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(54) Title: POWER QUALITY IMPROVEMENT BY ACTIVE FILTER

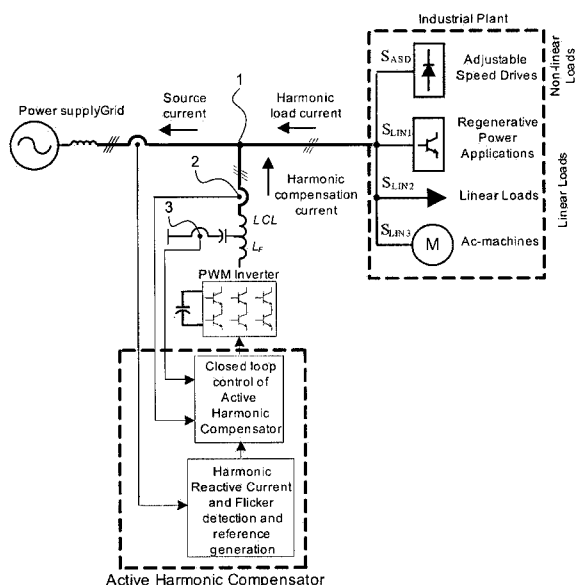


Fig. 2

(57) Abstract: The present invention relates to a method for suppressing one or more harmonic currents in a power supply network, said harmonic currents being generated by one or more loads operationally connected to said power supply network, the method comprising the steps of providing an active power filter comprising an electronic inverter comprising a number of controllable switches, said electronic inverter being operatively connected to an LCL-filter forming part of said active power filter, and providing PWM control signals to each of said controllable switches in response to a particular harmonic current or particular harmonic currents to be suppressed in the power supply network, said PWM control signals varying in response to a value of at least one measured electrical parameter. Moreover, the present invention relates to an active power filter suitable for carrying out the before-mentioned method.

## POWER QUALITY IMPROVEMENT BY ACTIVE FILTER

### FIELD OF THE INVENTION

The present invention relates to an arrangement and a method for improving power quality. In particular, the present invention relates to an arrangement and a method for improving power quality by measuring a current through a capacitor of a LCL-filter and using said current information to control a PWM inverter so as to generate harmonic compensation currents.

### BACKGROUND OF THE INVENTION

The quality of electrical power being distributed on power supply networks is important for consumers being supplied from such networks. In particular, sensitive consumer electronics may be damaged if the power quality of the supplied power do not fulfil specific demands in terms of, for example, allowable harmonic loads currents, noise etc.

Large and/or medium size industrial plants may generate harmonic load currents and introduce such disturbing harmonic load currents into the power supply network. Typically, the harmonic load currents are generated by high frequency switching devices, such as for example AC motor drive units. The high frequency harmonics propagate into the power supply network as high frequency switching harmonic currents. In order to suppress such currents LCL-filters consisting of two reactors and a capacitor connected therebetween are typically applied.

However, a LCL-filter has a self-resonance frequency. If the harmonic load currents provided from the power supply network or generated by PWM control switching coincide with this self-resonance frequency, unintentional resonance scenarios may occur and as result the LCL-filter can be overloaded. Conventionally, in order to suppress this resonance phenomenon, a damping

circuit is applied. In its simplest form the damping circuit consists of a damping resistor connected in series with the capacitor of the LCL-filter. However, such a damping circuit/resistor induces additional losses in the LCL-filter.

A conventional active filter approach is depicted in Fig. 1. The active filter  
5 depicted in Fig. 1 includes a LCL-filter operatively connected to a PWM inverter applying a fixed switching frequency. Moreover, the LCL-filter includes a damping circuit in the form of a damping resistor for damping resonance around the self-resonance frequency of the LCL-filter. In addition, the active filter includes an active harmonic compensation for controlling the PWM inverter in  
10 response to a measured grid current and a measured harmonic compensation current.

Whilst the use of an active filter has the advantage of improving the power quality, power losses will additionally occur within the inverter due to the switching losses in the switches which comprise the inverter.

15 It is an object of embodiments of the present invention to provide an active power filter and an associated method for improving power quality, and maintaining electrical losses at a minimum level.

## DESCRIPTION OF THE INVENTION

The above-mentioned object is complied with by applying an active power filter,  
20 said active power filter comprising a LCL-filter for harmonic current suppression without employing a damping resistor for suppression of the LCL-filter resonance. Moreover, a variable switching frequency is applied to a PWM inverter of said active power filter, said PWM inverter being controlled by at least one internally measured electrical parameter of said active power filter.  
25 The active power filter may be a single phase filter or a multiphase filter, such as a three phase filter.

