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Power quality enhancement using active power filter five-level cascade H-bridge under unbalanced and distorted grid

Introduction. *To improve the power quality of a supply system, the total harmonic distortion (THD) is the most important parameter in the quantification of harmonics caused by nonlinear loads. In practice, it must be less than 5 %. The novelty of the proposed work consists in the use of a cascaded five level active filter, when the converter consisting of six H-bridge pairs, each one includes four transistors.* ***Purpose***. *To increase the efficiency of this filter, two techniques for quantification of harmonic currents are proposed, first the PQ-theory which is simple but can only be used in case of a balanced grid, and second the synchronous reference frame theory (SFR-theory), which is capable of creating harmonic current not only in an unbalanced grid, but also in an unbalanced and distorted beam.* ***Methods***. *Using the control techniques, the harmonic current is extracted from load current and considered as a reference. The constructed current should follow this reference.* ***Results***. *The estimation of the active and reactive powers is based on the measurement of the currents crossing the load and the network voltages, these powers are used to determine the shape of the harmonic (reference) current. Using the PI regulator, the output current of the five-level inverter follows the reference current perfectly. The inverters output current is injected into the grid to eliminate harmonic currents.* ***Practical value***. *In practice, the harmonic distortion rate THD is the most widely used criterion for criticizing the waveform of the currents and judging the quality of the energy involved. For currents on the source side, the THD is considered acceptable if it is less than 5 %, in our proposal the THD is 0.85 % with the PQ-theory and 2.34 % with SFR-theory, so it is optimal.* References 11, figures 23.

Key words: **multilevel active power filter, total harmonic distortion, instantaneous active and reactive power, harmonic currents, synchronous reference frame theory.**

Вступ. *Для поліпшення якості електроенергії у системі електропостачання загальне гармонічне спотворення (ЗГС) є найважливішим параметром кількісної оцінки гармонік, викликаних нелінійними навантаженнями. На практиці вона має бути меншою за 5 %. Новизна запропонованої роботи полягає у використанні каскадного п'ятирівневого активного фільтра, коли перетворювач складається з шести пар Н-мостів, кожна з яких включає чотири транзистора.* ***Мета***. *Щоб підвищити ефективність цього фільтра, пропонуються два методи кількісного визначення гармонійних струмів: по-перше, PQ-теорія, яка проста, але може використовуватися лише у разі збалансованої сітки, і, по-друге, теорія синхронної системи відліку (теорія SFR). , який здатний створювати гармонійний струм не тільки в несиметричній сітці, а й у несиметричному та спотвореному пучку.* ***Методи***. *Використовуючи методи управління, гармонійний струм витягується зі струму навантаження і розглядається як опорний. Побудований струм повинен слідувати за цим посиланням.* ***Результати***. *Оцінка активної та реактивної потужностей заснована на вимірюванні струмів, що проходять через навантаження, та мережевих напруг, за цими потужностями визначається форма гармонійного (опорного) струму. При використанні ПІ-регулятора вихідний струм п'ятирівневого інвертора точно відповідає опорному струму. Вихідний струм інвертора подається до мережі для усунення гармонійних струмів.* ***Практична цінність***. *Насправді коефіцієнт гармонійних спотворень ЗГС є найбільш широко використовуваним критерієм для критики форми хвилі струмів та оцінки якості задіяної енергії. Для струмів на стороні джерела ЗГС вважається прийнятним, якщо він менше 5 %, за нашою пропозицією ЗГС становить 0,85 % з PQ-теорією і 2,34 % з SFR-теорією, тому він є оптимальним.* Бібл. 11, рис. 23.

Ключові слова: **багаторівневий фільтр активної потужності, повні гармонічні спотворення, миттєва активна та реактивна потужності, гармонічні струми, синхронна теорія системи відліку.**

Introduction. The use of power electronics equipment like large and small household appliances, computer and telecommunications equipment, lighting equipment, medical devices, monitoring and control instruments, presents a real problem because they degrade the quality of electrical energy, besides the environmental pollution due to the difficulty of recycling their electronic waste.

