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Power Quality Improvement of Electrified Transportation A Single-Phase Active Device

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Abstract- *A transformer less hybrid series active filter is proposed to enhance the power quality in single-phase systems with critical loads. This paper assists the energy management and power quality issues related to electric transportation and focuses on improving electric vehicle load connection to the grid. The control strategy is designed to prevent current harmonic distortions of nonlinear loads to flow into the utility and corrects the power factor of this later. While protecting sensitive loads from voltage disturbances, sags, and swells initiated by the power system, ridded of the series transformer, the configuration is advantageous for an industrial implementation. This polyvalent hybrid topology allowing the harmonic isolation and compensation of voltage distortions could absorb or inject the auxiliary power to the grid. Aside from practical analysis, this paper also investigates on the influence of gains and delays in the real-time controller stability. The simulations and experimental results presented in this paper were carried out on a 2-kVA laboratory prototype demonstrating the effectiveness of the propos.*

IndexTerms: Currentharmonics,electricvehicle,hybridseriesactivefilter(HSeAF),powerquality,real-timecontroled topology.

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I. INTRODUCTION

The forecast of future Smart Grids associated with electric vehicle charging stations has created a serious concern on all aspects of power quality of the power system, while widespread electric vehicle battery charging units [1], [2] have detrimental effects on power distribution system harmonic voltage levels [3]. On the other hand, the growth of harmonics fed from nonlinear loads like electric vehicle propulsion battery chargers [4], [5], which indeed have detrimental impacts on the power system and affect plant equipment, should be considered in the development of modern grids. Likewise, the increased rms and peak value of the distorted current waveforms increase heating and losses and cause the failure of the electrical equipment. Such phenomenon effectively reduces system efficiency and should have properly been addressed [6], [7]. Moreover, to protect the point of common coupling (PCC) from voltage distortions, using a dynamic voltage restorer (DVR) function is advised. A solution is to reduce the pollution of power electronics-based loads directly at their source. Although several attempts are made for a specific case study, a generic solution is to be explored. There exist two types of active power devices to overcome the described power quality issues. The first category are series active filters (SeAFs), including hybrid-type ones. They were developed to eliminate current harmonics produced by nonlinear load from the power system. SeAFs are less scattered than the shunt type of active filters [8], [9]. The advantage of the SeAF compared to the shunt type is the inferior rating of the compensator versus the load nominal rating [10]. However, the complexity of the configuration and necessity of an isolation series transformer had decelerated their industrial application in the distribution system. The second category was developed in concern of addressing voltage issues on sensitive loads. Commonly known as DVR, they have a similar configuration as the SeAF. These two categories are different from each other in their control principle. This difference relies on the purpose of their application in the system. The hybrid series active filter (HSeAF) was proposed to address the aforementioned issues with only one combination. Hypothetically, they are capable to compensate current harmonics, ensuring a power factor (PF) correction and eliminating voltage distortions at the PCC properties make it an appropriate candidate for power quality investments. The three-phase SeAFs are well documented, whereas limited research works reported the single-phase applications of SeAFs in the literature. In this paper, a single-phase transformerless HSeAF is proposed and capable of cleaning up the grid-side connection bus bar from current harmonics generated by a nonlinear load . With a smaller rating up to 10%, it could

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easily replace the shunt active filter . Furthermore, it could restore a sinusoidal voltage at the load PCC. The advantage of the proposed configuration is that nonlinear harmonic voltage and current producing loads could be effectively compensated. The transformerless hybrid series active filter (THSeAF) is an alternative option to conventional power transferring converters in distributed generation systems with high penetration of renewable energy sources, where each phase can be controlled separately and could be operated independently of other phases . This paper shows that the separation of a three-phase converter into single-phase H bridge converters has allowed the elimination of the costly isolation transformer and promotes industrial application for filtering purposes.. Then, the operation principle of the proposed configuration is explained. The third section is dedicated to the modeling and analysis of the control algorithm implemented in this work. The dc voltage regulation and its considerations are briefly explained, and the voltage and current harmonic detection method is explicitly described. To evaluate the configuration and the control approach, some scenarios are simulated. validate simulations. This paper is summarized with a conclusion and appendix where further mathematical developments are demonstrated.