So, in a first aspect the present invention relates to a method for suppressing one or more harmonic currents in a power supply network, said harmonic currents being generated by one or more loads operationally connected to said power supply network, the method comprising the steps of

- 5       - providing an active power filter comprising an electronic inverter comprising a number of controllable switches, said electronic inverter being operatively connected to an LCL-filter forming part of said active power filter, and
- providing PWM control signals to each of said controllable switches in response to a particular harmonic current or particular harmonic currents to
- 10       be suppressed in the power supply network,

wherein a modulation frequency of at least one PWM control signal varies continuously in response to a value of at least one measured electrical parameter.

Typically, harmonic currents are generated by large and medium size industrial

15       plants. These harmonic currents propagate onto the power distribution grid (power supply network) and they may, if they are not properly damped, cause damage to other electrical devices operatively connected to the same grid.

Continuously varying the frequency of the at least one PWM control signal in response to a value of at least one measured electrical parameter allows very

20       precise tailoring of the frequency to the rate of change of the value of at least one measured electrical parameter. The switching frequency may, for example, have a short cycle length where the rate of change of the desired output is highest. A longer cycle length may be applied where the desired output changes at a lower rate. The power losses in the controllable switches, which

25       are proportional to the frequency of the at least one PWM control signal, may therefore advantageously be lowered in comparison to the losses occurring if a single switching frequency is used. The average switching rate (and so power loss) can thus be lowered without losing accuracy of waveform produced when

compared with a method where a single high frequency is used as the at least one PWM control signal.

The modulation frequency of the at least one PWM control signal may vary within a time frame corresponding to a fundamental frequency of the power supply network. As the fundamental frequency of the power supply network is either 50 Hz or 60 Hz the modulation frequency may be varied within a time frame of 15-20 ms.

The at least one measured electrical parameter may be measured internally in the LCL-filter. Preferably, the measured electrical parameter comprises a measured current flowing internally in the LCL-filter. The measured current may be a current flowing through the capacitor or the LCL-filter.

The LCL-filter and the electronic inverter may be configured to suppress harmonic currents in a three phase power supply network. Thus, the LCL-filter may comprise three identical LCL-branches (one for each phase) and the electronic inverter may be implemented as a B6 coupling comprising three pairs of IGBTs (one pair for each phase).

In addition to measuring the current or currents flowing through the capacitor or capacitors the method may further comprise the step of measuring an output current from the active power filter. The output current from the active power filter is measured at a connection point before the point of common coupling (PCC), i.e. the connection point where the active filter feeds the harmonic compensation current or currents into the power supply network.

The method may further comprise the step of measuring a power supply network current or currents (in the case of for example a three phase network). A power supply network current is the current resulting from a combination of a harmonic load current (current from the network loads) and the harmonic compensation current (current from the active filter).

The modulation frequency of the at least one of the PWM control signals may vary within the range 1-10 kHz.

In a second aspect, the present invention relates to an active power filter for suppressing one or more harmonic currents being generated by one or more  
5 loads operationally connected to a power supply network, the active power filter comprising

- an electronic inverter comprising a number of controllable switches, said electronic inverter being operatively connected to an LCL-filter, and
- means for generating PWM control signals to each of said controllable  
10 switches in response to a particular harmonic current or currents to be suppressed in the power supply network,

wherein the means for generating PWM control signals is capable of continuously varying the modulation frequency of at least one PWM control signal in response to a value of at least one measured electrical parameter.

15 The active power filter may be implemented as a single phase filter or a multiphase filter, such as a three phase filter. Thus, the LCL-filter and the electronic inverter may be configured to suppress harmonic currents in a three phase power supply network. In that case the LCL-filter may comprise three identical LCL-branches (one for each phase) and the electronic inverter may be  
20 implemented as a B6 coupling comprising three pairs of IGBTs (one pair for each phase).

Continuously varying the frequency of the at least one PWM control signal in response to a value of at least one measured electrical parameter allows very precise tailoring of the frequency to the rate of change of the value of at least  
25 one measured electrical parameter. The switching frequency may, for example, have a short cycle length where the rate of change of the desired output is highest. A longer cycle length may be applied where the desired output

changes at a lower rate. The power losses in the controllable switches, which are proportional to the frequency of the at least one PWM control signal, may therefore advantageously be lowered in comparison to the losses occurring if a single switching frequency is used. The average switching rate (and so power loss) can thus be lowered without losing accuracy of waveform produced when compared with an active power filter where a single high frequency is used as the at least one PWM control signal.

The means for generating the PWM control signals may be capable of varying the modulation frequency of the at least one PWM control signal within a time frame corresponding to a fundamental frequency of the power supply network. As the fundamental frequency of the power supply network is either 50 Hz or 60 Hz the modulation frequency may be varied within a time frame of 15-20 ms.

