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Suppression factor as evaluation criterion for wide-frequency filtering equipment

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Abstract: Here, a novel harmonic suppression performance criterion, namely suppression factor (SF), is suggested for the wide-frequency power filtering equipment. Performances of single-tuned passive filter, combination of passive filters tuned to various frequencies, shunt active power filter (APF), and a shunt hybrid active power filter (HAPF) topologies have been evaluated considering their SF values over a defined frequency range. Moreover, effect of the control method for the active filtering equipment on SF values is also analysed by comparing both theoretical and the experimental results. The frequency range of harmonics to be suppressed is chosen using the field measurements of Induction melting furnace (IMF) load, one of the most problematic loads in terms of interharmonics, and a field implemented HAPF system is used for the experimental verifications.

1 Introduction

Various power filtering equipment, active and/or passive, have so far been used in power system for the suppression of harmonics and interharmonics caused by industrial loads. When the frequency range of the harmonics to be suppressed is narrow, filtering equipment can be optimised for maximum suppression performance. However in the case of wider frequency ranges, there should be a completely different definition for the performance evaluation of filtering equipment because the response of those filters may change as the frequency changes. There have been some filtering performance evaluations in [1–5] but neither of them gives enough information about the effective usage of filtering equipment over a wide-frequency range.

Here, a novel evaluation method, suppression factor (SF), for determining the wide-frequency range performance of filtering equipment is proposed. The proposed method is simulated for the response of various passive filter topologies and also for the active filtering equipment. Change in the filtering performance of the active filtering equipment which are controlled by voltage and current mode control techniques are also compared both theoretically and experimentally by using a field implemented hybrid active power filter (HAPF) system. The reference wide-frequency range is chosen using the field measurements of medium-frequency induction melting furnace (IMF) load.

2 Problem definition

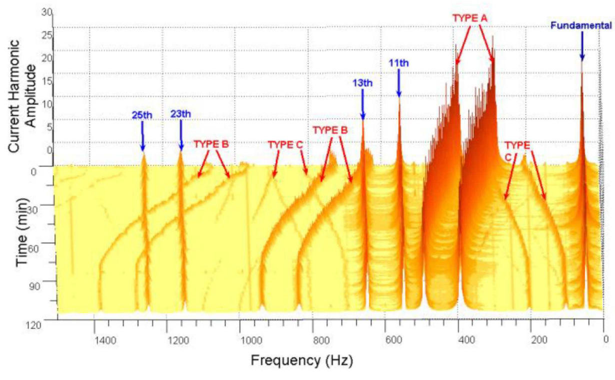

Fig. 1 *Harmonic spectrum of sample IMF load (field measurement) [6]*

IMF load of metal industry is one of the most problematic loads in power system in terms of harmonics and interharmonics [6–9]. The frequencies of harmonic components change both in frequency and magnitude during the metal melting process as given in Fig. 1 [6]. As can be understood from Fig. 1, the most dominant harmonics and interharmonics are located in a frequency range of 250 to 550 Hz for this particular IMF and they appear randomly by the type of metal melted in the ladle. The details of the types of harmonic frequencies illustrated in Fig. 1 can be found in [6, 7].

The harmonics and interharmonics of the IMF load under investigation has been filtered out in the field using two different control methods namely proportional control [7] and hysteresis current control [8]. In the following sections, definition of SF is mentioned in detail. Moreover, the suppression performance of various passive filter topologies, active power filter (APF), and HAPF together with voltage [7] and current control [8] methods are analysed in terms of SF criterion in the following sections.

3 Suppression factor as an evaluation criterion

Performance of the filtering equipment for the suppression of interharmonics and harmonics whose frequencies are varying in the range from 250 to 550-Hz can be quantified by using the suppression factor concept. By this way, effective percentage of filter current causing a decrease in source current harmonics can be determined for any harmonic or interharmonic frequency. Since the vector sum of load and filter current leads to source-side current, the magnitudes and phases of each current component have a great importance. For example, in order to decrease the load harmonic magnitude by the same amount of injected filter current magnitude at the source side, the filter current phase should be 180 degrees apart from (anti-phase) load current for that particular harmonic frequency. If there would be a phase difference other than 180 degrees for a frequency component, then the filtering equipment became inefficient and the mitigated load harmonic magnitude will be less than the magnitude of the injected filter current. Considering the above concerns, percentage value of SF corresponding to each harmonic or interharmonic frequency can be determined from (1).