2.HARMONICS

The typical definition for a harmonic is “a sinusoidal component of a periodic wave or\ quantity having a frequency that is an integral multiple of the fundamental frequency.” [1]. Some references refer to “clean” or “pure” power as those without any harmonics. Electrical generators try to produce electric power where the voltage waveform has only one frequency associated with it, the fundamental frequency The rate at which these changes occur is the trigometric function called a sine wave, as shown in figure 1. This function occurs in many natural phenomena, such as

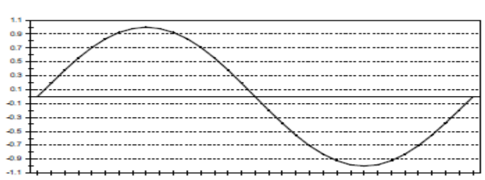

Fig1.1 Sine wave

The frequency of the harmonics is different, depending on the fundamental frequency. For example, the 2nd harmonic on a 60 Hz system is 2*60 or 120 Hz. At 50Hz, the second harmonic is 2* 50 or 100Hz. 300Hz is the 5th harmonic in a 60 Hz system, or the 6th harmonic in a 50 Hz system. Figure 2 shows how a signal with two harmonics would appear on an oscilloscope-type display, which some power quality analyzers provide.

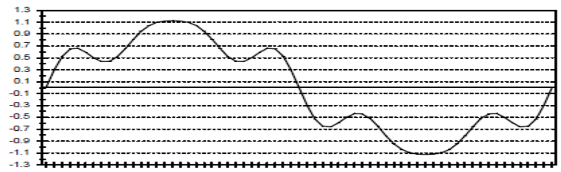

Figure1.2. Fundamental with two harmonics

In order to be able to analyze complex signals that have many different frequencies present, a number of mathematical methods were developed. One of the more popular is called the Fourier Transform. So more compatible processes, called the FFT for Fast Fourier transform, or DFT for Discrete Fourier The frequency values must not change during the measurement period. Hz and 200 Hz signals, the FFT cannot directly see the 200 Hz. It only knows 60, 120, 180, 240,..., which are often called “bins”. The result would be that the energy of the 200 Hz signal would appear partially in the 180Hz bin, and partially in the 240 Hz bin. An FFT-based processer could show The firing scheme refers to the controlling mechanism that determines how and when current is conducted. One major variation is the phase angle at which conduction begins and ends. A typical such converter is the switching-type power supplies found in most personal computers and peripheral equipment, such as printers. While they offer many benefits in size, weight and cost, the large increase of this type of equipment over the past fifteen years is largely responsible for the increased attention to harmonics.

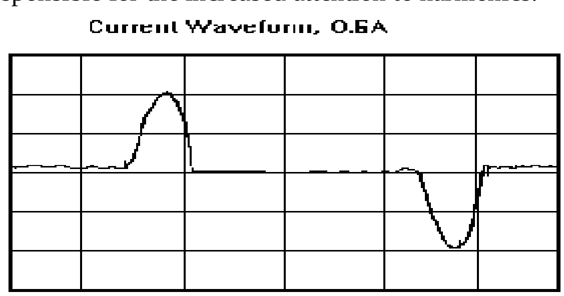

Figure1.3. Current Waveform

The above Figure shows how a switching-type power supply works. The AC voltage is converted into a DC voltage, which is further converted into other voltages that much energy is being taken out by the rest of the power supply.

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3.ELECTRICAL VEHICLES

In every home there is a lot of electric powered tools, some are used inside and other outside. We can toast our bread, dry our hair, vacuum clean and so on. But there is one thing that is not powered with electricity. We start the day of using this product, the workday ends often by using it, we use it after work and some people use it in work, on weekends and so on. This product can be a symbol of personality, a symbol of power status, a sign of success or sign of taste. I think It's now obvious that I'm talking about the car.

Effect The nature

We, the people on this earth, have some common growing problems. Pollution is one and a shortage of gasoline and crude oil is another. Oil is limited and the price of oil continues to increase worldwide. I will take Iceland as an example, it does not produce oil so it has to be imported and that is very expensive for the nation. There are added all sorts of surcharges, including taxes, duties assessment, shipping and more taxes.

Iceland is very dependent on the use of fuel and most habitants buy gasoline to get from place to place. We only have to monitor the morning traffic for a few minutes to see it. Most Icelanders want to have the freedom to move were they want when they want using the way to travel as suited to each, personal cars, busses or taxes. All these options consumes gasoline, and many other factors regarding the fuel engine, including the engine oil for lubrication of the engine and gearbox oil for lubrication of the gearbox . All these products are imported and so let's not forget that all these cars pollute our environment.

Fig 3.2 electrical vehicle

With the depletion of the earth's ozone layer and the shortage of our oil supply becoming an issue, we have had to look at alternative fueled vehicles that will not harm the environment, but will still provide us with a reliable source of transportation. What is really the solution to this problem? There is solution to solve how to travel from place to place without polluting and significantly reduce imports of oil and gas. That solution is electric! The future of transportation lies in electric cars! It is good for mother earth and in this case we would we are able to protect the environment and reduce maintenance costs that follow cars.

