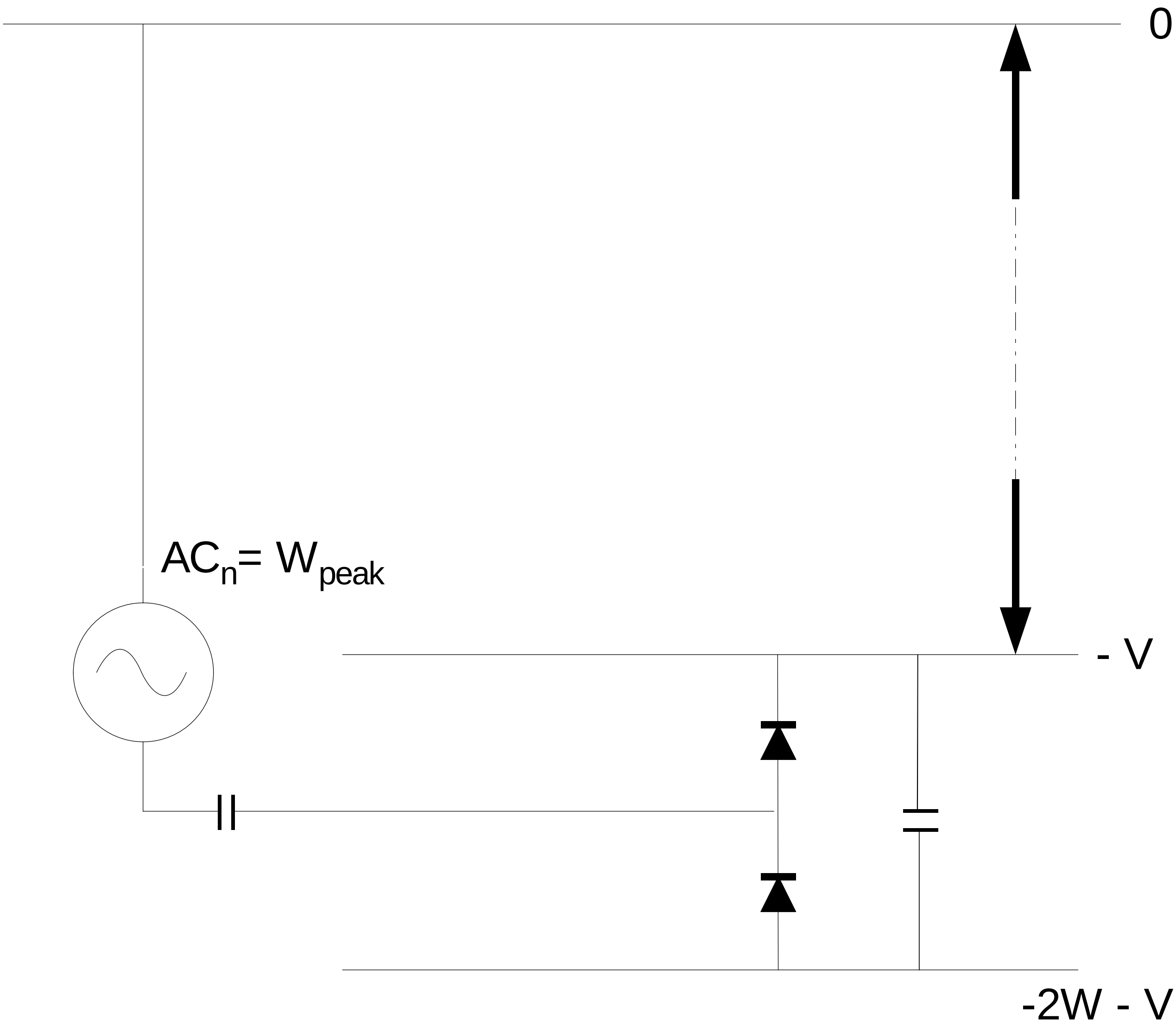


Figure 4

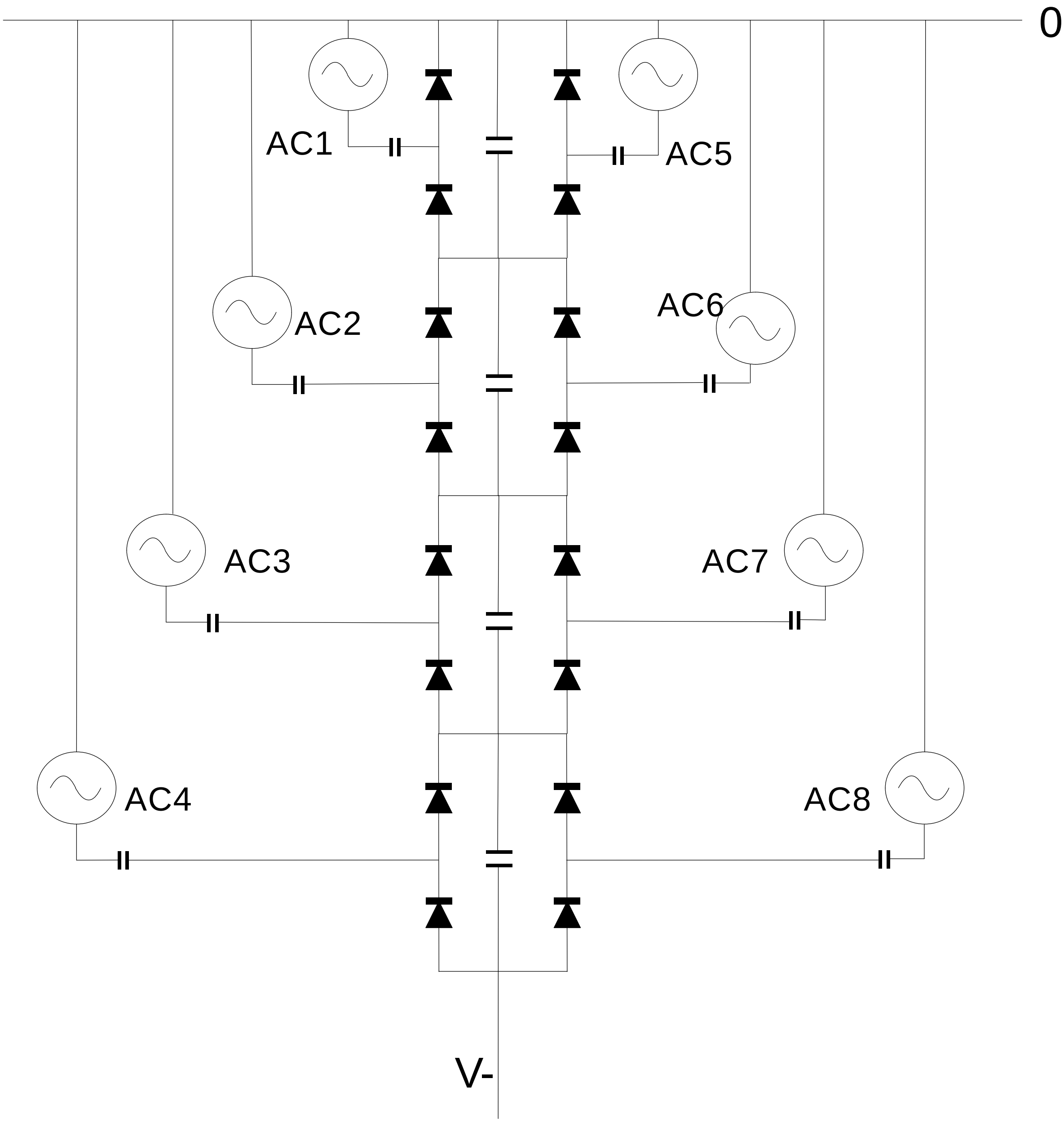


Figure 5