$$\%\mathrm{SF}_h = \frac{|I_{h,\,\mathrm{load}}| - |I_{h,\,\mathrm{source}}|}{|I_{h,\,\mathrm{filter}}|} \times 100 \qquad (1)$$

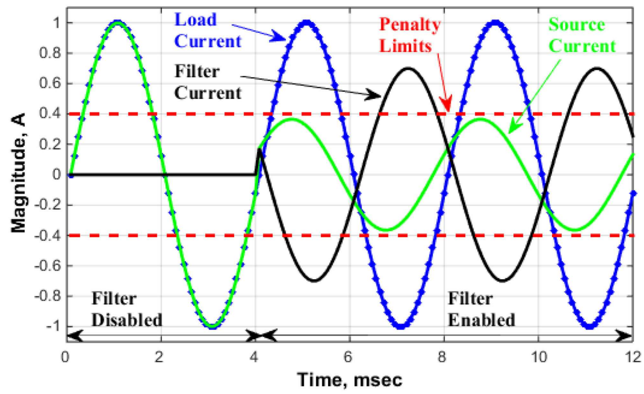

Fig. 2 *Illustration of practical filtering for a power filtering equipment*

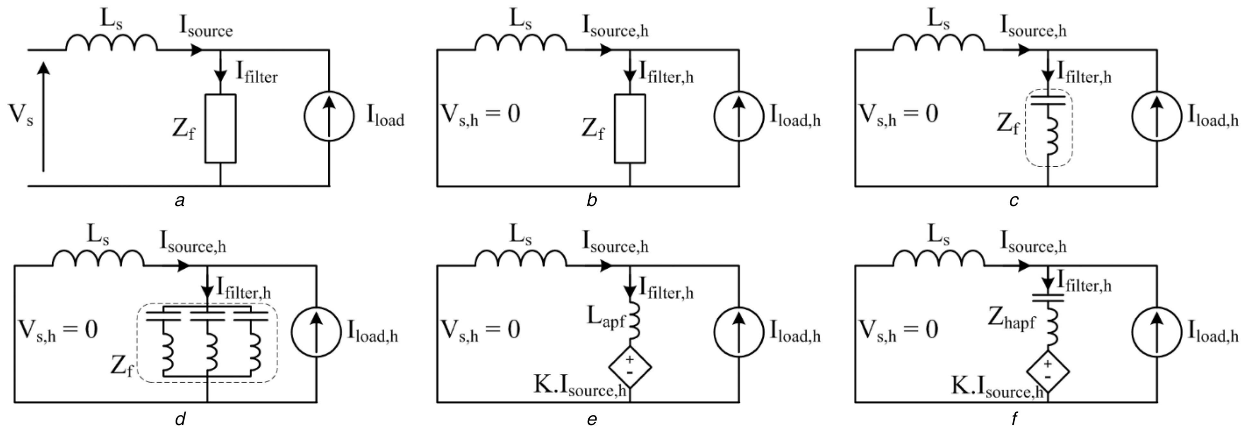

Fig. 3 *Equivalent circuit representations*
(a) Generalised equivalent circuit, ***(b)*** generalised harmonic equivalent circuit for, ***(c)*** single-tuned shunt passive filter, ***(d)*** combination of single-tuned shunt passive filters, ***(e)*** APF with proportional control, ***(f)*** HAPF with proportional control