The active power filter may further comprise means for measuring an output current from the active power filter, means for measuring the at least one electrical parameter, and means for measuring a power supply network current. The means for measuring the at least one electrical parameter may comprise a current sensor positioned so as to measure a current flowing through a capacitor of the LCL-filter.

The modulation frequency of at least one of the PWM control signals may be within the range 1-10 kHz.

The a third aspect, the present invention relates to a power supply network wherein one or more active power filters according to the second is/are connected in parallel to one or more loads generating one or more harmonic currents.

## BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will now be explained in further details with reference to the accompanying figures, wherein

Fig. 1 shows a conventional active filter arrangement including a damping resistor,

Fig. 2 shows an active power filter according to an embodiment of the present invention,

5 Fig. 3 shows various implementations of a LCL-filter, and

Fig. 4 illustrates various PWM scenarios.

While the invention is susceptible to various modifications and alternative forms, specific embodiments have been shown by way of examples in the drawings and will be described in detail herein. It should be understood, however, that the  
10 invention is not intended to be limited to the particular forms disclosed. Rather, the invention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined by the appended claims.

#### DETAILED DESCRIPTION OF THE INVENTION

In its broadest aspect the present invention is directed to a novel power active  
15 filter with minimal losses. This has been achieved by suppressing a self-resonance of a LCL-filter for harmonic current suppression without employing a damping resistance, and by applying a variable switching frequency in a PWM inverter being operatively connected to the LCL-filter.

Referring now to Fig. 2 an active filter injects power into the power supply  
20 network, the injected power having relatively low frequency components. Usually, the injected harmonic compensation currents are in the frequency range 100–2000 Hz. If the generated harmonic compensation currents are properly matched to the harmonic load currents the source current at the point of common coupling 1 will be without harmonics. Ideally the source current will  
25 be sinusoidal, but in practise a small amount of harmonics will remain in the source current. However, this small amount of harmonics will be well below the

amount allowed by the local grid code. The reactive currents of the nonlinear loads can be compensated at the same time as well.

The inverter of the active filter (denoted PWM Inverter in Fig. 2) operates in accordance with a so-called pulse width modulation technique (PWM  
5 technique). The frequency of the carrier wave that is employed in the PWM technique must be many times higher compared to the frequency of the output current/voltage of the PWM inverter. The frequency of the carrier wave is variable and thereby changeable during operation of the active filter.

As previously mentioned a LCL-filter consists of two reactors and a capacitor  
10 connected therebetween.

In order to implement a low-loss active power filter comprising an LCL-filter for harmonic current suppression, said LCL-filter comprises at least two reactors, a capacitor and an unavoidable internal resistance. An output current from the active power filter and a current flowing through the capacitor of the LCL-filter  
15 are measured and subsequently used to control of the PWM inverter of the active power filter.

In an embodiment of the present invention the source current and the current flowing through the capacitor of the LCL-filter are both measured respectively at points 2 and 3, in Fig. 2, and subsequently transformed into a space vector. The  
20 current error signal, i.e. the difference signal between the measured vector current and the vector reference value of this current, is transformed to form a voltage vector reference signal. The amplitude and the placement of this voltage vector reference signal are used for defining a switching signal of the PWM inverter. The frequency of the switching signal is varied so that the  
25 switching frequency of the PWM inverter depends on the current error signal.

Thus, in the active power filter according to the present invention, the current flowing through the capacitor of the LCL-filter is detected and applied as a current reference correction signal to correct the current reference. The PWM

inverter of the active power filter applies this corrected new current reference signal whereby the resonance current of the LCL-filter can be damped in the same way as if a damping resistance was applied.

Continuously varying the switching frequency of the PWM inverter allows very  
5 precise tailoring of the frequency. The switching frequency may, for example, have a short cycle length where the rate of change of the desired output is highest. A longer cycle length may be applied where the desired output changes at a lower rate. The power losses in the inverter switches, which are proportional to the switching frequency, may therefore advantageously lowered  
10 in comparison to the losses occurring if a single switching frequency is used. The average switching rate (and so power loss) can thus be lowered without losing accuracy of waveform produced when compared with an active power filter where a single high frequency is used.

The LCL-filter of the present invention may be implemented in various ways.  
15 Referring now to Fig. 3, single phase implementations are depicted in Fig. 3a and Fig. 3b. The only difference between these two implementations is the positioning of the current sensor 4, 5 for measuring the current flowing through the capacitor of the LCL-filter.

Fig 3c, 3d and 3e all depict three phase implementations. In Fig. 3c the currents  
20 are measured at point 6 prior to reaching the capacitors of the LCL-filter. In Fig. 3d only two currents are measured, the third current being estimated from knowledge of the known values of circuit components and/or historical measurements. In Fig. 3e the three capacitors are coupled in a  $\Delta$ -connection 7 while the three currents are measured at points 8 which lie between the  
25 reactors one of the three points forming the  $\Delta$ -connections of the capacitors.