4.FILTERS

Filters of some sort are essential to the operation of most electronic circuits. It is therefore in the interest of anyone involved in electronic circuit design to have the ability to develop filter circuits capable of meeting a given set of specifications. Unfortunately, many in the electronics field are uncomfortable with the subject, whether due to a lack of familiarity with it, or a reluctance to grapple with the mathematics involved in a complex filter design.

A clean network has less strain on appliances and their lifespan are lengthened. Maintenance and replacement costs are lowered. So we go for filters. Filters can be classified into three types:

1. Active filter
2. Passive filter
3. Hybrid filter

ACTIVE FILTER

An active filter is a type of analog electronic filter, distinguished by the use of one or more active components i.e. voltage amplifiers or buffer amplifiers. Typically this will be a vacuum tube, or solid-state (transistor or operational amplifier).Active filters have three main advantages over passive filters:

- Inductors can be avoided. Passive filters without inductors cannot obtain a high Q (low damping), but with them are often large and expensive (at low frequencies), may have significant internal resistance, and may pick up surrounding electromagnetic signals.
- The shape of the response, the Q (Quality factor), and the tuned frequency can often be set easily by varying resistors, in some filters one

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parameter can be adjusted without affecting the others. Variable inductances for low frequency filters are not practical.

- The amplifier powering the filter can be used to buffer the filter from the electronic components it drives or is fed from, variations in which could otherwise significantly affect the shape of the frequency response.

Pure active filters can be classified into two types according to their circuit configuration

I. Shunt (parallel) active filters

II. Series active filters

Shunt Active Filter Configuration

Shunt active filters have more advantage over series active filters regarding their form and function. So series active filters are basically suitable only for harmonic filtering. Shunt active filter circuit configuration:

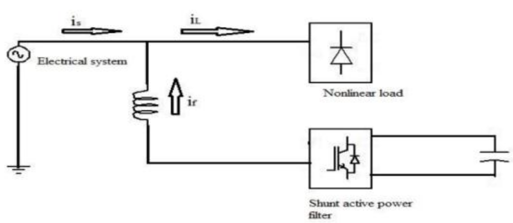

Fig.4.2. Schematic diagram of a shunt

TOPOLOGY OF SINGLE PHASE SHUNTS ACTIVE POWER FILTER

The SPSAPF shown in fig.1.14 consists of a single-phase full-bridge voltage–source PWM inverter, a DC bus capacitor C_{DC} and an inductor L_C .The inductance, through which the inverter is connected to the power supply network, ensures, firstly, the controllability of the active filter current and acts, secondly, as a first-order passive filter attenuating, thus, the high frequency ripples generated by the inverter. The filter operates as current source, which cancels the current-type harmonics and exchanges the necessary reactive energy required by the non-linear load. A single-phase diode bridge rectifier feeding a series R-L circuit is chosen to represent the non-linear load.

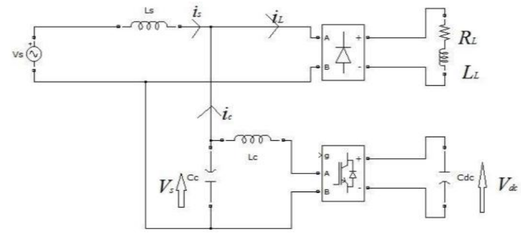

Fig. 4.10. Single phase shunt active power filter.

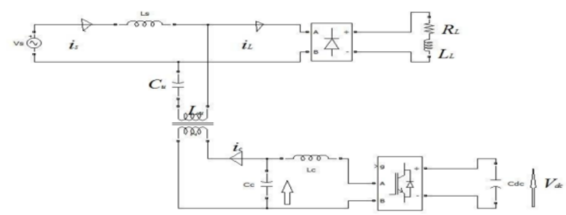

Fig. 4.11. Single phase hybrid power filter.

The SPSHPF shown in fig.1.15 consists of a full-bridge voltage–source PWM inverter, a DC side capacitor C_{DC}, an inductor L_C, a transformer and a power factor correction (PFC) capacitor C_C . The primary winding of the transformer is fed by the inverter. The PFC capacitor and the secondary winding of the transformer are connected in series to form a branch parallel to the non-linear load. The iron core of the transformer contains an air-gap in order to reduce its magnetizing inductance L_μ . The PFC capacitor C_C and the magnetizing inductance L_μ create a second-order filter tuned at the third harmonic.

SERIES CONNECTION OF PASSIVE AND ACTIVE FILTER TOPOLOGY

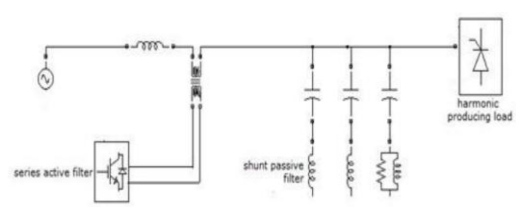

Fig.4.12. Combination of a series active filter and a shunt passive filter.