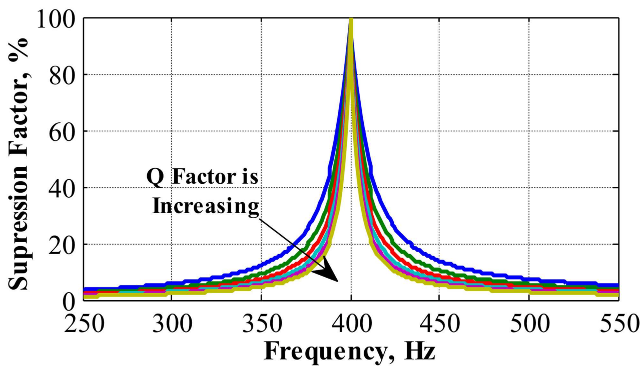

Fig. 4 *Theoretical %SF of single-tuned shunt passive filter*

Percentage SF of 100% stands for the perfect suppression of interharmonic or harmonic current component under evaluation. This does not mean that those interharmonics or harmonics are fully vanished by the filter. This only tells us that the filter injects the required interharmonic or harmonic current component nearly in correct phase (in anti-phase) with the associated load current component. In other words, injection of a certain amount of current by filter will lead to exactly the same amount of current reduction in source side for corresponding harmonic frequency. Fig. 2 shows the illustration of a practical filtering for a sample harmonic component. As can be observed from Fig. 2, the magnitudes of load, filter and source current waveforms are 1.0, 0.7, and 0.38 units, respectively. This means that only 0.62 units of load current can be suppressed by 0.7 units of filter current, which yields 88.6% suppression factor.

3.1 Evaluation of power filtering equipment

Theoretical evaluation of suppression performances in terms of SF for different active and passive filtering topologies, given in Fig. 3, is analysed using MATLAB environment and the details are given in this section.

3.2 Passive filters

Fig. 4 shows the SF of a single-tuned shunt passive filter, harmonic equivalent circuit of which is given in Fig. 3*c*, for increasing Q factors. The tuning frequency of the passive filter is chosen considering the midway (400 Hz) through the frequency range under investigation in order to show the filtering effect on as much frequency as possible. As can be understood from the figure that single-tuned passive filter is not enough for wide-frequency filtering applications but very useful for specific frequencies around tuning frequency. As harmonic frequency to be suppressed goes apart from tuning frequency, the series connection of inductor and capacitor causes phase difference due to their impedance characteristics, which causes inefficient filtering performance. This phenomenon can be observed with SF curves in Fig. 4. Although decreasing Q factor contribute to better suppression for frequencies around tuning frequency, it is not practical to decrease Q factor to cover larger frequency band due to physical and practical limitations. However, one can provide better suppression for other frequencies by using a combination of single-tuned shunt passive filters as shown in Fig. 3*d*. By this way, high SF values can be obtained for some other frequencies too, illustration of which is given in Fig. 5. Although combination of single-tuned filters covers more frequencies, it is still far from a perfect suppression performance due to the interaction of parallel branches when their tuning frequencies are close to each other.

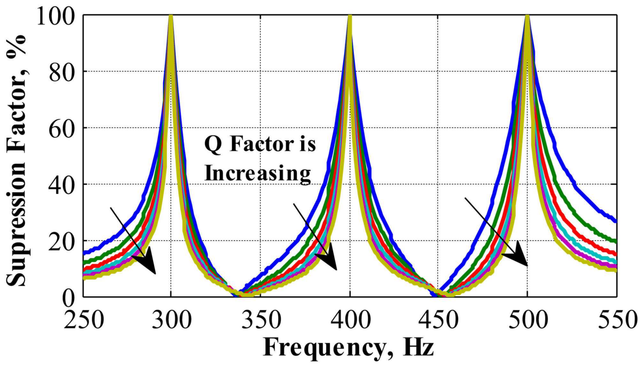

Fig. 5 *Theoretical %SF of the combination of single-tuned shunt passive filters*

