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Series Active Power Filter for High-Voltage Synchronous Generators

Marko Petkovšek, Aleš Leban, Mitja Nemec, Danjel Vončina and Peter Zajec

University of Ljubljana, Faculty of Electrical Engineering, Ljubljana, Slovenia

Abstract: In this paper, an approach for minimization of voltage harmonics in the output of synchronous generators (SG) is described. It is based on three single-phase series active power filters (SAPF) that are inserted close to the common point of SG through an injection transformer. A distinctive advantage of the proposed approach is the use of low-voltage components that can be used due to SAPF insertion point position. Another benefit of the injection transformer implementation is also the possibility to increase the turns ratio and therefore the same approach can be used also for high-voltage SG. The solution was experimentally verified on two synchronous generators of various nominal voltage and power ratings. Due to very promising results, the implementation of the approach in high-voltage applications requiring low harmonic distortion is fully justified.

Keywords: series active power filter, synchronous generator, harmonic distortion, magnetostriction, power supply, repetitive control, digital signal controller

Serijski aktivni močnostni filter za visokonapetostne sinhronske generatorje

Izvleček: V prispevku je predstavljen pristop za zmanjšanje harmonskega popačenja na izhodnih sponkah sinhronskih generatorjev (SG). Rešitev temelji na uporabi treh enofaznih serijskih aktivnih filtrov, ki so preko vmesnih transformatorjev vezani zaporedno s faznimi navitji sinhronskega generatorja. Posebna prednost predlagane metode je uporaba nizkonapetostnih komponent, saj je posamezni aktivni filter v sistem priključen na strani skupne nevtralne točke trifaznega navitja generatorja. Rešitev je primerna tudi za visokonapetostne generatorje, saj lahko zmanjšanje harmonskega popačenja dosežemo z obstoječimi nizkonapetostnimi komponentami aktivnega filtra ob ustrezno izbranem prestavnem razmerju vmesnega transformatorja. Zahvaljujoč zelo obetavnim eksperimentalnim rezultatom na dveh generatorjih različnih nazivnih napetosti in moči je predlagana zasnova nadvse primerna za uporabo v visokonapetostnih aplikacijah, kjer je zahtevano majhno harmonsko popačenje izhodne napetosti.

Ključne besede: serijski aktivni močnostni filter, sinhronski generator, harmonsko popačenje, magnetostrikcija, napajalni vir, repetitivna regulacija, digitalni signalni krmilnik

* Corresponding Author's e-mail: marko.petkovsek@fe.uni-lj.si

1 Introduction

A typical set-up for testing various equipment at high voltage and grid frequency relies on the use of a stand-alone synchronous generator (SG) and in majority of cases also a variable matching transformer. This solution assures that measurements can be performed electrically isolated from the grid and independent from the variable grid states. Furthermore, this approach also enables us to modify the voltage through SG excitation and transformer turns ratio and – if required – also the frequency (e.g. 50 Hz or 60 Hz) of the supply source. Although at first sight this solution is the obvious choice since it provides for a constant voltage waveform, it has some drawbacks that are connected with the SG itself and its design. Namely, when we look closely at the SG voltage waveform, we can observe that it is not perfectly sinusoidal. The reason for the presence of higher harmonics in the SG output voltage lies in the construction of the machine. Due to the fact that excitation winding is distributed in the slots across the SG perimeter, the magnetic field distribution in the air gap is not sinusoidal. Further increase of voltage distortion is a result of a non constant permeability of the air gap, different pole shapes, appearance of local magnetic saturation and a non-concentrically designed rotor. The presence of higher harmonics in SG voltage can represent quite a challenge in some applications where a device under test (DUT) undergoes a series of typical laboratory or final production-stage measurements. A typical example is testing of power transformers, where among other measurements also a noise measurement of DUT at no-load is performed. In this case, DUT is supplied with its nominal low-side voltage from the grid-independent source consisting of SG and a matching transformer. When the voltage is applied, a certain level of noise is to be expected in the vicinity of DUT [1]. Its level and frequency spectrum depends greatly on the frequency spectrum of the supplied voltage that is causing magnetostriction-related vibrations in the transformer steel core and its enclosure [2 - 7]. It is clearly obvious that comparison of results from noise measurements performed using different voltage sources is not justified.