Referring now to Fig. 4a a portion of the desired voltage vs. time is depicted. Traditionally the desired voltage is generated by a traditional PWM switch pattern where the width of each pulse (duty cycle) is varied throughout the cycle

of the fundamental but the PWM cycle length ( $T$ ) remains unchanged – cf. Fig. 4b.

Fig. 4c depicts a signal where a variable switching frequency is used. Here the switching frequency has a short cycle length ( $T_1$ ) where the rate of change of the desired output is highest. A longer cycle length ( $T_m$ ) is applied where the desired output does not change very much. Using this method the error between the desired and actual voltage output is similar over the whole cycle. In addition, the power loss in the switches, which is proportional to switching rate, is much lower than it would be if the cycle time of  $T_1$  was used over the whole fundamental cycle. The average switching rate (and so power loss) can thus be lowered without losing accuracy of waveform produced when compared with a method where the whole PWM signal is switched at a high switching frequency.

## CLAIMS

1. A method for suppressing one or more harmonic currents in a power supply network, said harmonic currents being generated by one or more loads operationally connected to said power supply network, the method comprising  
5 the steps of

- providing an active power filter comprising an electronic inverter comprising a number of controllable switches, said electronic inverter being operatively connected to an LCL-filter forming part of said active power filter, and

- providing PWM control signals to each of said controllable switches in  
10 response to a particular harmonic current or particular harmonic currents to be suppressed in the power supply network,

wherein a modulation frequency of at least one PWM control signal varies continuously in response to a value of at least one measured electrical parameter.

15 2. A method according to claim 1, wherein the modulation frequency of the at least one PWM control signal varies within a time frame corresponding to a fundamental frequency of the power supply network.

3. A method according to claim 1 or 2, wherein the at least one measured electrical parameter is measured internally in the LCL-filter.

20 4. A method according to claim 3, wherein the measured electrical parameter comprises a measured current flowing internally in the LCL-filter.

5. A method according to claim 4, wherein the LCL-filter and the electronic inverter are configured to suppress harmonic currents in a three phase power supply network.

6. A method according to any of the preceding claims, further comprising the step of measuring an output current from the active power filter.

7. A method according to any of the preceding claims, further comprising the step of measuring a power supply network current.

5 8. A method according to any of the preceding claims, wherein the modulation frequency of the at least one of the PWM control signals is within the range 1-10 kHz.

9. An active power filter for suppressing one or more harmonic currents being generated by one or more loads operationally connected to a power supply  
10 network, the active power filter comprising

- an electronic inverter comprising a number of controllable switches, said electronic inverter being operatively connected to an LCL-filter, and