This equipment affects the delivered power quality by modifying the reactive power with the generated harmonic currents, which disturb the rest of the receivers connected to the same electrical network. This can take many forms, starting with significant line losses, saturation in distribution transformers, and may even interfere with communication systems.

Many techniques are available to reduce harmonics with many disadvantages such as electromagnetic interference, risk of resonance, fixed compensation and bulkiness [1, 2].

The active power filter improves the shape of the current, adjusts the reactive power as a result of the suppression of the different harmonic levels caused by the nonlinear loads and prevents their propagation toward the network [3, 4].

In the structure of active filters, multilevel converters present significant advantages over traditional two-level converters, namely [5, 6]:

- smaller output voltage step;
- lower harmonic components;
- better electromagnetic compatibility;
- lower switching losses.

In this context, the present work consists in improving the power quality, by reducing the total harmonic distortion, using a three phase cascaded active filter. Each phase contains two H-bridges of 4 power transistors. Hereafter the functioning of this system is outlined.

Design of shunt active power line conditioner (APLC) system. The APLC is controlled in order to draw (supply) a current i_F from (to) the utility, in order to cancel the current harmonics on the network side. In this way, the APLC given by (Fig. 1) is used to eliminate the current harmonics and compensate the reactive power [7].

The nonlinear load current i_L is represented as:

$$i_L(t) = \sum_{n=1}^{\infty} I_n \sin(n\omega t + \phi_n)\,; \tag{1}$$

$$i_L(t)=I_1\sin(\omega t+\phi_1)+\sum_{n=2}^{\infty} I_n\sin(n\omega t+\phi_n)\,. \tag{2}$$

For harmonic compensation, the active filter must provide the compensation current:

$$i_F(t)=i_L(t)-i_S(t)\,. \tag{3}$$

At that time, the source current i_S will be in phase with the utility voltage and become sinusoidal.

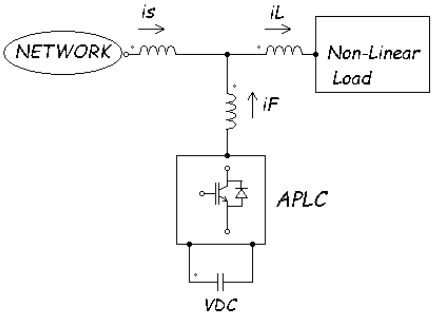

Fig. 1. Block diagram of basic APLC

Active filter structure. The cascaded five-level inverter. In this work, the APLC is a three-phase cascaded multilevel active power inverter. This filter is composed by three pairs of H-bridges; each one consists of 4 power transistors [7]. The design of the filter is shown in Fig. 2.

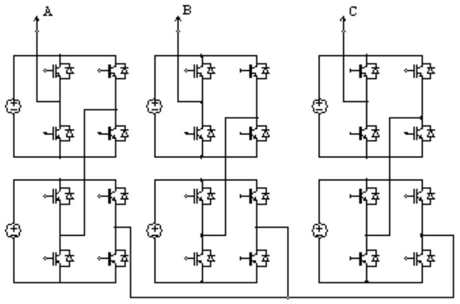

Fig. 2. Cascaded multilevel inverter design

Harmonic powers identification. The identification method chosen in first is called *the method of the real and imaginary instantaneous powers* [8, 9]. It offers the advantage of choosing the disturbance to be compensated with precision, speed and simplicity. The essential feature of this procedure is the reduction of the size of the system to be solved. Indeed, instead of having a system of 6 equations, one will have only to solve a system of four equations. Current and voltage are calculated according to Concordia transformation and given as [10]:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}=\sqrt{\frac{2}{3}}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}; \tag{4}$$

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix}=\sqrt{\frac{2}{3}}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}. \tag{5}$$

The expressions of the instantaneous real and imaginary load powers are given as follow:

$$\begin{bmatrix} p \\ q \end{bmatrix}=\begin{bmatrix} i_\alpha & i_\beta \\ -i_\alpha & i_\beta \end{bmatrix}.\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix}, \tag{6}$$

where p and q contain respectively the harmonic (oscillatory) and continuous terms which can be written as:

$$p=p_c+p_h; \quad q=q_c+q_h. \tag{7}$$

This method is described in detail in the diagram on Fig. 3, 4.