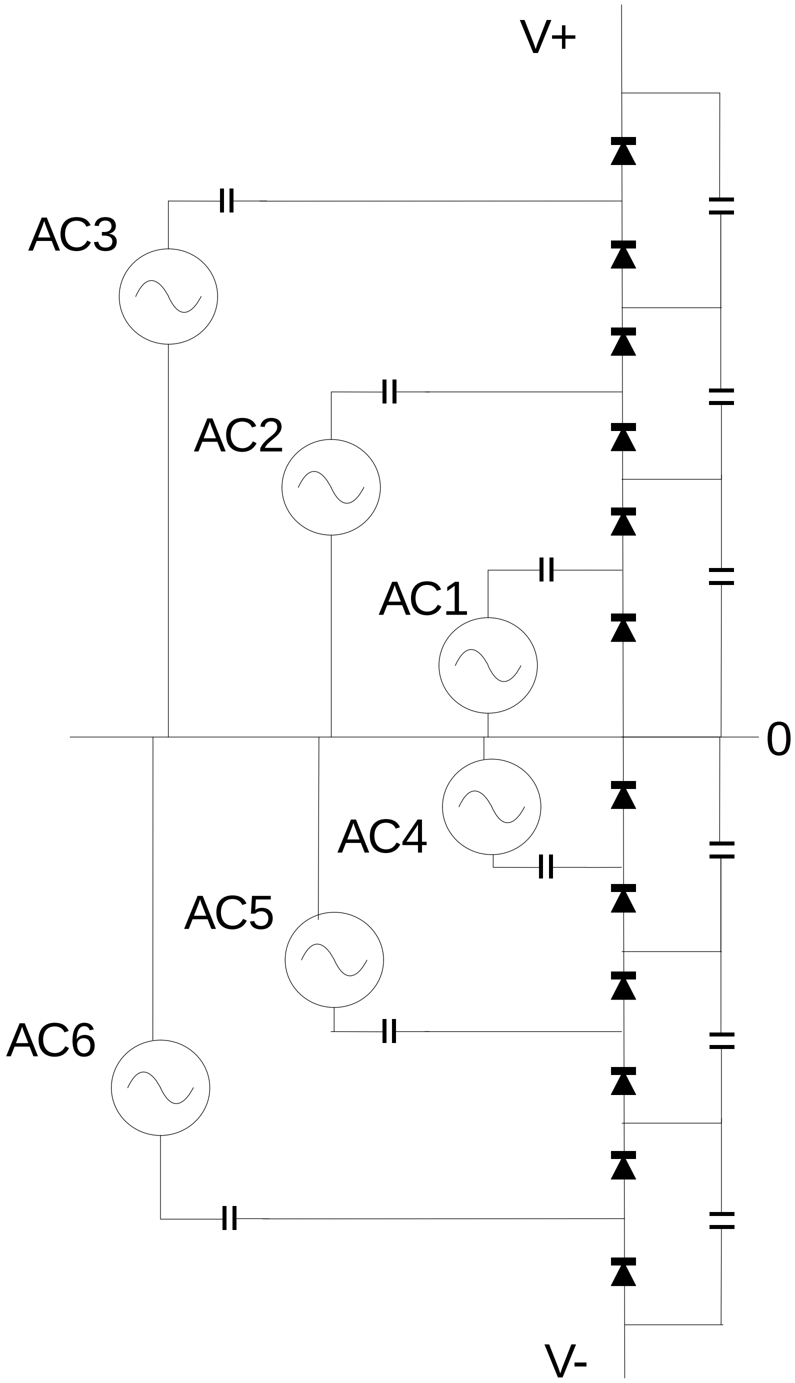
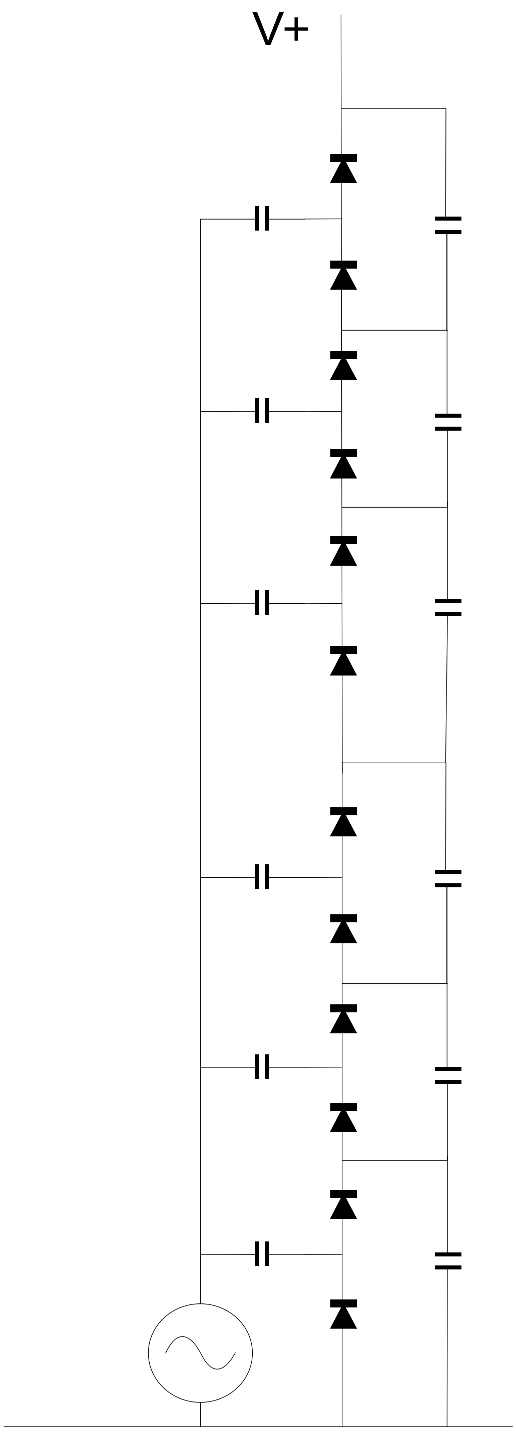
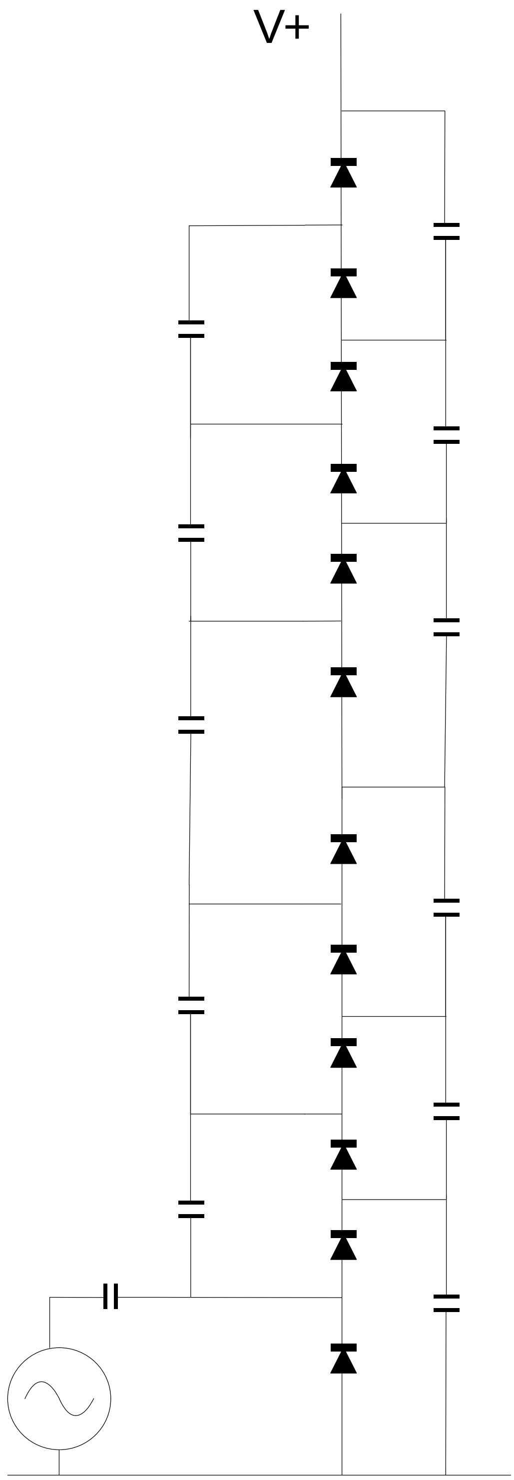


Figure 6



(i)