In the following chapters, a practical solution that actively suppresses higher voltage harmonics is described in detail. Although it is composed of low-voltage components, it is intended to be used together with high-voltage synchronous generators for special measurements requiring an improved voltage waveform.

2 Principles of harmonics reduction

Since the harmonic content in the output voltage of SG is a matter of a magnetic design, the first option for harmonic reduction would of course be optimization of SG magnetic characteristics [8, 9]. However, as this measure is not always effective enough, harmonic reduction should be performed with additional circuitry that enables suppression of certain harmonics or a certain frequency range. In general, these solutions are known as power filters and can be divided into two groups depending on the components used. The first group – the passive filters group – relies only on passive components, where using a combination of resistors, inductors and capacitors, a desirable transfer function as in low power electronics can be achieved. As it is often very hard to design a passive power filter with sufficiently high impedance compared to the load impedance to achieve effective suppression of voltage harmonics, another group – active power filters – is more common in power electronics.

Active power filters are divided into two subgroups depending on the harmonics to be cancelled from the system. The first type is known as a parallel active power filter (PAPF) and the second as a series active power filter (SAPF). Since PAPF is actually a current source, it is used where current harmonics are to be cancelled from the system [10-12]. Their position in the system depends on the reason causing the presence of harmonics – they can be placed closer to the supply or closer to the load. In the latter case, PAPF is connected in parallel with the supply source in a way that a sum of the load current and the power filter current results in a fundamental harmonic only.

On the other hand, SAPF filters are actually high frequency voltage sources that are connected in series with the supply to eliminate voltage harmonics from the system.

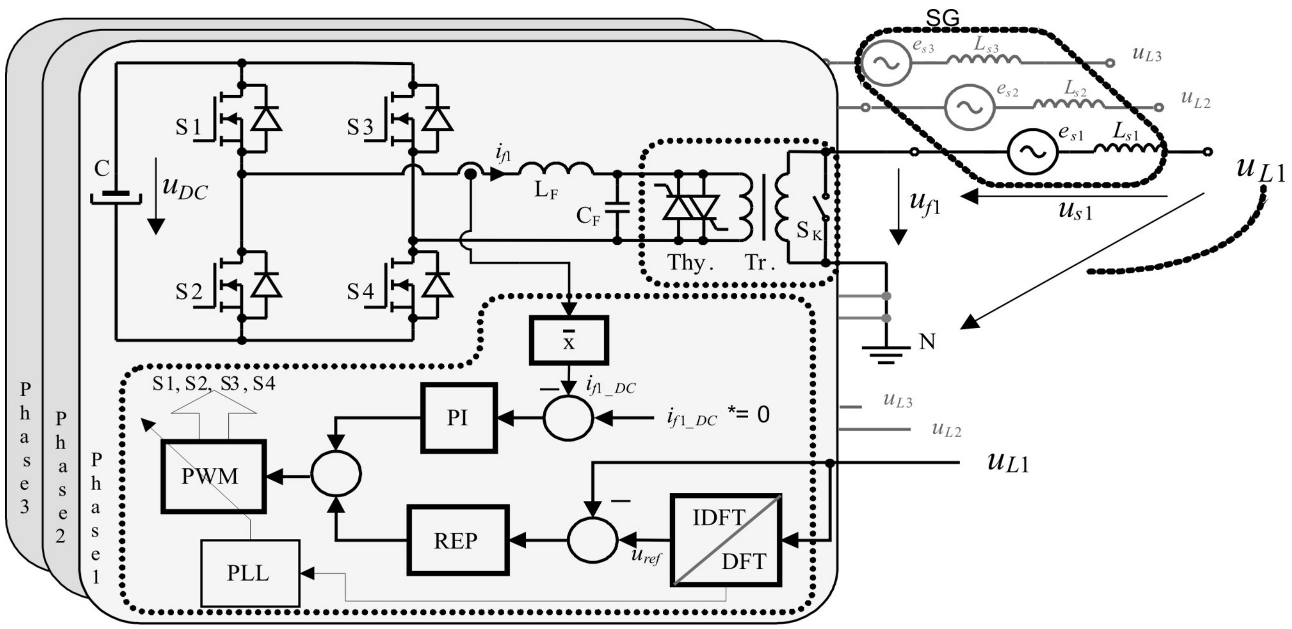

Figure 1: Diagram of the proposed system.