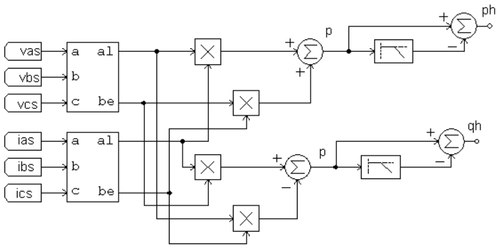

Fig. 3. Building block of calculation of harmonics powers reference

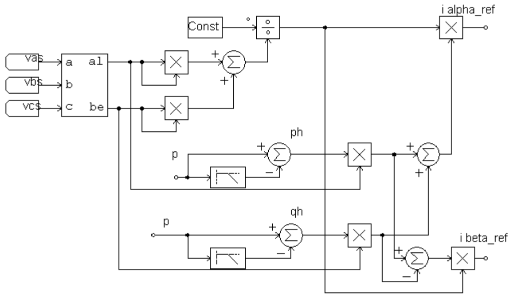

Fig. 4. Building block of the three reference currents calculation

Hereafter, the continuous power component is eliminated in order to preserve only the alternative one, which is related to the required harmonic content. This is feasible by a simple use of a second order low pass filter [4]. This is illustrated by the diagram in Fig. 5.

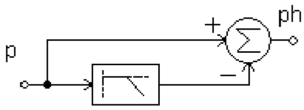

Fig. 5. Harmonic power separation

$$\begin{bmatrix} i_{\alpha ref} \\ i_{\beta ref} \end{bmatrix}=\frac{1}{\left|v_\alpha^2+v_\beta^2\right|}\begin{bmatrix} v_\alpha & v_\beta \\ v_\alpha & -v_\beta \end{bmatrix}.\begin{bmatrix} p_h \\ q_h \end{bmatrix}. \tag{8}$$

By a simple use of the reverse Concordia transformation [8] defined by (9), one arrives at the reference current i_{ref}, presented in Fig. 6.

$$\begin{bmatrix} i_{aref} \\ i_{bref} \\ i_{cref} \end{bmatrix}=\sqrt{2/3}\cdot\begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix}\cdot\begin{bmatrix} i_{\alpha ref} \\ i_{\beta ref} \end{bmatrix}. \tag{9}$$

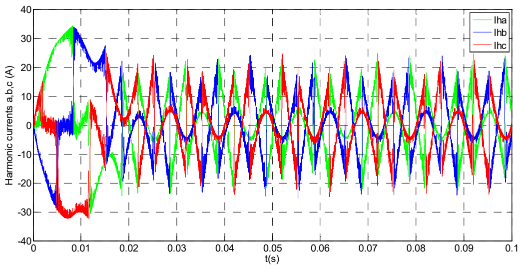

Fig. 6. Harmonic currents i_{ha}, i_{hb}, i_{hc} (reference currents)

Simulation results using theoretical active and reactive powers. The regulation current is realized by using a PI classic regulator as presented in Fig. 7.

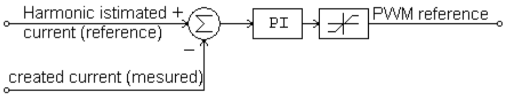

Fig 7.The current regulation scheme

The reference current follows very well the measured harmonic current (Fig. 8).

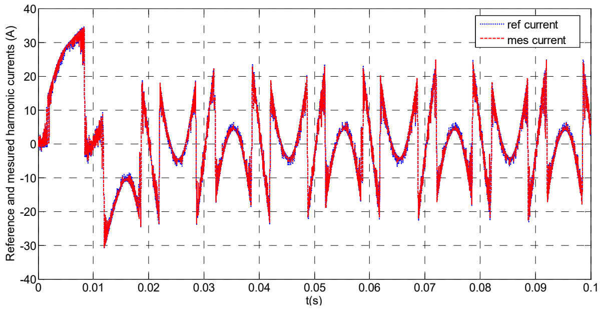

Fig. 8. Reference and measured harmonic currents

Pulse-width modulation (PWM) pulses generation. PWM technique solves the control problem of the commutation frequency while functioning with a fixed frequency, easy to filter downstream from the inverters. The general diagram of the PWM technique is given in Fig. 9.