(ii) Prior Art

Figure 7

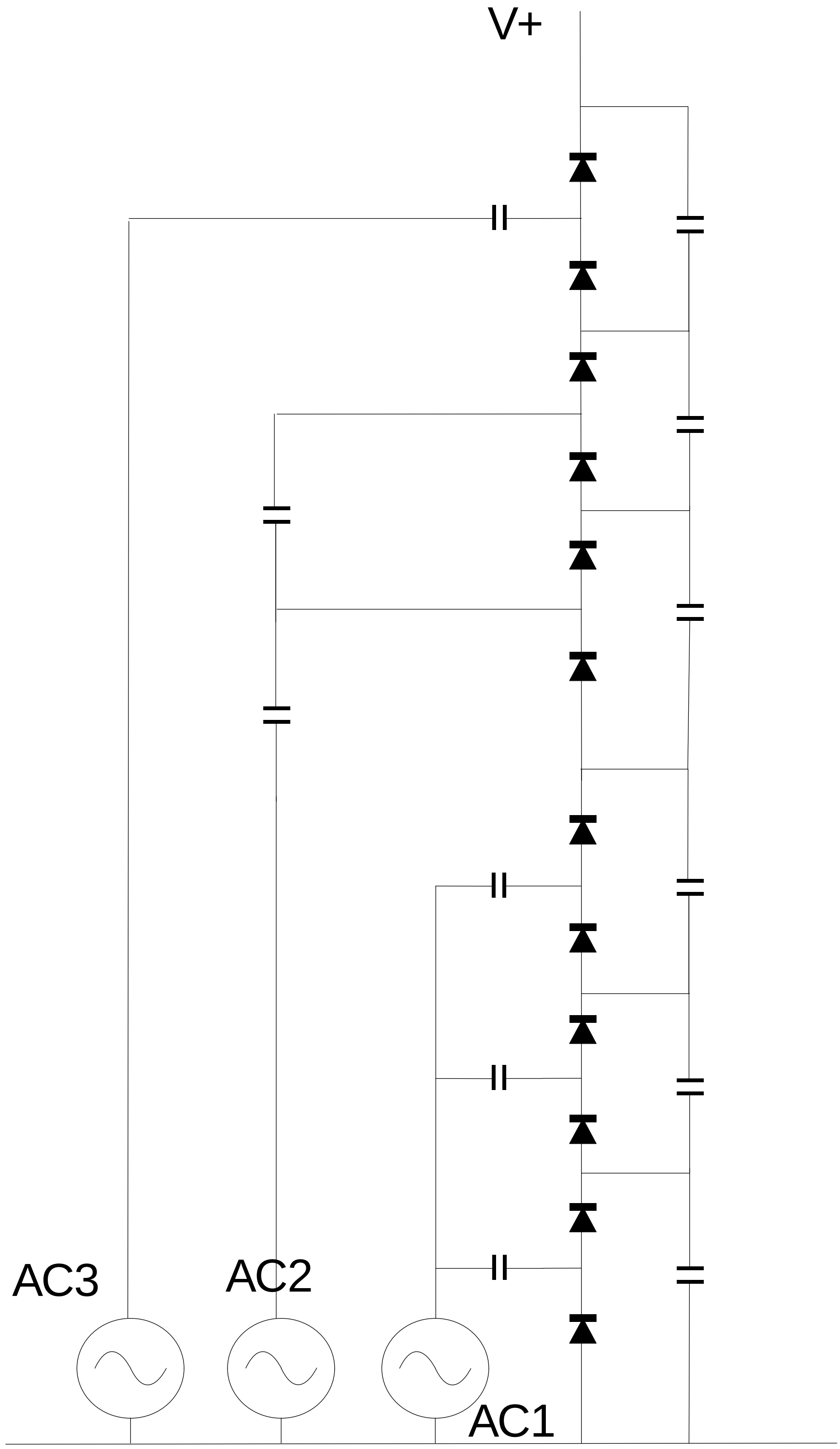


Figure 8

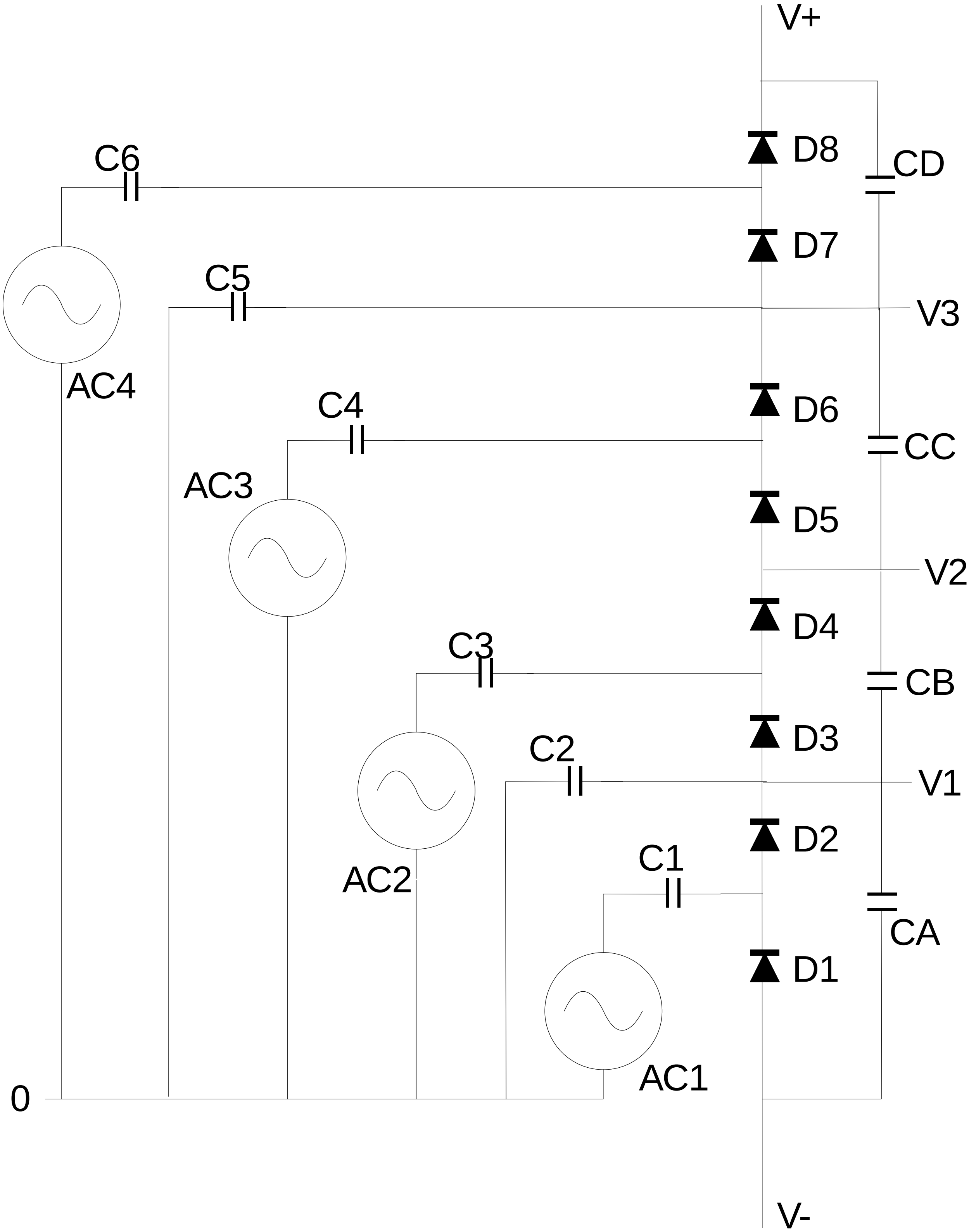

V+
D8
CD
C6
D7
C5
V3
AC4
D6
C4
CC
AC3
D5
V2
D4
C3
CB
D3
C2
V1
D2
C1
AC2
CA
D1
AC1
0
V-

Figure 9

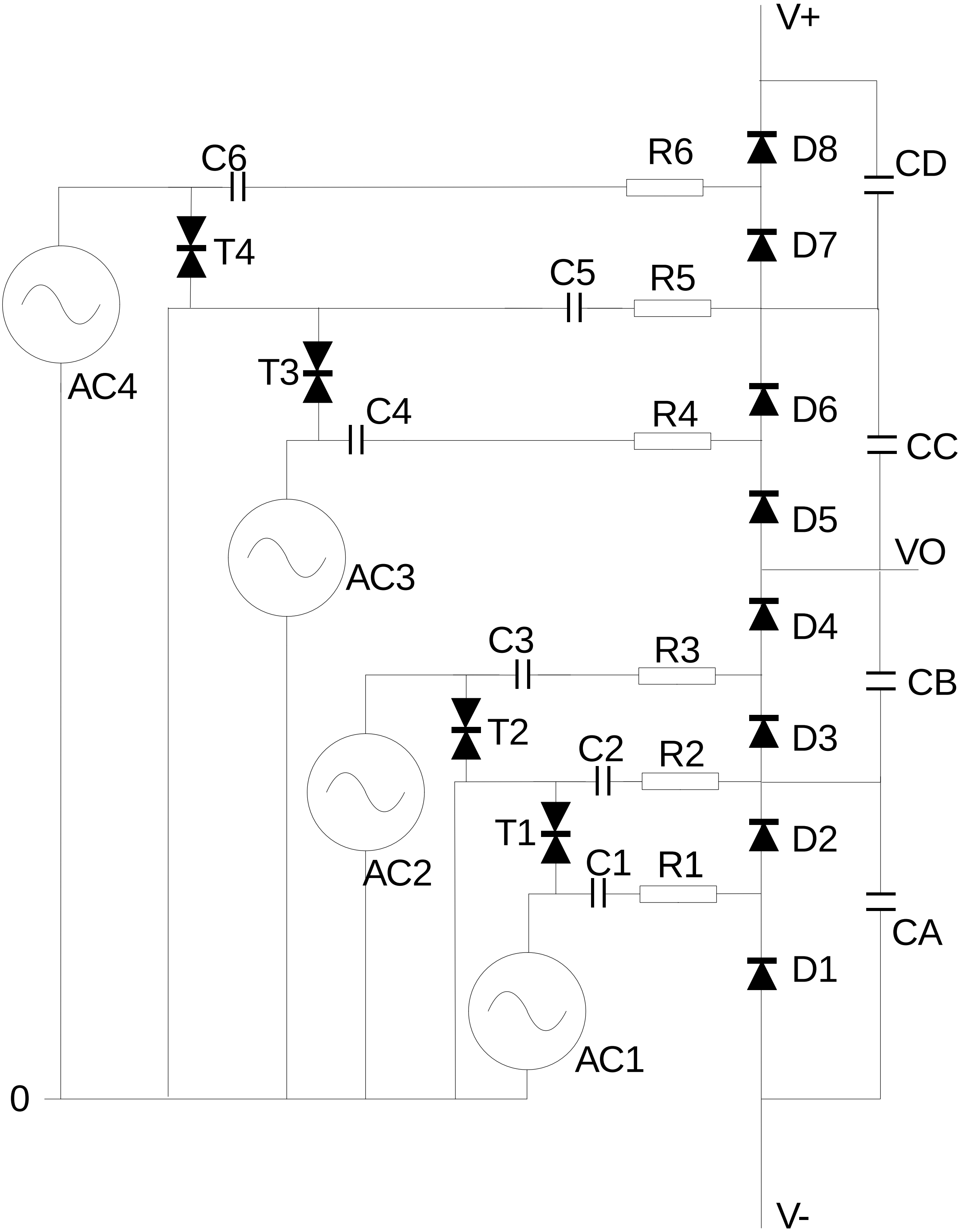

V+
D8
CD
R6
C6
D7
T4
C5
R5
AC4
T3
C4
R4
D6
CC
D5
AC3
VO
D4
C3
R3
CB
T2
D3
C2
R2
T1
D2
AC2
C1
R1