3 Proposed topology of SAPF

As the main objective of our research work was to cancel voltage harmonics from the SG voltage, we implemented a SAPF filter for that purpose [13]. A distinctive advantage of the SAPF, proposed in this paper, is its position. Namely, as it can be seen from Fig. 1, the SAPF position is close to the (normally grounded) common point of the SG three-phase windings. Consequently, being close to the ground potential, also insulation demands for filter components are significantly reduced. In that way, low voltage components that enable high frequency switching can be implemented.

3.1 Power stage of SAPF

The power stage of the proposed SAPF prototype consists of three subunits: a MOSFET transistor full bridge, an output low-pass LC filter for switching ripple suppression and an injection transformer. The latter enables an electrically isolated connection of high-frequency voltage to the SG voltage. When the SAPF is not active, anti-parallel thyristors (Thy.) on the primary side of the injection transformer and a power switch (S_K) on the secondary side are switched on. In this way, SAPF is bypassed and has no influence on the total system output voltage. When SAPF is active, both thyristors and the power switch are in their off state, so the voltage harmonics from SAPF can be transformed to the secondary side of the injection transformer.

3.2 Control algorithm

To be able to efficiently suppress higher harmonics from the SG spectrum irrespective of the SG operating point, an advanced repetitive control algorithm for SAPF is implemented. Basically, it can be divided into three functional control loops that are being executed by means of the supervising digital signal controller (DSC) TMS320F28335 and belonging input/output circuitry.

The first control loop is the voltage feedback loop. Among numerous approaches for reference voltage calculation [14 - 17], here, reference signal u_{ref} for the controller with repetitive action was calculated using the Discrete Fourier Transform (DFT) and Inverse Discrete Fourier Transform (IDFT). With DFT we derived A and B coefficients of the fundamental harmonic and then reconstructed it with IDFT. Since the control algorithm only requires the transform of the fundamental harmonic, a sliding DFT was used [18, 19] as it requires less computational power than the traditional DFT or FFT (Fast Fourier Transform). Its use is also beneficial since it can easily lock-in to the fundamental period in spite of its small frequency deviations or presence of higher harmonics in the synchronizing signal [14]. In such a way, the reference signal is perfectly synchronized with SG, thus preventing any active power being generated by SAPF. The preferred frequency span of the voltage controller was based on the SG voltage spectrum. In the final application, the controller frequency span was set to 5 kHz, while its sampling frequency was set to 51.2 kHz. In this way, 1024 samples per the fundamental period (50 Hz) were guaranteed. Yet, it should be noted that the voltage signal was actually acquired at a four-times higher frequency (204.8 kHz). This oversampling and the subsequent signal averaging improve the signal-to-noise ratio [20] and lower the requirements for an input anti-aliasing filter. Besides, the power stage PWM block was designed to run at twice the sampling frequency (102.4 kHz) thus minimizing the output LC filter size. The applied frequency relationships – affected by the built-in PWM timer - are shown in Fig. 2.