In fig.1.16 the shunt passive filter connected in parallel with a load suppresses the harmonic currents produced by the load, while the active filter connected in series to a source acts as a "harmonic isolator" between the source and the load. Hence a hybrid filter helps to overcome the drawbacks of passive filter and active filter used alone.

POWER QUALITY PROBLEMS

For the purpose of this article, we shall define power quality problems as: 'Any power problem that results in failure or mis operation of customer equipment, manifests itself as an economic burden to the user, or produces negative impacts on the environment.'

When applied to the container crane industry, the power issues which degrade power quality include:

• Power Factor
• Harmonic Distortion
• Voltage Transients
• Voltage Sags or Dips
• Voltage Swells

The AC and DC variable speed drives utilized on board container cranes are significant contributors to total harmonic current and voltage distortion. Whereas SCR phase control creates the desirable average power factor, DC SCR drives operate at less than this. In addition, line notching occurs when SCR's commutate, creating transient peak recovery voltages that can be 3 to 4 times the nominal line voltage depending upon the system impedance and the size of the drives. The frequency and severity of these power system disturbances varies with the speed of the drive. Harmonic current injection by AC and DC drives will be highest when the drives are operating at slow speeds. Power factor will be lowest when DC drives are operating at slow speeds or during initial acceleration and deceleration periods, increasing to its maximum value when the SCR's are phased on to produce rated or base speed. Above base speed, the power factor essentially remains constant. Unfortunately, container cranes can spend considerable time at low speeds as the operator attempts to spot and land containers. Poor power factor places a greater kVA demand burden on the utility or engine-alternator power source. Low power factor loads can also affect the voltage stability which can ultimately result in detrimental effects on the

Power quality can be improved through:

• Power factor correction,
• Harmonic filtering,
• Special line notch filtering,
• Transient voltage surge suppression,
• Proper earthing systems.

In most cases, the person specifying and/or buying a container crane may not be fully aware of the potential power quality issues. If this article accomplishes nothing else, we would hope to
provide that awareness.

• Consult with the utility company to determine regulatory or contract requirements that must be
satisfied, if any.

3. Power System Adequacy

When considering the installation of additional cranes to an existing power distribution system, a power system analysis should be completed to determine the adequacy of the system to support additional crane loads. Power quality corrective actions may be dictated due to inadequacy of existing power distribution systems to which new or relocated cranes are to be connected. In other words, addition of power quality equipment may render a workable scenario on an existing power distribution system, which would otherwise be inadequate to support additional cranes without high risk of problems.

4. Environment

No issue might be as important as the effect of power quality on our environment. Reduction in system losses and lower demands equate to a reduction in the consumption of our natural nm resources and reduction in power plant emissions. It is our responsibility as occupants of this planet to encourage conservation of our natural resources and support measures which improve our air quality

7.SYSTEM ARCHITECTURE

SYSTEM CONFIGURATION

The THSeAF shown in Fig. 1 is composed of an H-bridge converter connected in series between the source and the load. A shunt passive capacitor ensures a low impedance path for current harmonics. A dc auxiliary source could be connected to inject power during voltage sags. The dc-link energy storage system is described in

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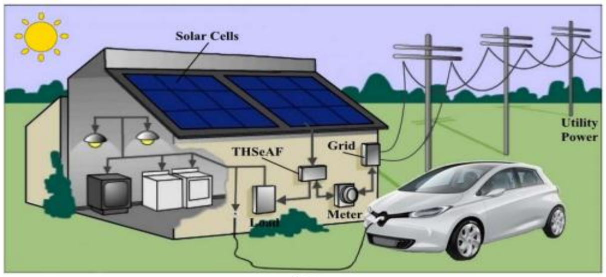

(a)

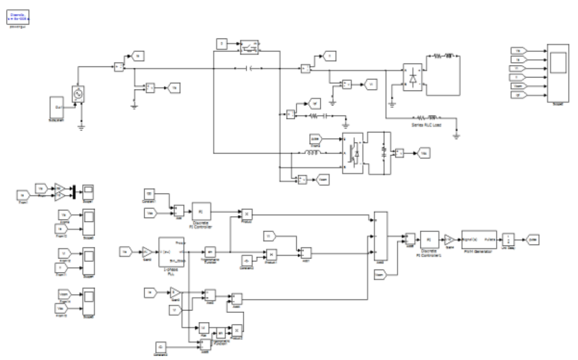

Fig 7.1. (a) Schematic of a single-phase smart load with the compensator installation. (b) Electrical diagram of the THSeAF in a single-phase utility.