CA
D1
AC1
0
V-

Figure 10

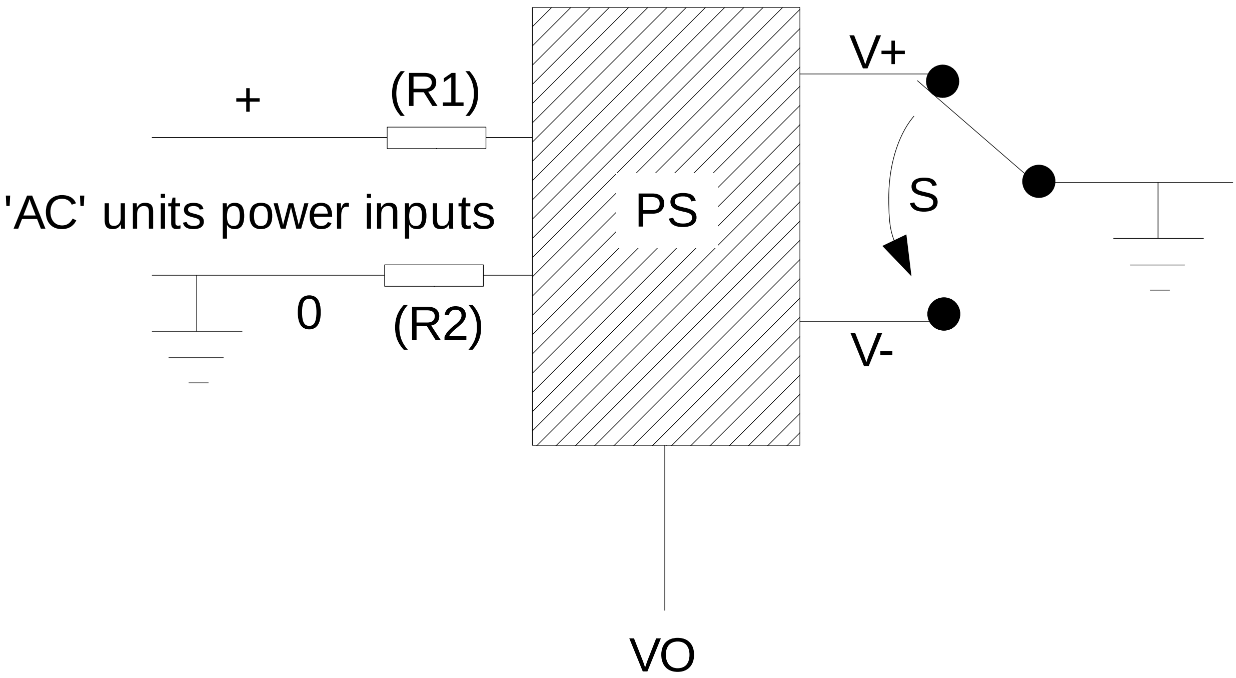
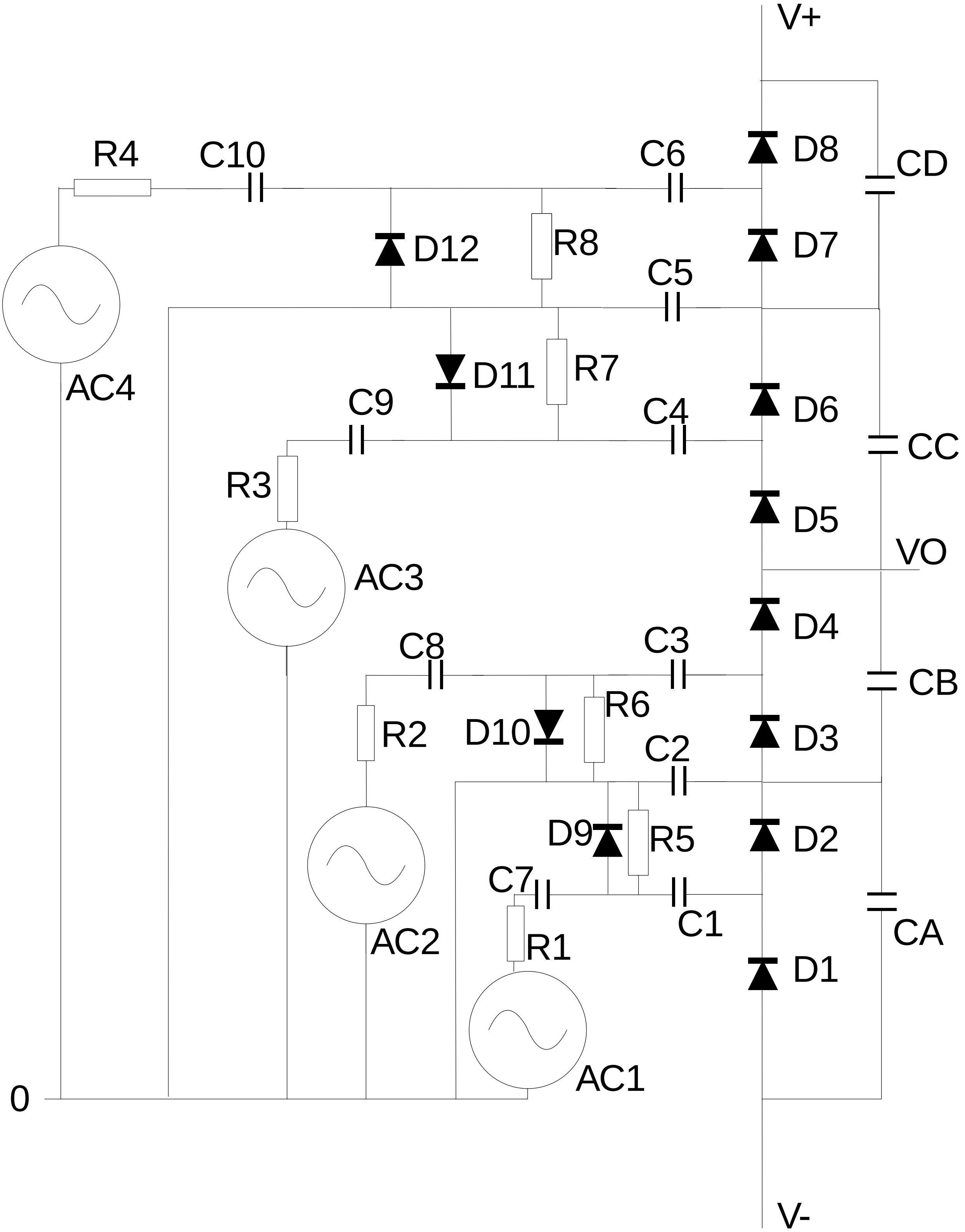


Figure 11


V+
D8
CD
R4
C10
C6
D7
D12
R8
C5
D11
R7
AC4
C9
C4
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CC
R3
D5
VO
AC3
D4
C8
C3
CB
R6
R2
D10
D3
C2
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R5
D2
C7
C1
CA
AC2
R1
D1
AC1
0
V-