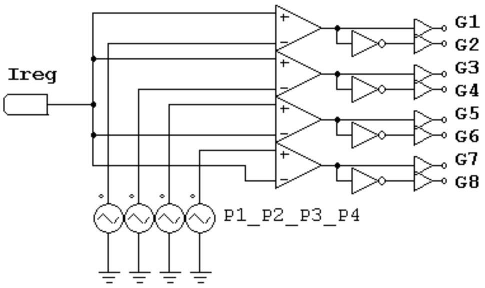

Fig. 9. PWM structure

These triangular signals obtained by the PWM are presented on Fig. 10.

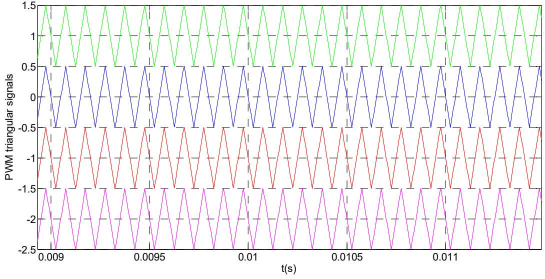

Fig. 10. Super imposed PWM triangular signals (zoom)

Simulation result without filter. In the simulation the model presented in Fig. 11, contain two parts.

Network. It consists of 3 AC voltages having an effective value of 400 V line to line, and a line impedance with L_s = 3mH, R_s = 0.5 Ω, the source frequency is 50 Hz.

Polluting load. It is a 6 diodes bridge, feeding a series *RL* load, where *L* = 0.1 H and *R* = 20 Ω.

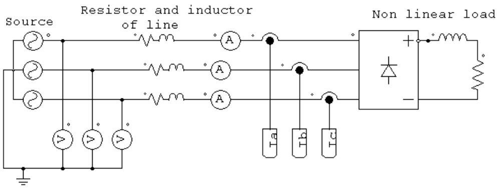

Fig. 11. Simulation model of network and polluting load without filters

The currents polluted by the non-linear load and their spectrum represented respectively in Fig. 12, 13.

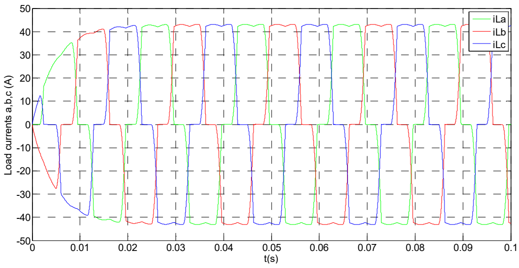

Fig. 12. Polluted load currents without filtering

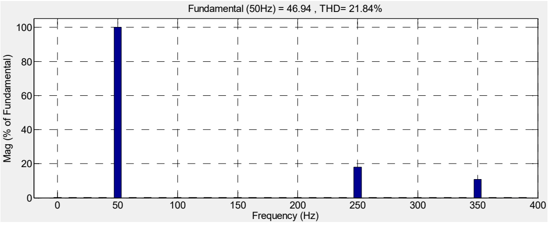

Fig. 13. Spectrum of polluted current i_{sa} without filtering

The cascaded five-level active filter includes 3 pairs of H-bridge, everyone characterized by a compensation DC source of 450 V. This filter is interfaced with the network by an inductive passive filter having L_f = 3 mH, in order to protect the network. Before using this filter the load currents are heavily polluted they have almost the form of a square signal, these are indicated in Fig. 14.

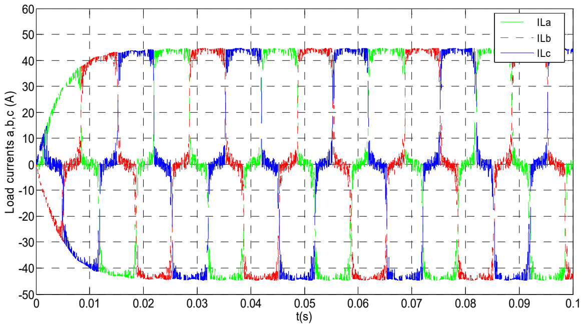

Fig. 14. Load currents

Figure 15 present the filtered source current by a five-level active parallel filter, followed by its harmonic spectrum and the corresponding total harmonic distortion (THD) in Fig. 16.