The system is implemented for a rated power of 2200 VA. To ensure a fast transient response with sufficient stability margins over a wide range of operation, the controller is implemented on. The system parameters are identified in Table I. A variable source of 120 Vrms is connected to a 1.1-kVA nonlinear load and a 998-VA linear load with a 0.46 PF. The THSeAF is connected in series in order to inject the compensating voltage. On the dc side of the compensator, an auxiliary dc-link energy storage system is installed. Similar parameters are also applied for practical implementation.

TABLE I
CONFIGURATION PARAMETERS

Symbol	Definition	Value
v_s	Line phase-to-neutral voltage	120 Vrms
f	System frequency	60 Hz
$R_{non\text{-}linear\ load}$	Load resistance	11.5 Ω
$L_{non\text{-}linear\ load}$	Load inductance	20 mH
P_L	Linear load power	1 kVA
PF	Linear load power factor	46 %
Lf	Switching ripple filter inductance	5 mH
Cf	Switching ripple filter capacitance	2 µF
T_S	dSPACE Synchronous sampling time	40 µs
f_{PWM}	PWM frequency	5 kHz
G	Control gain for current harmonics	8 Ω
V_{DCref}*	VSI DC bus voltage of the THSeAF	70 V
PI_G	Proportional gain (K_p), Integral gain (K_i)	0.025(4*), 10 (10*)

* Adopted value for the experimental setup

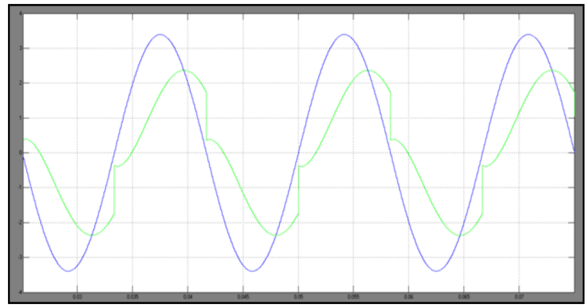

Fig. 7.2. Terminal voltage and current waveforms of the 2-kVA single phase system without compensator. (a) Regular operation. (b) Grid's voltage distortion (scales: 50 V/div for channel 1and 10 A/div for channel 2).

HSeAFs are often used to compensate distortions of the current type of nonlinear loads. For instance, the distorted current and voltage waveforms of the nonlinear system during normal operation and when the source voltage became distorted are depicted in Fig. 2. The THSeAF is bypassed, and current harmonics flowed directly into the grid. As one can perceive, even during

TABLE II
SINGLE-PHASE COMPARISON OF THE THSeAF TO PRIOR HSeAFs

Definition	Proposed THSeAF	[21]	[22]	[12]
Injection Transformer	Non	2 per phase	1 per phase	1 per phase
# of semiconductor devices	4	8	4	4
# of DC link storage elements	1+Aux. Pow.	1	2	1+Aux. Pow.
AF rating to the load power	10-30%	10-30%	10-30%	10-30%
Size and weight, regarding the transformer, power switches, drive circuit, heat sinks, etc.	The Lowest	High	Good	Good
Industrial production costs	The Lowest	High	Low	Low
Power losses, including switching, conducting, and fixed losses	Low	Better	Low	Low
Reliability regarding independent operation capability	Good	Low	Good	Good
Harmonic correction of Current source load	Good	Good	Good	Low
Voltage Harmonic correction at load terminals	Good	Better	Good	Good
Power factor correction	Yes	Yes	Yes	No
Power injection to the grid	Yes	No	No	Yes

normal operation the current harmonics (with a total harmonic distortion (THD) of 12%) distort the PCC, resulting in a voltage THD of 3.2%. The behavior of the system when the grid is highly polluted with 19.2% of THD is also illustrated. The proposed configuration could be solely connected to the grid with no need of a bulky and costly series injection transformer, making this topology capable of compensating source current harmonics and voltage distortion at the PCC. Even if the number of switches has

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increased, the transformerless configuration is more cost-effective than any other series compensators, which generally uses a transformer to inject the compensation voltage to the power grid. The optimized passive filter is composed of 5th, 7th, and highpass filters. The passive filter should be adjusted for the system upon load and government regulations. A comparison between different existing configurations is given in Table II. It is aimed to point out the advantages and disadvantages of the proposed configuration over the conventional topologies. To emphasize the comparison table fairly, the equivalent single phase of each configuration is considered in the evaluation. Financial production evaluation demonstrated a 45% reduction in component costs and considerable reduction in assembly terms as well.

OPERATION PRINCIPLE

The SeAF represents a controlled voltage source (VSI). In order to prevent current harmonics $i_{L\square}$ to drift into the source.