Figure 12

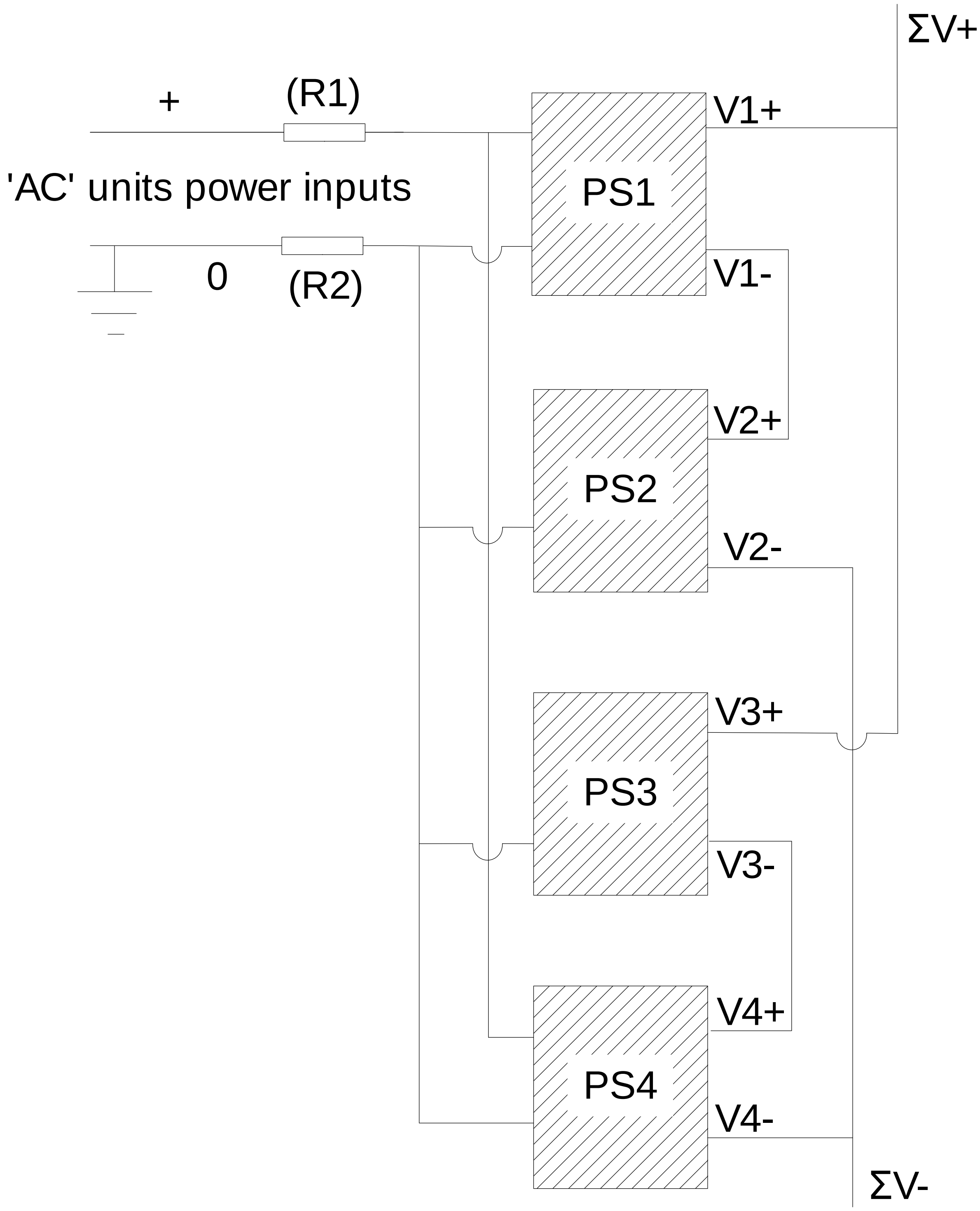
ΣV+
+
(R1)
V1+
'AC' units power inputs
PS1
0
(R2)
V1-
V2+
PS2
V2-
V3+
PS3
V3-
V4+
PS4
V4-
ΣV-

Figure 13

Voltage Cascade Using Multiple Alternating Current Supplies

Technical Field of the Invention

The present invention is a means to combine the power and voltages of multiple alternating current (AC), or pulsed direct current (DC), sources which may be sources of different peak voltages and different frequencies, onto an output stack of diodes and capacitors, from which DC may be drawn.

The cascading of voltage and power may find application wherever electrical power is generated and/or conditioned. The present invention may find particular use in regards the topology of high voltage power supplies.

The topology of the present invention also permits DC isolation between input and output power which provides a variety of useful functionality such as, and not limited to, rapid output polarity reversal, and also the capability to 'stack' such circuits in arbitrary series and parallel arrangements.

Background to the Invention

Voltage multiplication and voltage cascades have been known since early alternating current research established the basics of the field. In 1914, Heinrich Greinacher invented the Greinacher multiplier, also known as a 'voltage doubling rectifier', which is a circuit that doubles the peak voltage of an alternating current (AC) fed into it when rectified to provide a direct current. This circuit is shown in Figure 2 (i).

Further voltage multiplication can be obtained by cascading these circuits into what is commonly referred to as a Villard cascade, also known as a Cockroft-Walton voltage multiplier, as shown in Figure 7 (ii).

For the purpose of generating high voltage, it is common practice to use a high voltage AC supply from a high ratio transformer, fed with a lower voltage AC, as a driver to feed such cascades such that the number of stages of the cascade can be kept small for some given voltage output requirement. It is also common practice to use high frequencies so as to reduce the capacitance values required throughout the stack.

These matters are all well-known to practitioners in the field. The disadvantages of such an arrangement are that for each stage higher up the stack, the power of the driving source is diminished such that where a large number of stages is required, to achieve a desired voltage gain, the actual power that the cascade can supply may be relatively small compared with the input power of the single driver, due to the cumulative losses in each stage. Further, the driving power for such cascades usually comes from a high frequency and high voltage ferrite-based transformer, to keep the number of stages low, thus minimise losses and maximise achieved voltage. Such transformers of sufficient power can be expensive to manufacture, difficult to drive or design (with cost-effective switching electronics) due to highly reactive behaviour, and adverse loads (particularly such as shorting arcs) may cause unreliability of these expensive transformers due to thermal and electrical failures deep within the coil windings which are consequently irreparable.

The present invention provides the means to feed each stage of such a cascade independently of each other with a separate AC, or pulsed DC, supply. Such supplies may be for example, small, commonly available mass-produced parts, such as high frequency (typically 20 to 40 kHz) voltage inverters used for compact fluorescent lighting. As the present invention is a means to combine their voltages and powers, the failure of one such smaller part would lead to a diminution of the output power and voltage but not necessarily a complete failure of the system. In the event of such a component failure, the part may be replaced cost-effectively and easily.

The feature of the present invention, to combine various AC and/or pulsed DC supplies, also provides design flexibility to achieve, and select a topology that allows for close matching to, a desired requirement. The present invention is therefore intended to be a cheaper, more reliable and more flexible alternative to existing high voltage cascades driven with a single AC supply.

Further, an arbitrary point on the output stack may either be tied to a fixed potential relative to a supply/the supplies, thereby providing the capability to design for a positive or negative output with respect to a ground reference, or for dual positive and negative outputs. The stack may also be capacitively isolated such that the output stack may float freely and be DC-decoupled from any reference potential. In the latter case, groups of the multiple supplies may be packaged in separate parts such that they can be connected in serial to produce higher output voltages, and/or in parallel to produce higher output currents, which is a feature not commonly available in other designs of high voltage power supplies using cascades.

Other utilities also arise with a DC-isolated output stack, including a mechanism for fast reversal of the polarity of an output, relative to a reference ground.

Summary of the Invention

Voltage stacks, consisting of diodes and storage/coupling capacitors, are a well known topology in a variety of applications but have limitations due to the number of stages that can be driven by a single supply without excessive losses and due to practical limits of power (versus cost) that a single AC driver can provide to the stack.

The present invention provides solutions to a number of the practical and cost limitations with conventional topologies by providing a method to feed each stage, or group of stages, independently, thereby combining the power of multiple electrical supplies. This may therefore mitigate 'fold-back' of the output voltage of high voltage stacks under load, with higher maintainability at a lower build and repair cost.

The modification over existing topologies is to feed the centre of each diode rectifying pair directly with a capacitively coupled AC, or pulsed DC, source. Capacitive isolation can also be implemented, providing a DC uncoupled output that can be utilised for particular requirements.

Introduction of the Drawings

Figure 1 shows an embodiment of the invention, depicting multiple AC sources, AC1, AC2 and AC3 (such as maybe high frequency DC to AC inverters), independently feeding each stage of a voltage cascade through coupling capacitors C1, C2 and C3 respectively, with diodes D1 through D6 rectifying the coupled AC current to the stacked capacitors CA, CB and CC.

Figure 2 (i) shows the prior art, a Greinacher voltage doubling rectifier stage, which, when driven by an AC source, AC, to peak voltage W that a voltage of 2W appears across the capacitor. Figure 2 (ii) shows an arbitrary stage of a cascade of the present invention driven by an independent AC source, ACn, through a coupling capacitor, CN, and rectified to potential V and 2W+V across a capacitor, C.