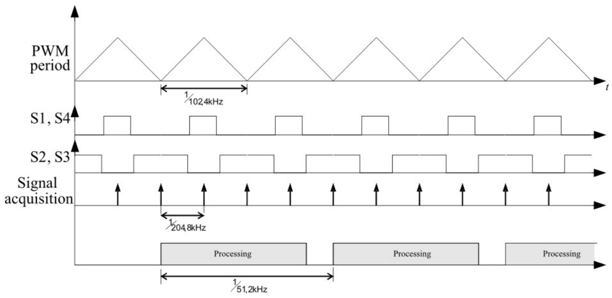

Figure 2: Timing diagram of sampling, switching and algorithm execution

Based on the reference signal u_{ref} and actual line voltage u_{L1} an error signal for the repetitive controller (REP) is obtained for each phase of the system. For a proper operation of the repetitive controller [21, 22], the line voltage sampling has to be synchronized with the period of the fundamental harmonic. For that purpose, a PLL (phase-locked loop) loop is implemented as a part of the control algorithm. Finally, the third control loop forces the SAPF DC current to be near zero and therefore prevents the saturation of the injection transformer.

4 Results and discussion

Firstly, the proposed prototype of SAPF was tested on a laboratory SG (P_n = 40 kVA, U_n= 400 V, n_n = 1500 min^{-1}). To determine what harmonic content is to be expected in the whole SG voltage range, a series of measurements was performed for different excitation levels and various loads. Based on experimental results, no significant change in the harmonic spectrum of the SG voltage was observed. As initially expected and then experimentally confirmed, the presence of harmonics in the voltage spectrum is predominantly a matter of SG magnetic design. The SG waveform and frequency spectrum for one of the operation points at nearly half of the nominal voltage, are given in Fig. 3 and Fig. 4. The presence of voltage harmonics – especially beyond the frequency of 1 kHz – can be clearly observed from the voltage spectrum, resulting in a total harmonic distortion (THD) of 6.7 %.

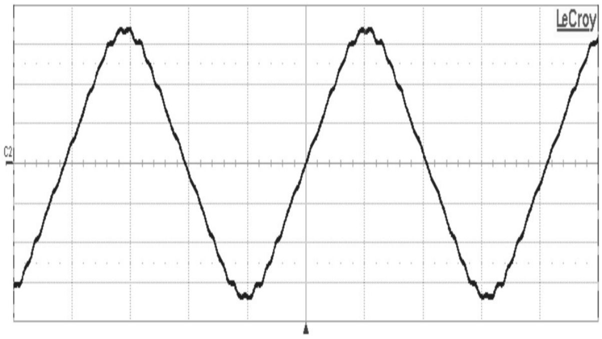

Figure 3: SG output voltage (k_u = 50 V/div, k_t = 5 ms/div).

Further tests were done with the SAPF inserted in the common point of the star connected SG windings as described in section 3. For the SAPF to be able to eliminate voltage harmonics from the SG spectrum efficiently, appropriate DC voltage should be applied to the transistor bridge inside the SAPF. Based on the harmonic spectrum measurements and SG nominal voltage, the DC link voltage was set to 60 V. With the SAPF active and for the same operating point as in Fig. 3, the overall system voltage waveform changed notably, as depicted in Fig. 5. A great improvement is also seen in the voltage harmonic spectrum (Fig. 6). Higher harmonics were efficiently suppressed, yielding in a THD of 0.29 %.

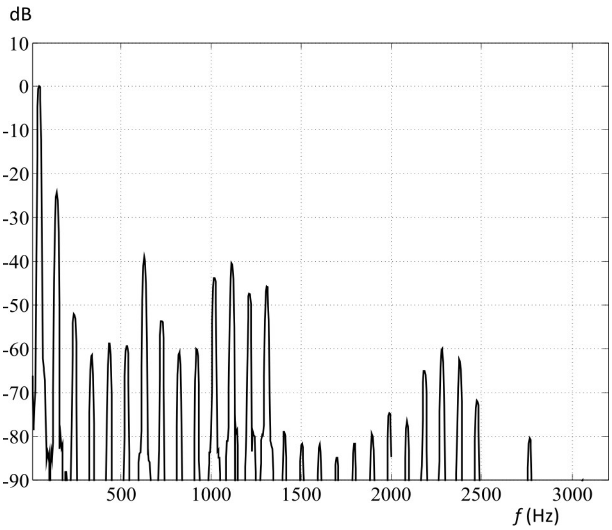

Figure 4: SG output voltage spectrum.