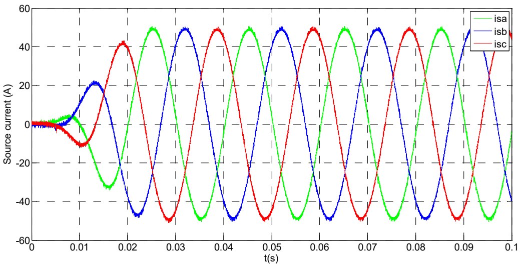

Fig. 15. Filtered source currents

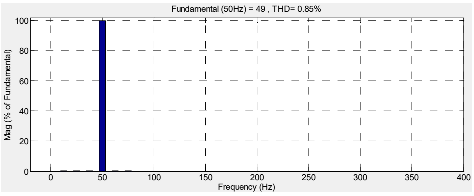

Fig. 16. Spectrum of filtered current i_{sa}

We clearly observe a significant reduction of the secondary spectral peaks, indicating the efficiency of our approach. Indeed, according to the harmonic spectrum and its calculated THD, there is an improvement of the filtering quality. The total harmonic distortion of the current fell from 21.84 % to 0.85 %.

The results obtained demonstrate the efficiency of the theoretical PQ technique for a balanced network, but when the network is unbalanced, the technique cannot sustain these performances. The proof is the unbalanced shape of the currents even after filtering as shown in Fig. 17.

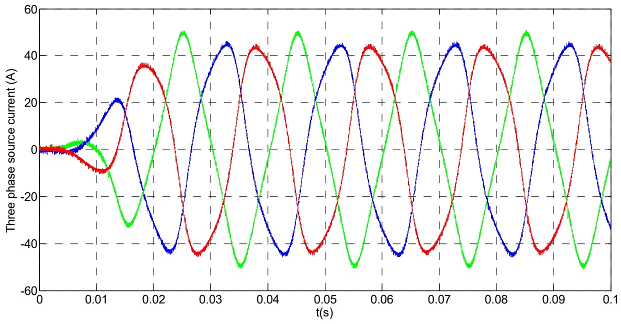

Fig. 17. Three phase current for unbalanced grid using PQ powers theory

An imbalance consists of a 25 % decrease in the voltage of one phase compared to the others.

Synchronous reference frame (SRF) theory. The block diagram of the SRF strategy is given in Fig. 18.

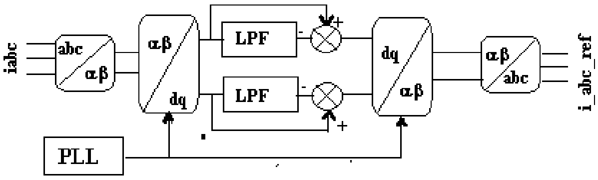

Fig. 18. Block diagram of SRF structure

We use (4) to transform the measured 3 phase current into 2 phase *α*-*β* stationary frame, and then the transformation from 2 phase *α*-*β* stationary frame to 2 phase *d*-*q* rotating frame is given by:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \sin\theta & -\cos\theta \\ \cos\theta & \sin\theta \end{bmatrix} \cdot \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}, \qquad (10)$$

where i_d and i_q are given by:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \bar{i}_d & \tilde{i}_d \\ \bar{i}_q & \tilde{i}_q \end{bmatrix}. \qquad (11)$$

The out of low-pass filter gives continuous current component. The inverse transformation the transformation from 2 phase *d*-*q* rotating frame to 2 phases *α*-*β*-0 stationary frame is given by:

$$\begin{bmatrix} i_{\alpha ref} \\ i_{\beta ref} \end{bmatrix} = \begin{bmatrix} \sin\theta & -\cos\theta \\ \cos\theta & \sin\theta \end{bmatrix}^{-1} \cdot \begin{bmatrix} i_d \\ i_q \end{bmatrix}. \qquad (12)$$

The 3-phase compensation currents can be calculated using the same Eq. (9). Finally, the synchronization angle of reference frame is determined using dual second order generalized integrator phase locked loop with prefilter DSOGI-PLL-WPF technique described in [11] (Fig. 19).