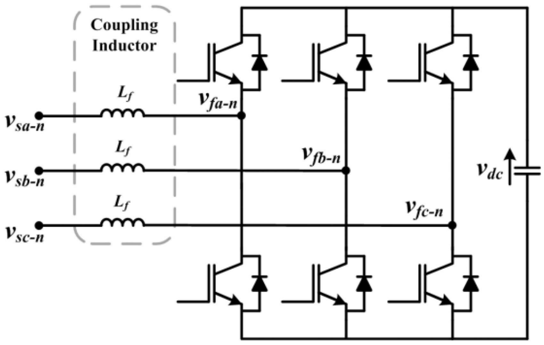

Fig. 6 *Circuit topology of active power filter*

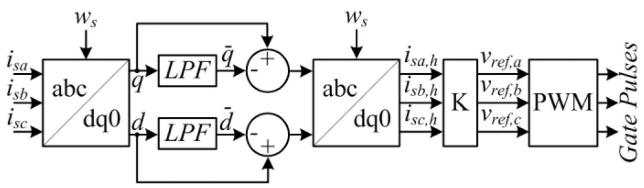

Fig. 7 *Simplified block diagram representation of proportional control method*

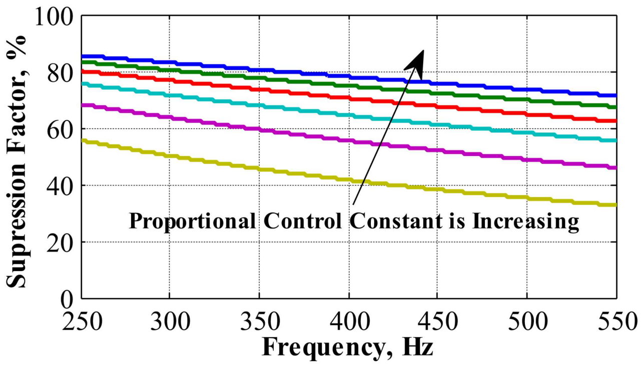

Fig. 8 *Theoretical %SF of APF controlled by proportional control method*

3.3 Active filters

Active filtering techniques, on the other hand, have a great potential to effectively suppress all the harmonic and interharmonic frequencies spread over a wide range. An APF topology composed of a voltage sourced converter coupled with an inductor, as given in harmonic equivalent circuit Fig. 3*e* and circuit topology in Fig. 6, is evaluated with proportional control method suggested in various papers [7, 10–13]. The block diagram showing the simplified form of proportional control method can be seen in Fig. 7, where *K* stands for the proportional control constant. The corresponding SF curves for various proportional control constants are as shown in Fig. 8. The SF values show that shunt APF is a much better solution for the suppression of the loads containing harmonics spread over a wide range. Please note that the increase in proportionality constant of control system improves the suppression performance at the expense of reduction in stability [7]. For this reason, proportional control constant cannot be increased too much.

Shunt HAPF topology has been used for the mitigation of harmful harmonics by various researchers [14–17]. Due to series LC filter coupling of HAPF, it has some advantages over traditional shunt APF converters [8]. In order to enhance the filtering performance, the IMF load can be mitigated via HAPF topology controlled by proportional control method given in harmonic equivalent circuit Fig. 3*f* and circuit topology Fig. 9. The corresponding SF curves for increasing proportional control constants are given in Fig. 10. As can be seen from the figure, the HAPF topology yields a perfect suppression around the tuning frequency of input filter and it reduces towards 250 and 550 Hz. Increase in proportional control constant provides better SF curves but it is again at the expanse of decreased stability of converter.

Some researchers have tried to increase the filtering performance of HAPF systems by adding a combination of input filters tuned to different frequencies [10] as given in Fig. 11. By this way, the filtering performance can be dramatically increased for most of the frequencies except some narrow band located between tuning frequencies of parallel branches, SF evaluation of which is given in Fig. 12.

When voltage control methods are used for active filtering of current harmonics, the suppression performance cannot be high over the whole frequency unless some advanced control techniques are used. Adaptive proportional resonant controllers, adding feedforward loops for each harmonic or interharmonic frequency etc. may help the correction of reference signal-phase resulting in better suppression performance, at the expanse of computational burden. Another solution to improve harmonic suppression performance is to use voltage source converter in current control mode. The easiest way of applying current control for a voltage-sourced converter is hysteresis band current control [18–20]. By this way, the voltage-sourced converter can act as a controlled current source as illustrated by harmonic equivalent circuit in Fig. 13. The simplified block diagram of hysteresis band control method is as given in Fig. 14. In order to obtain the current references, fundamental component is subtracted from the load current by using synchronous reference frame method and a low pass filter. Then the resultant signal is multiplied by a constant G in order not to fully filter out the harmonics instead they are mitigated below allowed limits. Once the current reference signals are obtained, they are compared with HAPF line currents and corresponding gate pulses are generated according to hysteresis current modulation philosophy given below.