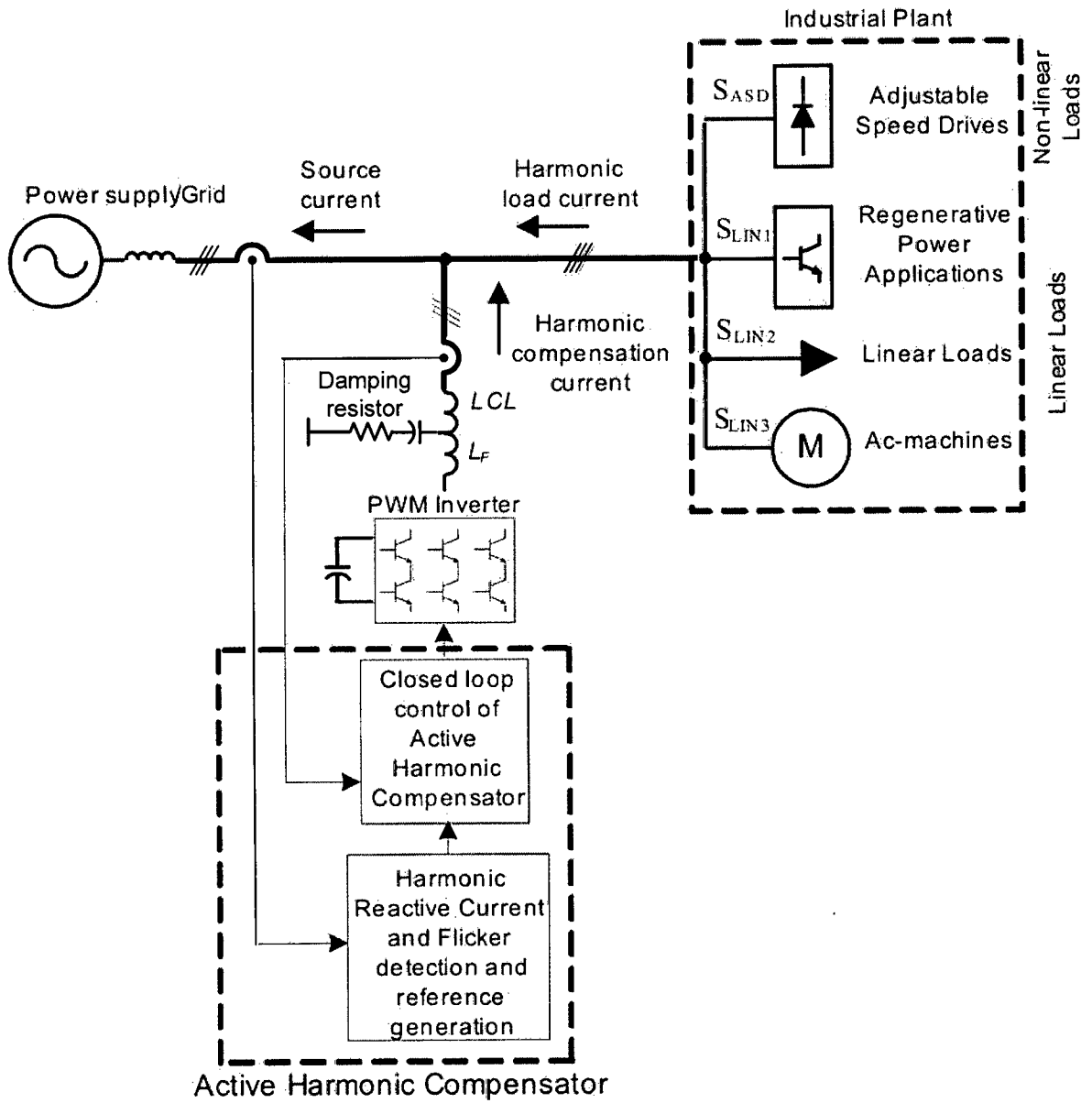
- means for generating PWM control signals to each of said controllable switches in response to a particular harmonic current or currents to be  
15 suppressed in the power supply network,

wherein the means for generating PWM control signals is capable of continuously varying the modulation frequency of at least one PWM control signal in response to a value of at least one measured electrical parameter.

10. An active power filter according to claim 9, wherein the means for  
20 generating the PWM control signals is capable of varying the modulation frequency of the at least one PWM control signal within a time frame corresponding to a fundamental frequency of the power supply network.

11. An active power filter according to claim 9 or 10, wherein the LCL-filter and the electronic inverter are configured to suppress harmonic currents in a three  
25 phase power supply network.

12. An active power filter according to any of claims 9-11, further comprising means for measuring an output current from the active power filter, means for measuring the at least one electrical parameter, and means for measuring a power supply network current.
- 5 13. An active power filter according to claim 12, wherein the means for measuring the at least one electrical parameter comprises a current sensor positioned so as to measure a current flowing through a capacitor of the LCL-filter.
- 10 14. An active power filter according to any of claims 9-13, wherein the modulation frequency of at least one of the PWM control signals is within the range 1-10 kHz.
15. A power supply network wherein one or more active power filters according to any of claims 9-14 is/are connected in parallel to one or more loads generating one or more harmonic currents.



(Prior Art)