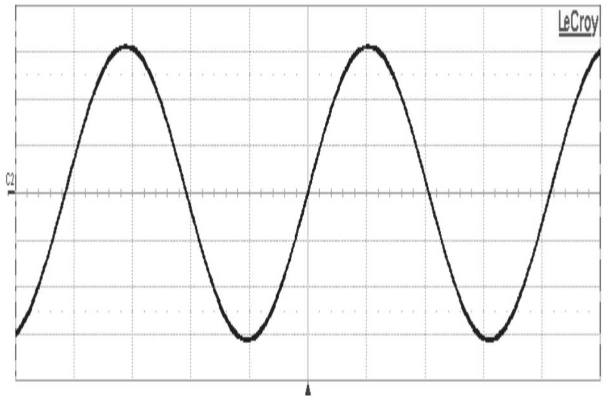

Figure 5: Total system voltage with SAPF active (k_u = 50 V/div, k_t = 5 ms/div).

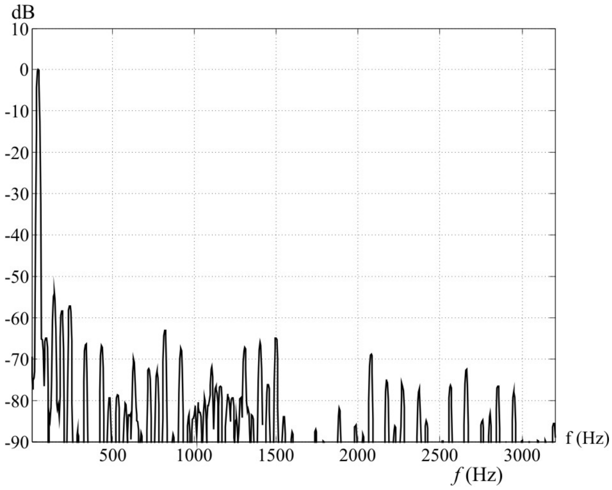

Figure 6: Total system voltage spectrum with SAPF active.

A second series of measurements was performed on the production site of a large producer of power transformers (Kolektor ETRA, Ljubljana, Slovenia). There, final quality control measurements of power transformers are done using a SG (U_n = 6 kV, P_n = 3.5 MVA) and a variable matching transformer in a similar way as described in chapter 1.

During the experiments, one of the power transformers (U_n = 6.3/20 kV, P_n = 8.5 MVA) from the production line was used as a DUT.

As the output voltage of the SG on the production site is substantially higher than the voltage of the laboratory SG, we performed an initial measurement of the SG output voltage and its spectrum in order to get an estimate value for the DC voltage of the SAPF. Similarly as with the previous SG, the output voltage (Fig. 7) is quite heavily distorted with higher harmonics (THD = 4.94 %) – especially around 2 kHz and 4 kHz, as can be observed from Fig. 8. In Fig. 9, also SG output current spectrum is given (THD = 8.75 %). A brief comparison of Fig. 8 and Fig. 9 reveals a close correlation between the distorted SG voltage and the presence of harmonics in the load current that are consequently resulting in increased mechanical vibrations in the DUT core.

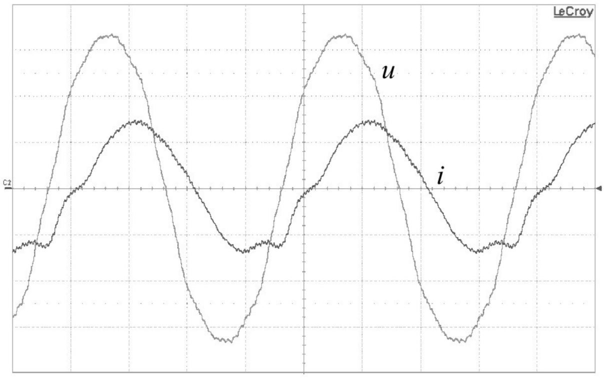

Figure 7: SG output voltage and load current (k_u = 1000 V/div, k_i = 5 A/div, k_t = 5 ms/div).