Figure 3 shows an arbitrary stage of a cascade, as per Figure 2 (ii), but driven by multiple parallel sources, ACn1 to ACnN, of nominally identical voltage.

Figure 4 is as Figure 2 (ii), but shown for a negative potential.

Figure 5 is an example stack generating a negative polarity from 4 stages, with two AC supplies (of identical nominal peak-to-peak voltages) feeding each stage.

Figure 6 is a 6 stage stack showing the tying of the common AC supply output to the potential between the 3rd and 4th stage, thereby creating a two-pole (positive and negative) voltage output with respect to 'ground', 0.

Figure 7 (i) shows a 6 stage stack can be fed from any arbitrary AC source, in this case a single AC supply, each stack coupled by an independent capacitor to the supply. Figure 7 (ii) shows likewise, but each stage is fed from a node in a serial chain of capacitors, thereby reducing the voltage specification requirement on those capacitors. This is prior art and is the common 'Villard cascade'.

Figure 8 is a hybrid topology showing that multiple AC supplies can feed one, or multiple, or multiplier groups of stages, in an essentially arbitrary manner. Each of these topologies can be combined within one circuit so as to best achieve some given electrical output requirement.

Figure 9 depicts the output stack without direct DC connection to the individual power supplies. Capacitive decoupling can be achieved as the multiple supplies feed multiple stages that will act together to form the overall potential in the output stack. In the place of a direct DC connection, capacitors C2 and C5 are employed to approximately maintain each stage of the output stack with respect to a reference potential, thereby mitigating oscillations in the stack that may compromise performance. Figure 9 also depicts multiple voltage outputs from the stack, V-, V1, V2, V3 and V+, which may be used to power equipment requiring multiple voltage stages, such as an electrostatic accelerator.

Figure 10 shows additional parts, resistors R1 to R6 and transient voltage suppressors (TVS) T1 to T6 (which might equally be gas discharge suppressors, or any other suitable type). Either, or both, resistors and/or TVS may be used to help reduce damage to the individual power supplies, AC1 to AC4, under conditions of output shorts and arcing.

Figure 11 schematically shows an assembly, such as described in Figure 10, packaged as the power supply unit PS. “'AC' unit power inputs” depicts (in this example) DC power lines supplying each of the 'AC' supplies within the PS unit. The outputs V+ and V- (as references in Figure 10) may then be switched to ground, thereby inverting the output VO.

Figure 12 shows additional capacitors, diodes and resistors (acting as charge pumps) that are an example of means to help mitigate damage to the 'AC' supplies in the event that an output is rapidly discharged to ground (as per the operation of the embodiment shown in Figure 11).

Figure 13 schematically shows four assemblies, such as described in Figure 10, packaged as power supplies PS1 to PS4 which have been connected serially in pairs to create higher summed voltages, ΣV, of the combined voltage outputs, and each pair then connected in parallel to increase the effective current capacity. Any such assembly of power supplies, as described in Figure 10, may be added on to each other arbitrarily either in series and/or in parallel groups, due to the DC isolation the circuit provides, providing the isolation capacitors' ratings are not exceeded.

Detailed Description

Figure 1 depicts an essential embodiment of the invention, demonstrating how the electrical power sources, AC1, AC2 and AC3 (which may be AC or pulsed DC sources) can be fed into each stage of a voltage cascade, each stage being in the form of a Greinacher voltage doubling rectifier stage.

The ACx sources (AC1, AC2 & AC3) need not be of the same voltage nor frequency. There may be an advantage in the frequencies being different and/or not in phase which is that the output voltage will be an averaged value of the cycles of each of the stages which, if not relatively synchronised, will therefore contain a more 'quasi-uniform' frequency ripple content that a conventional multiplier stack output may suffer when under load.

(In the general case, it is inferred that these 'ACx' sources have external power supplied [not shown in Figures 1 to 10] that may be, for example, an AC input such that 'ACx' is a transformer, or a DC input such that the 'ACx' sources may be ferrite, or piezoelectric, transformer based voltage inverter parts with internal pulsed supply circuitry, such as those commonly used for compact fluorescent lighting (CFL) purposes.)

The capacitors, C1, C2 and C3, require voltage specifications according to the likely voltages on each stage. For example, if each of the supplies is an AC supply of 1000 V peak then the capacitors C1, C2 and C3 should be a minimum of 2000 V, 4000 V then 6000 V rated, respectively*. The diodes should be a minimum rating of 1000 V and the capacitors, CA, CB and CC, should be 2000 V. These issues, and the requirements to ensure sufficient isolation between stages, will be well understood by anyone familiar with voltage multipliers.

*(Notwithstanding isolation within the AC supplies. For example, if 'ACx' are transformers rated for 5000 V continuous isolation and the highest stack voltage is under 5000 V, then there is no need to rate the capacitors for isolation purposes. In this case, the capacitors need only be chosen on the basis of what the maximum voltage across them might be on powering up the circuit. The use of piezoelectric transformers may be a practical means to achieve very high isolation without requiring coupling capacitors with high voltage specifications. These matters will be well-understood by practitioners in the field once the operation of the circuit is understood.)

Figure 2 (i) shows a Greinacher multiplier stage which doubles the peak AC voltage. In the case of a pulsed DC, the output is the voltage of the DC pulse. (In fact, the output of such multiplier stages is the peak-to-peak voltage difference, rather than, strictly, 'doubling' the AC peak voltage.)

Figure 2 (ii) shows a generic stage of the present invention. A diode pair is fed by a capacitively coupled feed from the alternating supply. If the lower voltage, V+, is higher in potential than the side of the capacitor, CN, to the diodes, then current will flow from V+ to charge the capacitor. As the supply lifts the capacitor voltage to V+2W [where 2W is the peak-to-peak voltage, or pulse voltage] then if the capacitor, C, has a voltage lower than V+2W, then current will flow from CN to C. In this way, a potential of up to V+2W is maintained across C. As current is drawn from C when the circuit is under load, this voltage will drop below V+2W as a function of the current drawn (according to well-known principles of rectifier circuits).

To provide more power into any particular stage of a circuit embodying the present invention, multiple supplies in parallel may also feed one stage. Figure 3 depicts such a stage in which any number of multiple power supplies, ACn1, ACn2...ACnN, may feed a stage within a cascaded stack of such stages. In this case, the peak-to-peak voltages of ACn1, ACn2...ACnN should be nominally identical else the supply with the highest voltage may end up providing all of the electrical power without gaining the benefit of being in parallel with the other supplies. The circuit of Figure 3 will be recognised as being essentially a bridge rectifier for a poly-phase input.

It will be understood by a practitioner in the field that this principle can be equally reversed in polarity and a summation of power at negative voltages also achieved. Figure 4 shows this, which is essentially the same as Figure 3 (ii), but feeding a voltage stage held to a negative potential.

Figure 5 depicts a practical 4 stage, negative polarity output, stack supplied by 8 power supplies. Each stage is fed by two such supplies. The supplies feeding any one stage should be matched in nominal voltage, thus AC1 and AC5 should have the same nominal voltage, likewise AC2 & AC6, AC3 & AC7, etc.. If identical AC supply units are used, then the electrical output of this circuit may therefore be up to 4 times the nominal peak-to-peak voltage of the supplies with the combined power output of all 8 units.

A common implementation may be, for example, using mass-produced inverter modules as the 'ACx' supplies. Such modules typically operate in the 20~50 kHz frequency range with voltage outputs of ~1000 V. For example, 20 modules of 5 watts output each capable of 1000 V and 5 mA peak output may be combined in 10 stacks, two each feeding each stage. This will provide a stack with a nominal output of 20 kV and 100 W power at a cost of a few euros for each of the 10 stages.

Voltage control of such a circuit may be performed in two particular ways. Such inverter parts are usually driven by a low voltage DC source. The level of the voltage supply of that DC source usually influences the output of the inverter, accordingly, so adjusting the input power voltage will control the output voltage of the stack. However, a minimum voltage is typical (due to the internal logic-driven driving circuits that make such inverters operate) therefore there will be a lower threshold of voltage adjustment. The second approach is to power the inverter modules off-or-on, according to the voltage required. This provides a discrete set of nominal voltage outputs from the stack, because when a stage does not receive its input current, the voltage of the stage will collapse and the output voltage of the stack will consequently reduce. A supply could therefore be run off a fixed supply (such as a 12 V battery) and discrete switching of the 'ACx' modules will provide discrete voltage control of the stack output without recourse to potentially complex and expensive power regulator circuits. Both techniques of control may be used together, for yet further improvement in power output control.

It is noteworthy that the topology of the circuits described herein is such that AC supply modules may be held at, or around, the ground potential such that any switching and power supplies are not at risk of any high voltage threat. It is appropriate, however, to use transient suppression components at the power inputs and/or outputs of the AC power supplies so that if a coupling capacitor breaks down, or an output circuit arc event to another potential occurs, and high voltage from the stack can flow back into the AC supply, that it is shorted to the ground line and not able to find a route to ground externally, through the source of the electrical power driving the 'AC' supplies. These are safety points well-known to practitioners in the field.