$$\text{If } i_{fx(s)} > i^*_{fx(s)} + \Delta I \quad \text{then } S_X = 1$$

$$\text{If } i_{fx(s)} < i^*_{fx(s)} - \Delta I \quad \text{then } S_X = 0$$

$$\text{If } i^*_{fx(s)} - \Delta I < i_{fx(s)} < i^*_{fx(s)} + \Delta I \quad \text{then the previous switching pattern sustained}$$

where ΔI is the hysteresis band, $i^*_{fx(s)}$ the HAPF reference current for phase *x* corresponding to sampling instant *s*, $i_{fx(s)}$ the HAPF current for phase *x* corresponding to sampling instant *s*, S_X stands for the switching pattern of the phase *x*. $S_X = 1$ means the IGBT in the upper leg of the converter in Fig. 9 for the phase *x* is turned on, while $S_X = 0$ means the IGBT in the lower leg is turned on.

Since the current reference contains harmonic components having exactly the same phase with load current harmonics, the suppression factor should be almost 100% over the whole frequency spectrum for the hysteresis band controlled APF and HAPF converters. This hypothesis is correct only if the DC link voltage is high enough to generate necessary voltage waveform at the terminals of HAPF converter [8].

Theoretical SF values can be calculated individually for each frequency; however, the performance of filtering devices may vary during operation in practice. Thus, percentage SF as a performance evaluation criterion should indicate the filtering performance during the whole inspection period.

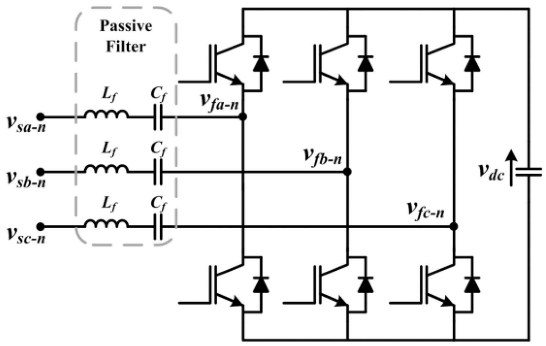

Fig. 9 *Circuit topology of hybrid active power filter*

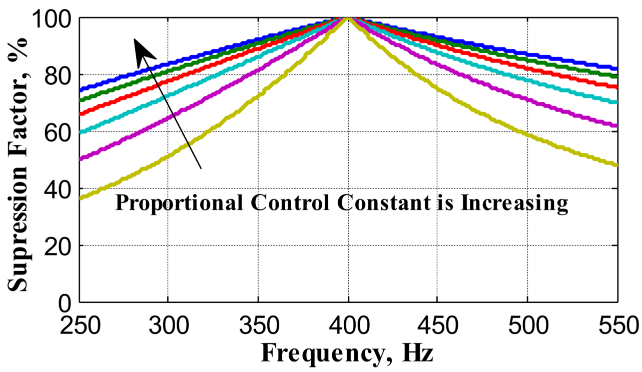

Fig. 10 *Theoretical %SF of HAPF controlled by proportional control method*

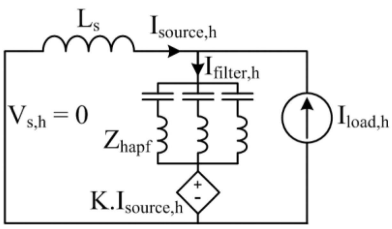

Fig. 11 *Harmonic equivalent circuit of the HAPF topology coupled by the combination of passive filters*

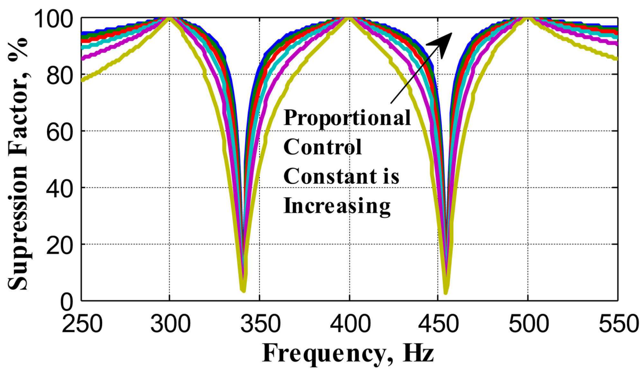

Fig. 12 *Theoretical %SF of HAPF controlled by proportional control method coupled by the combination of passive filters*