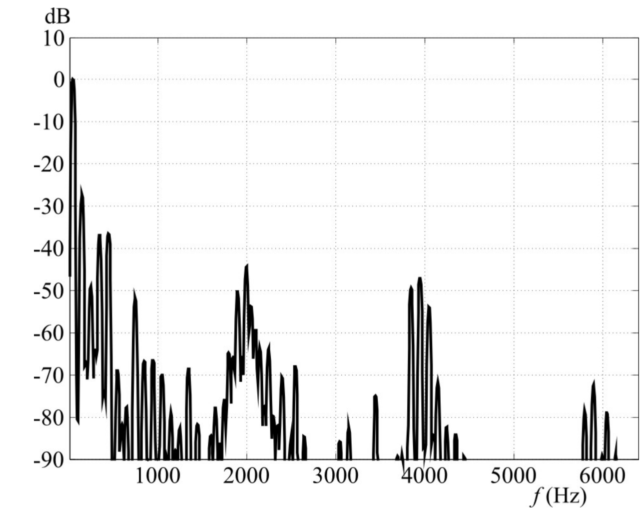

Figure 8: SG output voltage spectrum.

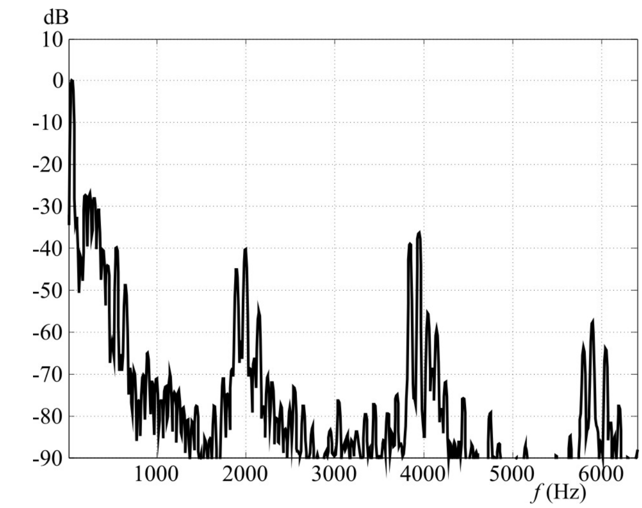

Figure 9:. SG output current spectrum.

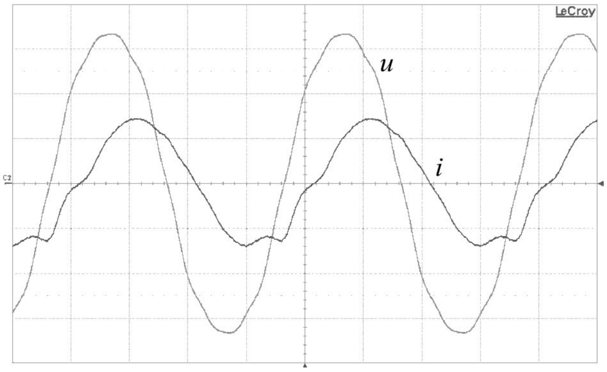

Figure 10: Total system output voltage and load current with SAPF active (k_u = 1000 V/div, k_i = 5 A/div, k_t = 5 ms/div).