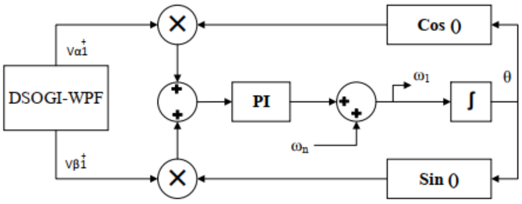

Fig. 19. Synchronization angle determination [11]

Simulation results using SRF theory. In this simulation the grid is unbalanced and also affected by a third rang harmonic applied in the first voltage curve (Fig. 20).

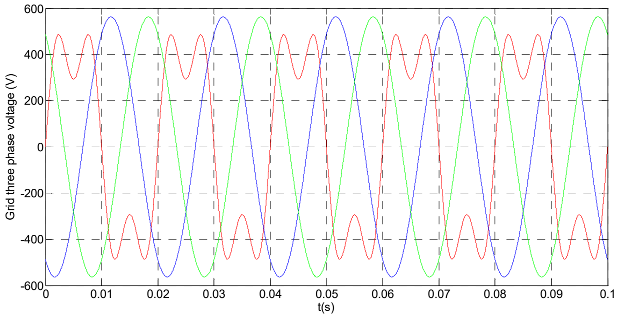

Fig. 20 Three phase voltage for unbalanced and distorted grid

The reference current follows very well the measured harmonic current (Fig. 21).

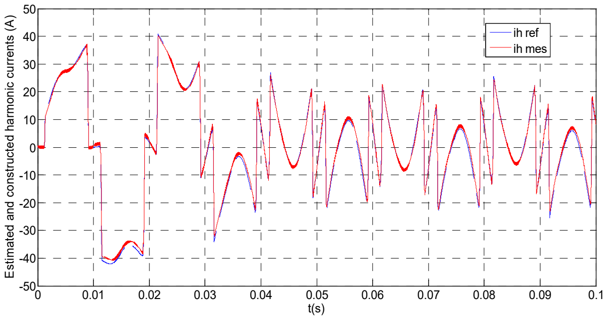

Fig. 21. Reference and measured harmonic currents for SRF

The 3 currents filtered using the SRF and their spectrum are respectively represented in Fig. 22, 23.

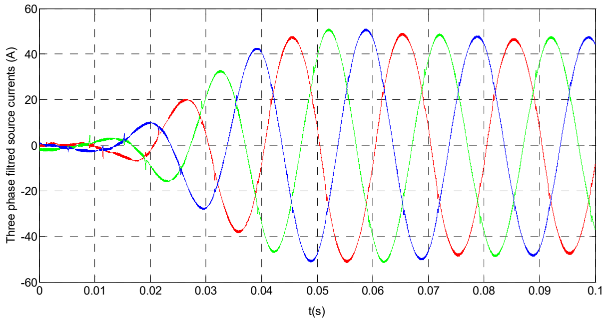

Fig. 22. Three phase filtered source current for unbalanced and distorted grid using SRF

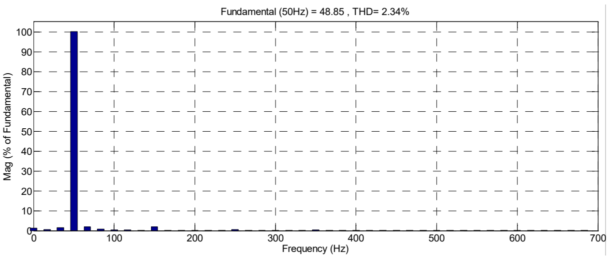

Fig. 23. Spectrum of filtered current i_{sa} of SRF for unbalanced and distorted grid

The unbalanced and distorted grid is considered a critical situation and with a nonlinear load makes the grid very polluted and disturbed. Although the THD is larger comparing with that of the theoretical PQ technique, but under these network conditions it is very acceptable especially that it is still within the allowable range.