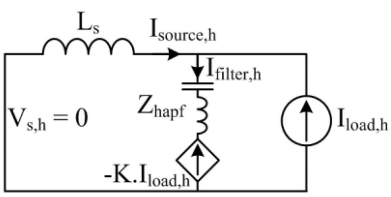

Fig. 13 *Harmonic equivalent circuit of the HAPF converter topology with current control mode*

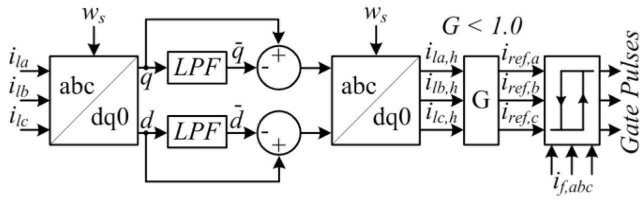

Fig. 14 *Simplified block diagram representation of hysteresis band control method*

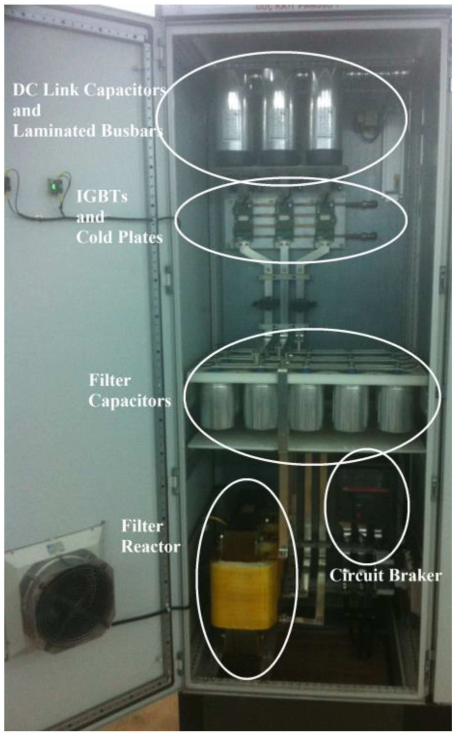

Fig. 15 *Implemented HAPF system (one of the nine parallel units)*

Since the SF values are calculated by using the FFT analysis for a very small windows, 200 ms for 5 Hz frequency resolution, the SF values should be calculated for every 200 ms time intervals during inspection period and plotted in the same graph, as a cloud diagram, instead of using only one SF value for each frequency. By this way, the overall performance of the filtering device can be analysed during the entire measurement period.

4 Experimental verification

Harmonics and interharmonics of the IMF load introduced here have been successfully mitigated by a 2.5 MVA HAPF system using both proportional [7] and hysteresis band current [8] control techniques. The commissioned HAPF system has been properly working in the field since 2013. Field photograph for one of the nine identical HAPF converters is given in Fig. 15.

Figs. 16 and 17 show the suppression performances of the HAPF system controlled by proportional and hysteresis controllers, respectively. Please note that the SF values are calculated over the whole dominant frequency band and 11th and 13th characteristic harmonics. The cloud diagram structure of the SF gives an idea about the sustainability of the suppression.

SF cloud diagram, Fig. 16, of the HAPF system with proportional control shows that the harmonic and interharmonic suppression performances of voltage controlled HAPF system provides a perfect suppression around tuning frequency, and modest suppression towards 250 and 550 Hz, as expected.