Fig. 1

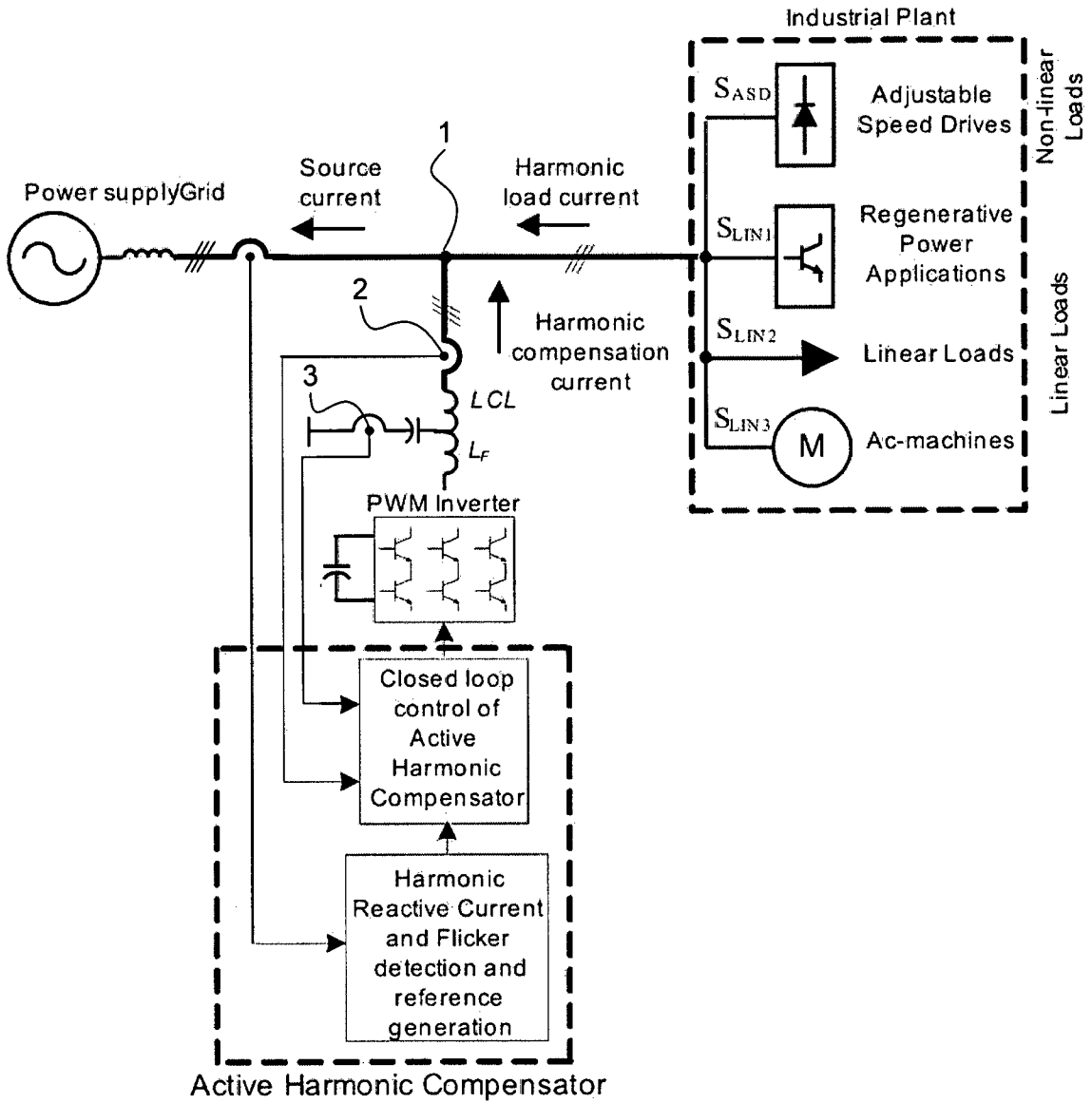


Fig. 2

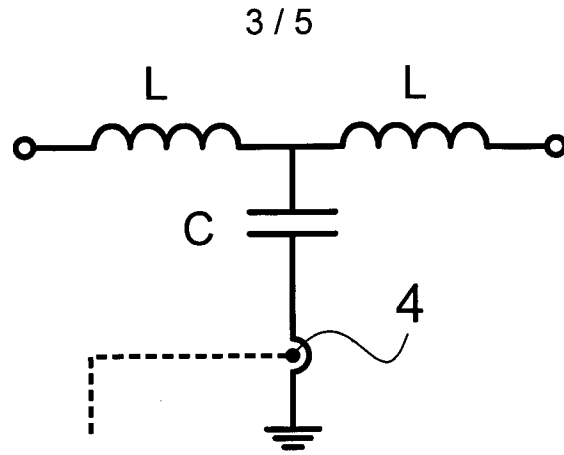


Fig. 3a

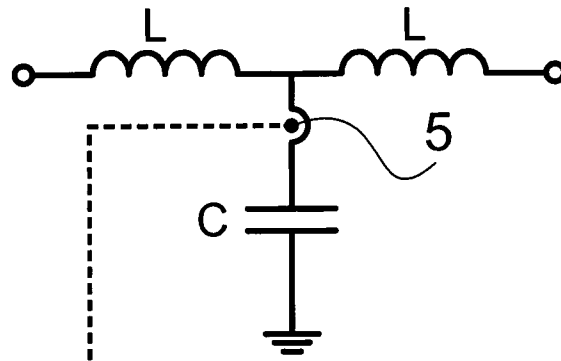