The topology also allows for the 'ground' to be selected at an arbitrary stage in the stack, such that if an output of, for example, +10 kV and -10 kV, is required then stacks above and below the arbitrary ground may be selected. This is easy to implement in practice and allows for, relatively simple, adjustment of where the ground potential will be set. All that is required for alteration of the circuit ground is that the 'ground', as specified as '0' in the Figures, is coupled to the stage at which the ground reference potential is wanted. This could be a feature within a practical design where a 'pre-set' coupling wire may be part of the design such that the reference potential (usually ground) can be user-connected to the particular stage to achieve the desired voltage outputs with respect to that reference potential.

In this way, the diodes do not need to be physically inverted on the stack to invert its polarity (as is generally the case for common multiplier stacks) but, merely, that the common coupling of the AC supplies is tied to the desired level. That is, if the polarity is to be reversed then the common line from the 'ACx' supplies is tied to the other end of the stack of stages. Figure 6 shows how the common 'ACx' connections have been coupled to a mid-point on the stack, thereby producing a positive/negative output (which may be more desirable for certain high voltage applications, e.g. to reduce coronal effects when driving an unreferenced potential across a load, or to reduce the voltage specification requirements of the coupling capacitors).

It is also possible to supply all of the stages with a single capacitively coupled AC supply in much the same way as is the principle of the present invention. Figure 7 (i) shows a series of capacitors feeding the diodes of multiple stages, all from a common output of one AC supply. It might also be noted that if capacitors are used in series (so as to achieve high voltage specifications from serial capacitors of lower voltage specification) that they may then be stacked in the manner shown in Figure 7 (ii), which is repeating a Villard cascade. In this way, the present invention can be seen in context of existing multiplier stack methods.

It is also possible to employ a partial degree of 'voltage multiplication' of a given supply within the stages, such that some (but not necessarily all) stages are driven in the manner of a 'Villard cascade'. Figure 8 shows a 6 stage stack driven by 3 AC supplies. The lower 3 stages are driven by one supply, AC1, each stage with its own coupling capacitor. The next 2 stages are driven by AC2 into a 'Villard cascade' type (in which the voltage specifications of the capacitance of the capacitors feeding stages 4 and 5 do not need to be as high as the voltages in stage 5, because they are configured serially). AC3 feeds the top most stage.

By way of example of the flexibility of the various topologies that can be designed to achieve a particular purpose, it can be seen in Figure 8 that AC1 may be of a lower frequency output, which can then make use of lower voltage, but higher capacitance, capacitors. AC2 may then need a higher frequency so that the capacitors can be conveniently sized. AC3 may be of a higher frequency again (but possibly of lower power as it feeds only one stage) such that the coupling capacitor of stage 6 can be reasonably sized whilst being able to couple its power into the circuit whilst under load.

It is anticipated that once a practitioner in the field recognises that each stage (or group of stages) of a conventional voltage multiplier can be fed independently with multiple AC supplies, or by an additional set of parallel AC supplies, by the means given in the present invention, that they will then be able to design many such variations in which the use of various AC, or pulsed DC, supplies can be selected and optimised so that together they drive a voltage stack which combines their power and voltages for a given application.

Figure 9 shows a further advantage of the present invention. As the multiple power supplies will likely be operating in a de-synchronised fashion (or may be made to work thus, by intent), it is possible to fully, and effectively, DC isolate the stages by capacitive coupling of the output stack to a reference potential, rather than by a direct connection. This is because the combined 'ACx' outputs will tend to act together so as to charge the capacitors and the stages that are, schematically speaking, 'between' the given output potentials of each 'ACx' supply. However, the output stack still requires a reference potential else all stages may tend to float and oscillate, thus causing an ineffective current output.

Therefore, for a DC-isolated embodiment of the invention, additional capacitance is required to couple points on the stack to a reference potential. Figure 9 includes two additional capacitors, C2 and C5, compared with the equivalent circuit (that is not DC-isolated) given in Figure 1. In prototypes it has been found that the optimum and efficient means to couple an output stack of several stages is to include coupling capacitors every other stage (though this is not essential). In this way, each stage will have either its upper or lower potential capacitively coupled to the reference potential, and this is sufficient to mitigate performance-degrading oscillations within the stack during operation under load.

Figure 9 therefore represents an embodiment capable of being 'floated' with respect to any other specified potential. However, it remains DC-isolated rather than fully-floating, and this renders the 'ACx' supplies vulnerable if the potential of the output stack (relative to a reference potential common to the power source(s) of the 'ACx' supplies) is suddenly altered. For example, consider if V-, of Figure 9, is being held to ground potential and V+ is being powered to +20 kV above ground. If V+ experiences an arc to ground potential, the capacitor C6 still has 20 kV across it. As V+ drops to ground, the output side of AC4 will be pulled down to -20 kV by the capacitor. In the circuit of Figure 9 this can only be discharged through AC4 itself. If AC4 cannot withstand the 20 kV potential across it and breaks down, it may be irreparably damaged.

In short-circuit prototype robustness testing (and as per the above comment in regards robustness and repairability) such events have occurred. As it is usually the ACx supply closest to the highest potential that will fail and will short the excess potential in such cases, the other ACx supplies have been, typically, saved from damage. In a number of incidents, the whole stack went on functioning without it being realised that the upper supply had failed (this being one of the benefits of the present invention). Once noted, the damaged ACx supply was replaced as a module, which could be done quickly, easily and cheaply. This is a failure mode not unique to the present invention, and shorting of the outputs of stacks driven by single supplies may also experience such failures. However, in the case of a stack driven by a single supply, the whole unit may have failed. Failure of the large, single supply (which is usually a dominant cost element of such supplies) would possibly render the supply and stack beyond economic repair.

Further robustness of the stack can be achieved by varied means that would be obvious to a practitioner in the field. Figure 10 shows how prototype units have been improved following robustness testing. Here, resistors R1 to R6 have been included, the purpose of which is to slow down the discharging of the capacitors, C1 to C6, through the ACx supplies. In doing so, the internal impedance of the ACx supplies becomes significant as this is the route through which the capacitors will discharge. In prototype builds, resistors, R1 to R6, have been used which are approximately 10 times the internal impedance of the ACx supplies. This mitigates the peak voltages seen in the ACx supplies, thereby mitigating shorting within them and keeping them within their tolerance of voltage isolation (to the input, 'primary' side, power lines - not shown in Figure 10).

Further transient suppression components may be used by coupling the ACx outputs to the reference potential. In this case, as the capacitor is pulled through a high voltage (as an output is shorted) it will discharge through the voltage suppression device (once the voltage across it has exceeded its breakdown voltage). The use of a resistor in this circuit also provides a sufficient time period for the voltage suppression device to perform its protective function during an output stack arc/short-circuit event.

Figure 11 shows how the DC-isolated circuit of Figure 10 may be exploited as a rapid-reversal polarity high voltage supply. As the switch, S, opens from V+ and contacts V-, the stack of capacitors (shown as CA, CB, CC & CD in Figure 10) will jump up to the new potential, without needing to be discharged. Instead, it is the coupling capacitors, C1 to C6, that will discharge as they cycle through their AC frequency and start feeding each stack stage again. As there is essentially nothing discharging on the power output stack, the polarity switching is effectively instantaneous, (notwithstanding a dip in voltage output within the AC period of the ACx current feeding the output stages).

In prototyping work, it has been established that the coupling capacitors, C1 to C6, need only be quite small in comparison with the output stack capacitors. In one set of prototypes, 10 nF capacitors were used for the output stack capacitors, CA to CD, whilst the coupling capacitors, C1 to C6, were varied from 50 pF to 1 nF, with the power supplies operating at 40 kHz. Little advantage was found in using coupling capacitor much above ~470 pF in this example when the output stack capacitors were delivering 5 mA at 25 kV from a 6 staged topology.

Using 100 pF capacitors provided efficiencies better than 90% of the 470 pF capacitors (which were, in turn, practically indistinguishable from using larger capacitances). Using such relatively small capacitances for the coupling capacitors therefore provided a significant cost advantage in prototype assembly because these capacitors need to withstand the full output voltage of the stage they are feeding, yet higher capacitances at high voltages are costly, so there is a strong commercial advantage to minimising the capacitance specification of the coupling capacitors.

In a further prototype design, two 100 pF 30 kV capacitors were connected in serial to provide an isolation of 60kV. The 50 pF effective capacitance was still satisfactory to drive a 2.5 mA current at 55 kV into a stack composed of 12 stages of 10 nF capacitors with only a further loss of efficiency not measurably greater than 5% over the variant using 100 pF coupling capacitors. The ripple current was measured under load and found to be related principally to the output stack capacitors' values, not the coupling capacitors values. Lower coupling capacitor capacitance only appeared to reduce efficiency, rather than affecting ripple current.