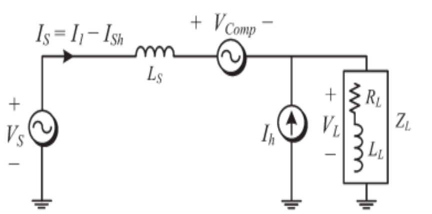

Fig. 7.3. THSeAF equivalent circuit for current harmonics.

This series source should present low impedance for the fundamental component and high impedance for all harmonics as shown in Fig. 3. The principle of such modeling is well documented in [20]. The use of a well-tuned passive filter is then mandatory to perform the compensation of current issues and maintaining a constant voltage free of distortions at the load terminals. The behavior of the SeAF for a current control approach is evaluated from the phasor's equivalent circuit shown in Fig. 3.The nonlinear load could be modeled by a resistance representing the active power consumed and a current source generating current harmonics. Accordingly, the impedance Z_L represents the nonlinear load and the inductive load.

The SeAF operates as an ideal controlled voltage source (V_{comp}) having a gain(G)proportional to the current harmonics ($I_{s\square}$) flowing to the grid (V_s)

$$V_{comp} = G.I_{s\square} - V_{L\square}. \quad (1)$$

This allows having individual equivalent circuit for the fundamental and harmonics

$$= V_{s1} + V_{s\square}, \quad V_L = V_{L1} + V_{L\square}. \quad (2)$$

The source harmonic current could be evaluated

$$V_{s\square} = -Z_s.I_{s\square} + V_{comp} + V_{L\square} \quad (3)$$

$$V_{L\square} = Z_L(I_{\square} - I_{s\square}). \quad (4)$$

Combining (3) and (4) leads to (5)

$$I_{s\square} = \frac{V_{s\square}}{(G - Z_s)} \quad (5)$$

If gain G is sufficiently large (G→∞), the source current will become clean of any harmonics(Ish→0). This will help improve the voltage distortion at the grid side. In this approach, the THSeAF behaves as high-impedance open circuit for current harmonics, while the shunt high-pass filter tuned at the system frequency creates a low-impedance path for all harmonics and open circuit for the fundamental; it also helps for PF correction.

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8.MODELING AND CONTROL OF THE SINGLE-PHASE THSeAF

Average and Small-Signal Modeling

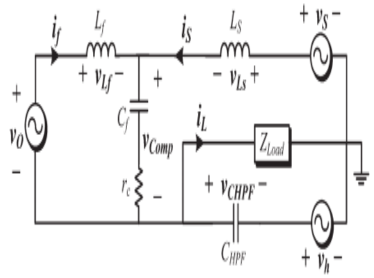

Fig. 8.1. Small-signal model of transformer less HSeAF in series between the grid and the load.

Based on the average equivalent circuit of an inverter [23], the small-signal model of the proposed configuration can be obtained as in Fig. 4. Here after, *d* is the duty cycle of the upper switch during a switching period, whereas $\bar{v}$and $\bar{\imath}$ denote the average values in a switching period of the voltage and current of the same leg. The mean converter output voltage and current are expressed by (6) and (7) as follows.

where the (2d−1) equals tom, then

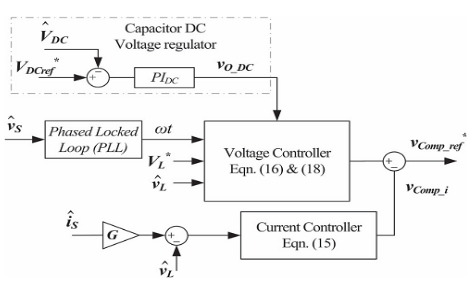

Fig. 8.2. Control system scheme of the active part.

The transfer function T_{Vm}presents the relation between the output voltages of the converter versus the duty cycle of the first leg converter's upper switch The further detailed derivation of steady-state transfer functions is described in Section V. A dc auxiliary source should be employed to maintain an adequate supply on the load terminals. During the sag or swell conditions, it should absorb or inject power to keep the voltage magnitude at the load terminals within a specified margin. However, if the compensation of sags and swells is less imperative, a capacitor could be deployed. Consequently, the dc-link voltage across the capacitor should be regulated as demonstrated in Fig. 8.2.

9.Voltage and Current Harmonic Detection

The outer-loop controller is used where a capacitor replaces the dc auxiliary source. This control strategy is well explained in the previous section. The control gain G representing the impedance of the source for current harmonics has a sufficient level to clean the grid from current harmonics fed through the nonlinear load.