Conclusions. In this paper, the elements constituting the structure of a cascaded five-level active filter are presented. At first we presented the structure of the five-level inverter which is the basic element of our study, as well as the PWM technique with superimposed carriers, which offers a precise and fast control of the output quantities of the converter.

To identify harmonic currents, the active and reactive power method is firstly used for balanced grid condition. For unbalanced network PQ theoretical technique is not effective, so we replace it with synchronous reference frame strategy which needs an exact synchronization angle determination. This technique is asily achievable and requires only simple current and voltage sensors.

Compared with the load current THD which is 21.84 %, using the five-level structure, the source current remains slightly infected with noise due to the nonlinear load, the source current THD drops to a value of 2.34 %.

Conflict of interest. The authors declare that they have no conflicts of interest.

REFERENCES

1. Sanjan P.S., Gowtham N., Bhaskar M.S., Subramaniam U., Almakhles D.J., Padmanaban S., Yamini N.G. Enhancement of Power Quality in Domestic Loads Using Harmonic Filters. *IEEE Access*, 2020, vol. 8, pp. 197730-197744. doi: https://doi.org/10.1109/ACCESS.2020.3034734.

2. Das S.R., Ray P.K., Sahoo A.K., Ramasubbareddy S., Babu T.S., Kumar N.M., Elavarasan R.M., Mihet-Popa L. A Comprehensive Survey on Different Control Strategies and Applications of Active Power Filters for Power Quality Improvement. *Energies*, 2021, vol. 14, no. 15, art. no. 4589. doi: https://doi.org/10.3390/en14154589.

3. Fujita H., Akagi H. A practical approach to harmonic compensation in power systems-series connection of passive and active filters. *IEEE Transactions on Industry Applications*, 1991, vol. 27, no. 6, pp. 1020-1025. doi: https://doi.org/10.1109/28.108451.

4. Karuppanan P., Mahapatra K. A novel SRF based cascaded multilevel active filter for power line conditioners. *2010 Annual IEEE India Conference (INDICON)*, 2010, pp. 1-4. doi: https://doi.org/10.1109/INDCON.2010.5712667.

5. Colak I., Kabalci E., Bayindir R. Review of multilevel voltage source inverter topologies and control schemes. *Energy Conversion and Management*, 2011, vol. 52, no. 2, pp. 1114-1128. doi: https://doi.org/10.1016/j.enconman.2010.09.006.

6. Barkati S., Baghli L., Berkouk E.M., Boucherit M.-S. Harmonic elimination in diode-clamped multilevel inverter using evolutionary algorithms. *Electric Power Systems Research*, 2008, vol. 78, no. 10, pp. 1736-1746. doi: https://doi.org/10.1016/j.epsr.2008.03.010.

7. Yin X., Yi H., Yang Z., Zhuo F. Global Configuration Strategy of SAPFs Combined with Comprehensive Evaluation of Power Quality in Distribution Network. *2022 International Conference on Power Energy Systems and Applications (ICoPESA)*, 2022, pp. 430-436. doi: https://doi.org/10.1109/ICoPESA54515.2022.9754415.

8. Seung-Gi Jeong, Myung-Ho Woo. DSP-based active power filter with predictive current control. *IEEE Transactions on Industrial Electronics*, 1997, vol. 44, no. 3, pp. 329-336. doi: https://doi.org/10.1109/41.585830.

9. Buso S., Malesani L., Mattavelli P. Comparison of current control techniques for active filter applications. *IEEE Transactions on Industrial Electronics*, 1998, vol. 45, no. 5, pp. 722-729. doi: https://doi.org/10.1109/41.720328.

10. Afonso J., Couto C., Martins J. Active Filters with Control Based on the p-q Theory. *IEEE Industrial Electronics Society Newsletter*, 2000, vol. 47, no. 3, pp. 5-10. Available at: https://hdl.handle.net/1822/1921 (Accessed 26 April 2022).

11. Kalkoul S., Benalla H., Nabti K., Abdellatif R. An adaptive harmonic compensation strategy for three-phase shunt active power filter based on double second-order generalized integrator with prefilter. *Electrical Engineering & Electromechanics*, 2020, no. 3, pp. 58-64. doi: https://doi.org/10.20998/2074-272X.2020.3.09.

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