This may be useful information to practitioners in the field if diagram 7(ii) is reconsidered. This depicts the prior art of a 'standard' multiplier stack in common use. The above tests suggest that the capacitors to the left of the diode chain may be of significantly smaller values than the output stack capacitors to the right of the diode chain, without increase in ripple current and only a minor loss of efficiency, if any*. It is common practice in these stacks for all the capacitors to be of a given value, or, otherwise, for the lower capacitors to be given higher values so as to 'support' the upper stages. However, the work on prototypes of this present invention show that the capacitors in series with the power supply can be significantly smaller; employing coupling capacitors with less than 10% of the capacitance of those in series with the output load has not been significantly detrimental on performance in the prototypes built.

*(Once it is recognised that, in a Villard design, the 'coupling' capacitors that feed the central diode node of the pair that rectify across each 'output stack' capacitors (serially connected to the load) serve different functions, then it can be appreciated that the coupling capacitor will tend to swing through at least twice the voltage as may be present on the output stack capacitors, therefore the capacitance value needs be only one quarter (as the energy content that the capacitors can deliver per AC cycle is the square of the voltage). In practice, when load is being drawn from the output stack capacitors then the voltages on the coupling capacitors may swing through an even larger voltage, such that the capacitors would still likely be suitable with a lower capacitance still.)

Figure 12 shows a further means to mitigate damage against shorting and arcing of the external loads, and is presented particularly with regard to the polarity reversal embodiment given in figure 11. Where the outputs will be repetitively and periodically shorted, more robust means may be required to ensure survival of the 'AC' supplies than relying on their internal impedances or other 'transient', occasional, safety components (that is, in the circumstances that 'AC' does not, itself, have sufficient isolation to withstand the output voltages involved). In Figure 12, an additional capacitor and diode is used which creates a 'charge-pump' arrangement on the inputs to the rectifier stages closest to the voltage outputs. Consider AC1;- as its voltage output initially rises, so the connection note between C1, C7 and D9 will try to rise. The diode D9 will prevent the voltage of that node rising above the reference level '0' (notwithstanding the 'forward voltage drop' of the diode). As the AC1 supply reverses, so the capacitors C1 and C7 will, together, act as the coupling capacitor driving that rectifier stage. The C1/C7/D9 node will then oscillate along with the output of AC1, but will do so only at negative potentials with respect to the reference potential. In the event that V- is shorted to ground, the charged capacitor C1 will try to pull the C1/C7/D9 node high, but the diode D9 prevents it rising above the reference potential, thereby protecting AC1. Diode D9 may be of the same type as used in the rectifier stage. However, as this may not be a very fast transient-type diode, a resistor, R1, may be included to slow down the rate at which C7 will pull AC1 high and provide a time interval during which diode D9 turns 'on'. For the stages closest to the opposite polarity, the diodes are reversed. It is anticipated that once the basic application of this charge-pump arrangement is understood, it will be clear to a practitioner in the field how other circuit protection schemes can be employed to achieve improved designs.

Figure 13 shows 'packaged' versions of the circuit type given in Figure 10 connected by pairs in series for additional voltage, and those pairs in parallel for additional current capacity. With the DC-isolation feature of Figure 10, such 'packaged' units can then be arbitrarily stacked in series and in parallel, so that a set of such units can be used in a flexible manner, either for high voltages and lower current (by connection in series) or higher current lower voltage (by connection in parallel) or any other arbitrary configuration as per Figure 12, providing the internal coupling capacitors voltage ratings are not exceeded between input and output potentials.

Figure 11 and Figure 13 also show optional ballast resistors on the input leads. If the output stack shorts, these resistors will help protect the power leads from being the route of high voltages to ground during the discharging of the packaged units. The units may float momentarily, aiding survival of the internal ACx supplies. Also, if there is a sudden load on the combined output stacks, the additional current will mean these optional ballast resistors may prevent high power loads on the internal parts and may act as a coarse current regulation. (These resistors would therefore be high power, low resistance type resistors for this purpose, which will be an application understood by practitioners in the field.)

This description has not sought to provide further circuitry that may be employed to achieve fine power, voltage or current regulation. In practice, where the, 'ACx', are transformers and/or CFL inverters, then the outputs of the example circuits given in the diagrams would tend to be, approximately, 'constant power' outputs (providing the power source(s) to the individual power supplies is, or approximates to, a voltage stabilised source), such that as the output load draws a high current then the voltage will decrease, and if the current drawn is low so the voltage will increase (and will reach a nominal peak voltage at zero current drawn, according to the characteristics of the individual power supplies). Electrical regulation of the output may be achieved by means commonly known to practitioners in the field, the most common types being shunt or regulator [resistive] type circuits.

However, the present invention may introduce, either in whole or in part, new means to regulate (particularly the voltage) output of such voltage cascades in the following manner: Some stages of an output stack may be unregulated and fed by low-cost parts that provide a 'base supply' to the stack whilst one, or more, other stage(s) are driven by a more expensive switching power supply operating a modulated pulse scheme in which fast control of that particular stage, or stages, will compensate for changes in the unregulated stages. As described previously, further coarse adjustment may be made by powering off, or on, unregulated stages to ensure the overall voltage output remains in range.

The following is an example to illustrate: A set of 10 stages is rated to 5 kV at a maximum current of 10 mA, and each stage can deliver 1 kV with no load. If one of those stages was a regulated output (which may use a switched mode as described above with closed loop monitoring of the output and the capacity to switch the other stages on or off) and the output demand was 4 kV then when the unit is switched on without load, 3 unregulated stages may power up, together with the regulated stage, each contributing ~1 kV to the output stack. When a load is attached which draws 5 mA such that each stage can deliver ~750 V, the unit may then power up 2 further unregulated stages, whilst the one regulated stage continues to fine tune the output voltage in the range ~500 V. By these means, regulation of a high DC voltage may be accomplished with high efficiency, without need for particularly complex circuits that would switch the whole output voltage as a means to regulate it, nor by resistive or shunt means that are lossy.

Claims

1. An electrical circuit comprising a series of stacked Greinacher voltage doubling rectifier stages and multiple independent alternating current, and/or pulsed direct current, electrical sources in which each stage, or group of stages, or combination of individual and groups of stages, is fed by an independent electrical source and that together form a cascade of electrical stages which combine the power and voltage outputs of the independent electrical sources.
2. The electrical circuit of claim 1 in which any given rectifier stage may be fed by multiple parallel independent sources of nominally identical peak-to-peak voltage.
3. The electrical circuit of claim 1 in which one point on the cascade of stages is commonly and directly electrically coupled to one of the two output lines of each of the independent electrical sources, while the other line of each supply is capacitively coupled to a rectifier stage, or multiple rectifier stages, which together form the cascade of such rectifier stages.
4. The electrical circuit of claim 1 in which no point on the stacked stages is commonly and directly electrically coupled to the independent electrical sources, but instead one output of each of the independent electrical sources are connected so as to form a common electrical connection, and this common electrical connection is linked via a capacitor, or capacitors, to a point, or points, on the stacked stages, while the other line of each supply is capacitively coupled to a rectifier stage, or multiple rectifier stages, which together form the cascade of such rectifier stages.
5. The electrical circuit of claim 1, 2, 3 and/or 4 when used with an electrostatic accelerator.
6. The electrical circuit of claim 4 in which the intended electrical output from the output stages is a middle stage, and where the upper or lower stage, exclusively, may be connected to a reference potential such that the potential of the middle stage, with respect to that reference potential, will depend on whether the upper or lower stage is held to that reference potential, and that the polarity of the middle stage will effectively reverse, with respect to that reference potential, when the connection from that reference potential to the upper stage is swapped to the lower stage, or vice versa, thereby providing essentially instantaneous polarity reversal of the middle stage with respect to the reference potential.
7. An electrical circuit of claims 1, 2, 3, 4, 5 and/or 6 in which the rectifier stages are fed from the independent electrical sources via capacitors with capacitances which are no greater than one quarter of any capacitances of the capacitors in the rectifier stages in series with the output load.
8. An electrical circuit of claim 6 in which the stages are fed from the independent electrical sources via capacitors with capacitances which are no greater than one twentieth of any capacitances of the capacitors in series with the output load, such that the polarity switching rate may be maximised.

Abstract

Stacked Greinacher doubling stages are fed by multiple capacitively coupled alternating current, or pulsed direct current, electrical sources, thereby combining their voltage and power into one direct current output. This facilitates the use of parts of smaller size and power, and of cheaper mass-produced construction, compared to the current practice of driving a Villard cascade (Cockroft-Walton voltage multiplier) with a single driver source. Cost, reliability and maintainability improvements are gained over current practice. Additional utility is also gained as the circuit can be implemented to provide DC isolation of the output, which allows for a variety of functions not commonly available with voltage multiplier stacks, such as; essentially instantaneous high voltage polarity reversal capability, and the facility to modularise and 'stack' such circuits in arbitrary series and parallel arrangements.