The second proportional integrator (PI) controller used in the outer loop was to enhance the effectiveness of the controller when regulating the dc bus. Thus, a more accurate and faster transient response was achieved without compromising the compensation behavior of the system. According to the theory, the gain G should be kept in a suitable level, preventing the harmonics from flowing into the grid . As previously discussed, for a more precise compensation of current harmonics, the voltage harmonics should also be considered. The compensating voltage for current harmonic compensation is obtained from

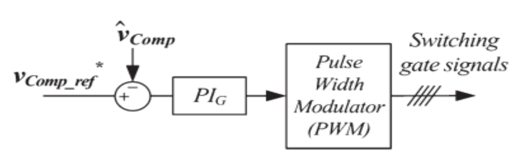

Fig. 9.1. Block diagram of THSeAF and PI controller.

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Hereby, as voltage distortion at the load terminals is not desired, the voltage sag and swell should also be investigated in the inner loop. The closed-loop equation (16) allows to indirectly maintain the voltage magnitude at the load side equal to V_L^*as a predefined value, within acceptable margins

The entire control scheme for the THSeAF presented in Fig. 5was used and implemented in MATLAB/Simulink for real-time simulations and the calculation of the compensating voltage. The real-time toolbox of dSPACE was used for compilation and execution on the dsp-1103 control board. The source and load voltages, together with the source current, are considered as system input signals. According to Srianthumrong *et al.* , an indirect control increases the stability of the system.

The source current harmonics are obtained by extracting the fundamental component from the source current A phase-locked loop was used to obtain the reference angular frequency (ωs). Accordingly, the extracted current harmonic contains a fundamental component synchronized with the source voltage in order to correct the PF. This current represents the reactive power of the load. The gain Grepresenting the resistance for harmonics converts current into a relative voltage.The generated reference voltage v_{comp_i}required to clean the source current from harmonics is described in .

According to the presented detection algorithm, the compensated reference voltage $v^*_{Comp_{ref}}$ is calculated. Thereafter, the reference signal is compared with the measured output voltage and applied to a PI controller to generate the corresponding gate signals as inFig.6.

10.Stability Analysis for Voltage and Current Harmonics

The stability of the configuration is mainly affected by the introduced delay of a digital controller. This section studies the impact of the delay first on the inclusive compensated system according to works cited in the literature. Thereafter, its effects on the active compensator is separated from the grid. Using purely inductive source impedance (see Fig. 4) and Kirchhoff's law for harmonic frequency components,is derived. The delay time of the digital controller, large gain G, and the high stiffness of the system seriously affect the stability of the closed-loop controlled system.

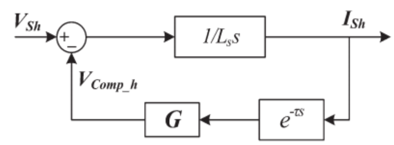

Fig. 10.1. Control diagram of the system with delay

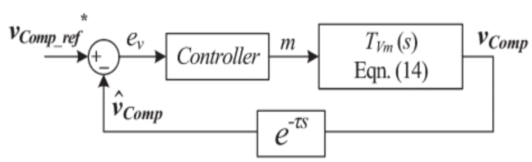

Fig. 10.2. Closed-loop control diagram of the active filter with a constant delay timeτ.

The compensating voltage including the delay time generated by the THSeAF in the Laplace domain [see (1)] isConsidering and, the control diagram of the system with delay is obtained as in Fig. 7. For the sake of simplicity, the overall delay of the system is assumed to be a constant value τ. Therefore, the open-loop transfer function is obtainedFor the sake of simplicity, the overall delay of the system is assumed to be a constant value τ. Therefore, A system with a typical source inductance L_s of 250μH and a delay of 40μs is considered stable according to when the gain G is smaller than 10Ω. Experimental results confirm the stability of the system presented in this paper. Moreover, the influence of the delay on the control algorithm should also be investigated. According to the transfer functions (13) and (14), the control of the active part is affected by the delay introduce by the digital controller. Thus, assuming an ideal switching characteristic for the IGBTs, the closed-loop system for the active part controller is shown in Fig. 8.

The open-loop transfer function in Fig. 8turns to, where the τ is the delay time initiated by the digital controller. A PI controller with system parameters described in Table I demonstrates a smooth operation in the stable region. By means of MATLAB, the behavior of the system's transfer function F(s) is traced in Fig. 9. The root locus and

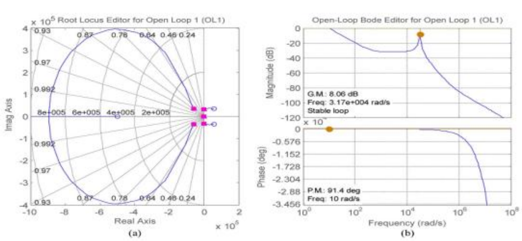

Fig. 10.3. Compensated open-loop system with delay time of 40μs. (a) Root locusdiagram.(b) Bode diagram

SIMULATIONS RESULTS

The proposed transformer less-HSeAF configuration was simulated in MATLAB/Simulink using discrete time steps of Ts=10μs. A dSPACE/dsp1103 was used for the fast control prototyping. To ensure an error-free and fast implementation, the complete control loop was executed every 40 μs. The parameters are identified in Table I.