Fig. 3b

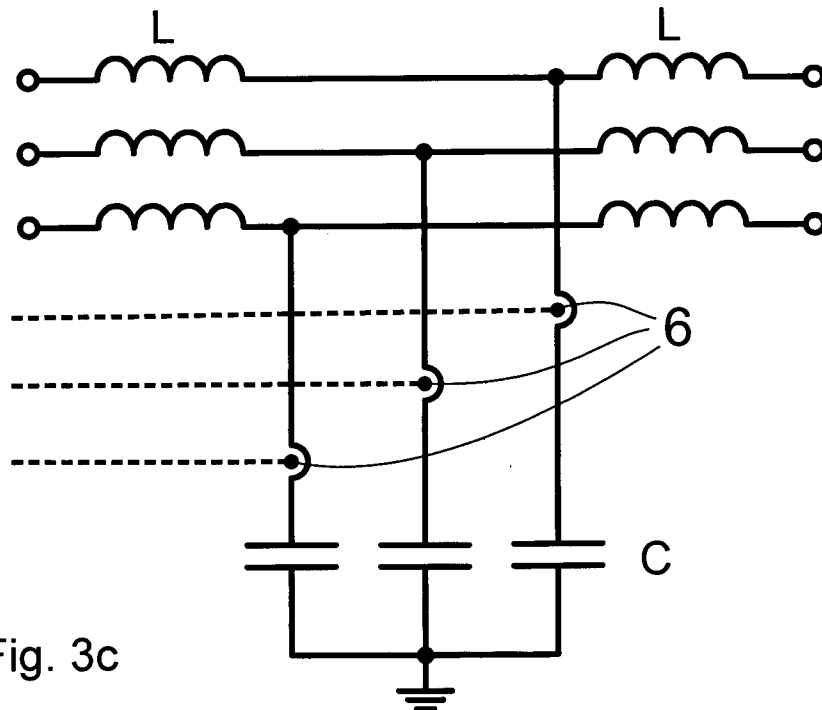


Fig. 3c

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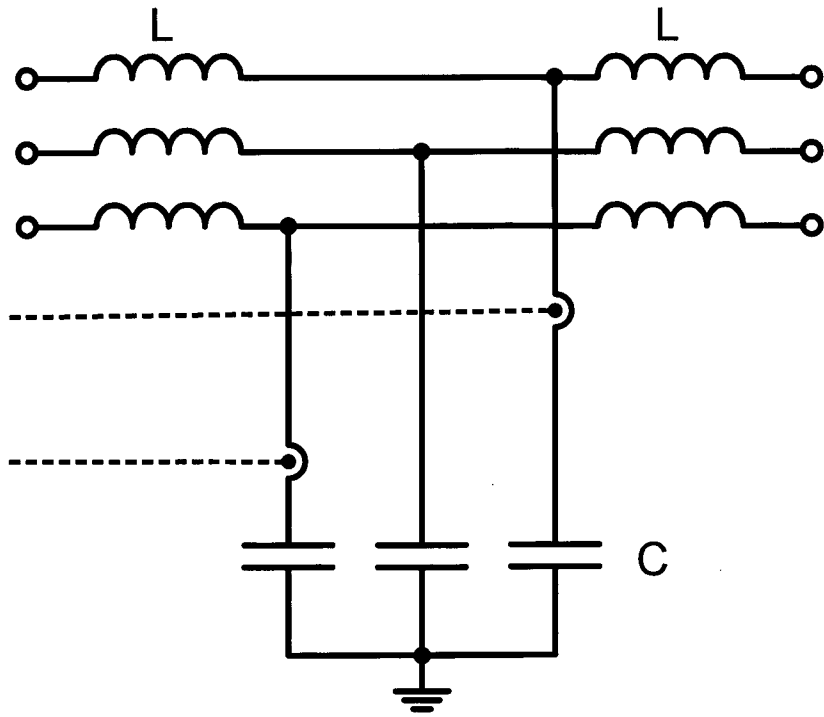