Based upon the harmonic spectrum (Fig. 8) analysis, we estimated that the required DC link voltage of SAPF should be in the range of 600 V (for the installed injection transformer (Tr.) with turns ratio 1:1), which is substantially higher than the allowed maximum value of installed components. Namely, installed SAPF components - especially low voltage MOSFET transistors with high frequency switching capability - were selected in order to guarantee a sufficient precision for higher harmonics suppression. Since our focus during this stage was to eliminate only harmonics above the frequency of 1 kHz, the required superimposed voltage u_{f1} (Fig. 1) from SAPF could be achieved with a DC link voltage that is lower than the estimated 600 V for full harmonic reduction. Having that in mind, we set the DC link voltage to 90 V in this case, compared to 60 V that we used with the low voltage laboratory SG. Also, the main reference signal for the repetitive controller was calculated slightly different as in the case of the low voltage SG. Instead of calculating the reference voltage for suppressing all higher harmonics, here, the reference was calculated only for suppression of harmonics above the 9th. In that way, the resulting system output voltage (Fig. 10) was composed of a fundamental component and the 3rd, 5th, 7th and 9th harmonic component still present. Although there is no significant decrease in the voltage and current THD (voltage THD dropped from 4.94% to 4.83 % and curent THD from 8.75 % to 8.63 %), all harmonics above the 9th were efficiently suppressed as seen from the voltage (Fig. 11) and current spectrum (Fig. 12). Of course, if all harmonics are to be cancelled, firstly, the reference voltage calculation is to be modified back again and the DC link voltage or the injection transformer turns ratio should be increased accordingly to prevent SAPF PI controllers from saturation.

5 Conclusion

A low-voltage series active power filter was introduced for the minimization of harmonic distortion in the out-

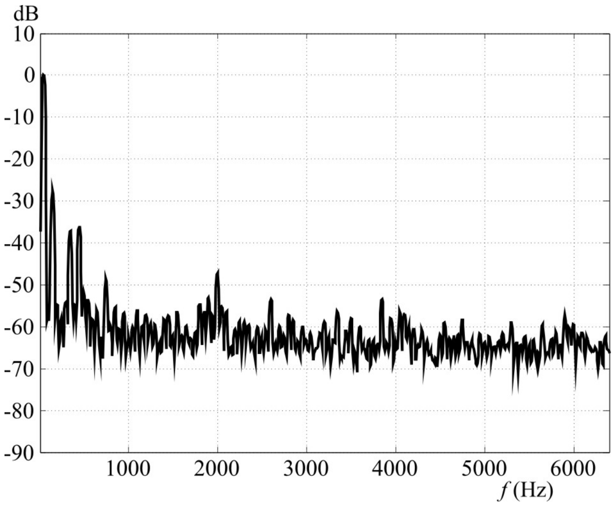

Figure 11: Total system output voltage spectrum with SAPF active.

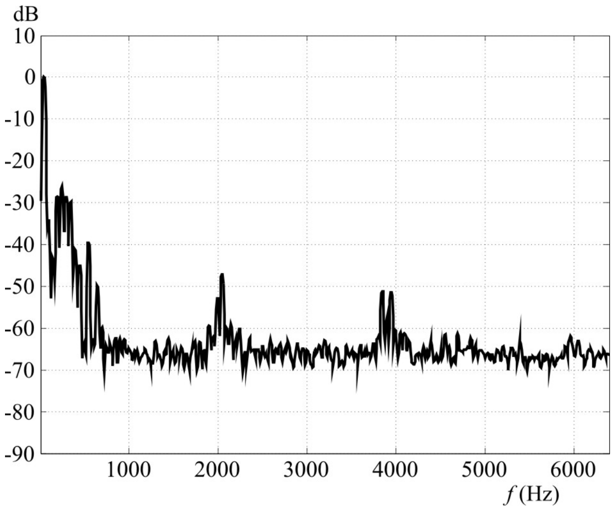

Figure 12: Output current spectrum with SAPF active

put voltage of synchronous generators. Instead of a more common three-phase solution, a single-phase topology was chosen due to a modular design, to simplify maintenance and finally, to achieve efficient harmonic suppression irrespective of voltage disproportions among individual phases. Due to the use of high-speed low-voltage MOSFET transistors in the SAPF full bridge and an advanced repetitive control algorithm, extremely low distortion of voltage can be achieved. Furthermore, due to sophisticated reference voltage calculation, various options for harmonics suppression can be achieved (i.e. full suppression, certain harmonic or a percentage of certain harmonic,…).

Our further work will be focused on implementation of the proposed topology for final production stage measurements of power transformers. A special research topic will be the correlation of the applied voltage with a certain level of harmonics and the produced noise level and frequency spectrum of the DUT.

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