The combination of a single-phase nonlinear load and a linear load with a total rated power of 2 kVA with a 0.74 lagging PF is applied for laboratory experiments and simulations. For experiments and simulations, a 2-kVA 120-Vrms 60-Hz variable source is used. THSeAF connected in series to the system compensates the current harmonics and voltage distortions. The complete experimental system is demonstrated in Fig. 10.

A gain G=8Ωequivalent to 1.9 p.u. was used to control current harmonics. As mentioned earlier, the capability of operation with low dc voltage is considered as one of the main advantages of the proposed configuration. For this experiment, it is maintained at 130 Vdc. During a grid's voltage distortion, the compensator regulates the load voltage magnitude, compensates current harmonics, and corrects the PF. The simulated results of the THSeAF illustrated in Fig. 11demonstrates improvement in the source current THD. The load terminal voltage VL THD is 4.3%, while the source voltage is highly distorted (THDVS= 25%).

The grid is cleaned of current harmonics with a unity power factor (UPF) operation, and the THD is reduced to less than 1% in normal operation and less than 4% during grid perturbation. While the series controlled source cleans the current of harmonic components, the source current is forced to be in phase with the source voltage. The series compensator has the ability to slide the load voltage in order for the PF to reach unity. Furthermore, the series compensator could control the power flow between two PCCs.

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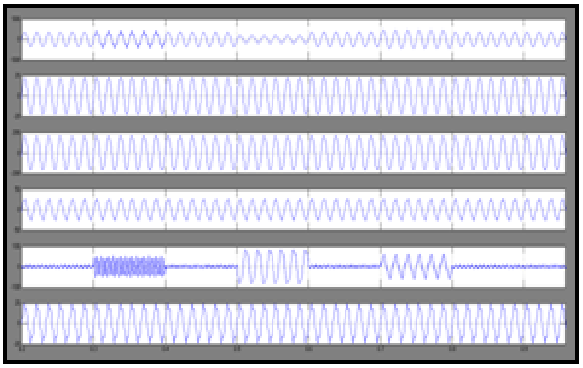

Fig. 11. Simulation of the system with the THSeAF compensating current harmonics and voltage regulation. (a) Source voltage V_s, (b) source current i_s, (c) load voltage V_L, (d) load current i_l, (e) active-filter voltage V_{comp}, and (f) harmonics current of the passive filter i_{PF}.

sag and swells initiated from the utility source as shown in the following figures. While cleaning the source current from harmonics and correcting the PF, the compensator regulates the load terminal voltage. Clarified in Section III, the auxiliary source provides the necessary amount of power to maintain the supply at the load terminals despite variation in the source magnitude. The behavior of the proposed compensator during dynamic load variation could be depicted from Fig. 14, where the load is suddenly changed.

The THSeAF reacts instantly to this variation and does not interfere its operation functionality. Meanwhile, it is normal to observe a slight transient voltage variation depending on the momentum of the load disengagement or connection. To evaluate the compensator during utility perturbation, the power source became distorted as depicted in Fig. 15. The source current became cleaned of the majority of harmonics available in the load current and has a unity PF.

The existing perturbation on the grid's voltage to propagate on the load PCC. It protects sensitive loads and maintains a sinusoidal and regulated voltage across the PCC of loads with a 3.9% of distortion. Moreover, in a worst possible scenario, the already distorted utility's voltage is subjected to voltage magnitude variation. Thus, the compensator should also inject power to maintain the load PCC voltage regulated at the desired level. During voltage sag and swell, the auxiliary source supplies the difference of power to maintain the magnitude of the load side voltage regulated. The harmonic content and THD factor of the source utility and load PCC presented show dramatic improvements in THD, while the load draws polluted current waveforms. Furthermore, although the grid's voltage is polluted, the compensator in a hybrid approach regulates and maintains a harmonic-free load voltage.

CONCLUSION

In this paper, a transformerless HSeAF for power quality improvement was developed and tested. The proposed transformerless configuration was simulated and experimentally validated. It was demonstrated that this active compensator responds properly to source voltage variations by providing a constant and distortion-free supply at load terminals. Furthermore, it eliminates source harmonic currents and improves the power quality of the grid without the usual bulky and costly series transformer.For the sake of simplicity, the resistance r_c of the switching capacitor filter C_f is neglected, and the inductance L_f has an ideal behavior.

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