Fig. 3d

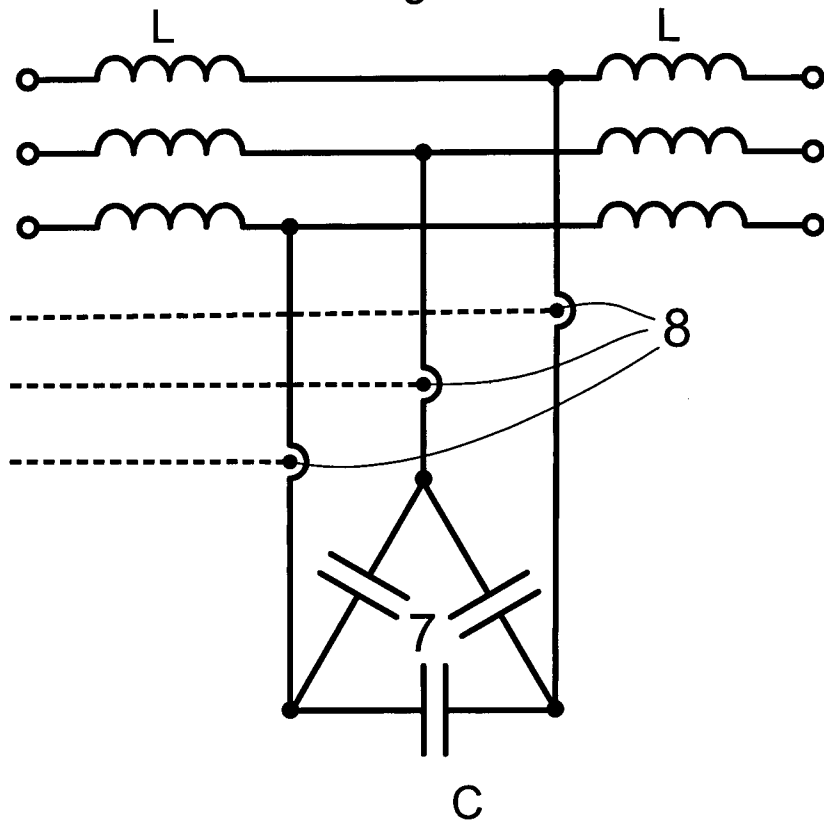


Fig. 3e

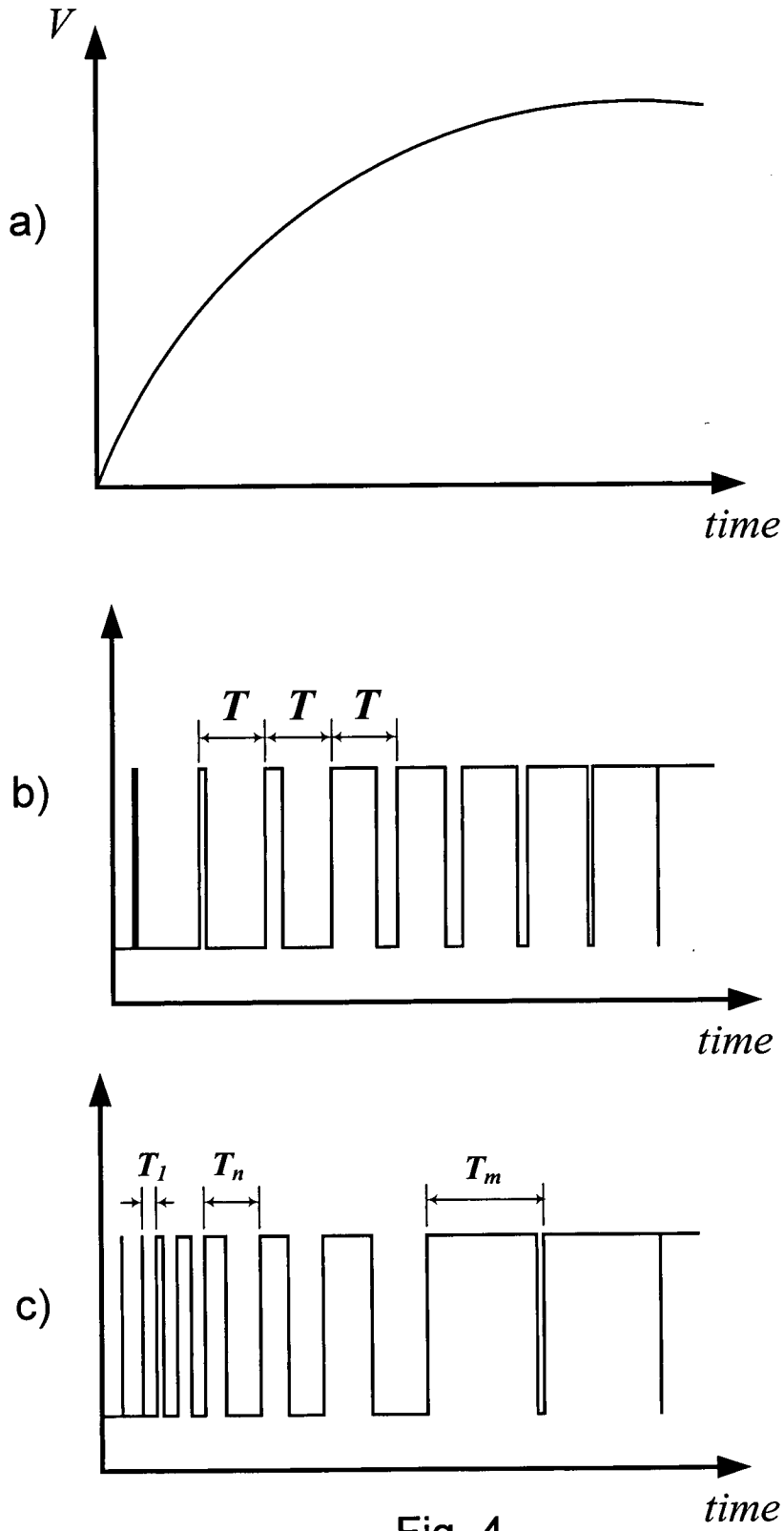


Fig. 4