Higher suppression performance for 11th and 13th characteristic harmonics than expected, on the other hand, is due to the contribution of integrated feedforward loop for those characteristics harmonics [7]. The HAPF system implemented in the field has also been modified to be used in hysteresis current

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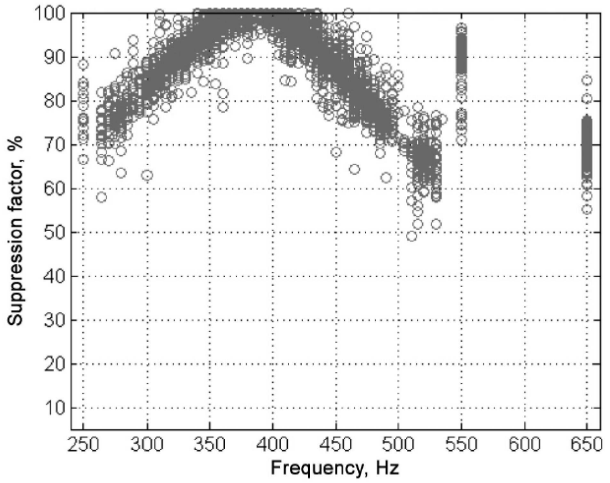

Fig. 16 *Percentage suppression factor of the HAPF system controlled by proportional control technique (field measurements)*

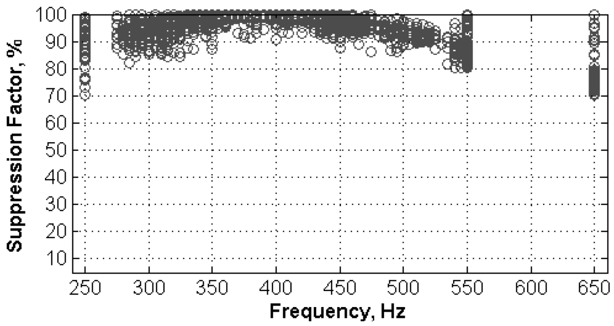

Fig. 17 *Percentage suppression factor of the HAPF system controlled by hysteresis band control technique (field measurements)*

control mode [8]. As can be seen from Fig. 17, the harmonic and interharmonic suppression performances of the current controlled HAPF system is very close to its theoretical expectations, 100% for the whole frequency spectrum. Although SF values slightly decrease towards 250 and 550 Hz, they lay above 80% for the entire frequency spectrum. Indeed, SF values for most of the frequencies are above 90%. SF values tend to reduce for higher frequencies, which can be improved by increasing the DC link voltage at the expanse of higher losses and extra voltage stress on semiconductors.

Importance of cloud diagram representation can be observed by looking at both of the figures Figs. 16 and 17. It can be seen that the SF value for a harmonic or interharmonic frequency may vary up to 10% during the operation, which may cause misguidance in terms of filtering equipment performance analysis.

5 Conclusion

Here, a criterion for the performance evaluation of wide-frequency filtering equipment is introduced. The proposed criterion, SF, is shown to be very informative for the comparison of different converter control methods via field implementation. Moreover, cloud diagram representation of proposed SF criterion makes it easier to understand the dynamical performances of the control systems in terms of harmonic suppression performance, since it contains information for every 200 ms during a long recording time.

It is also verified here that the active filtering techniques are far more effective to suppress harmonics and interharmonics spread over a wide range than various combinations of passive filter solutions. Although one can approximate the performance of active filtering equipment by simply observing its total harmonic distortion (THD) value or the percentage of each individual harmonic in terms of fundamental component, those information is not sufficient to assess the equipment's capacity usage and effectiveness. With the proposed SF criterion, comparison of the filtering equipment topologies as well as their control methods among each other can be made. In addition, their capacity usage and dynamic behaviour can be easily analysed.

6 References

[1] Duke, R.M., Round, S.D.: 'The steady-state performance of a controlled current active filter', *IEEE Trans. Power Electr.*, 1993, **8**, pp. 140–146

[2] Lai, J.-S., Key, T.S.: 'Effectiveness of harmonic mitigation equipment for commercial office buildings', *IEEE Trans. Ind. Appl.*, 1997, **33**, pp. 1104–1110

[3] Thomas, T., Haddad, K., Jous, G., *et al.*: 'Design and performance of active power filters', *IEEE Ind. App. Mag.*, 1998, **4**, pp. 38–46

[4] Chang, G.W.: 'A new approach for optimal shunt active power filter control considering alternative performance indices', *IEEE Trans. Power Deliv.*, 2006, **21**, pp. 406–413

[5] Bhattacharya, A., Chakraborty, C., Bhattacharya, S.: 'Parallel-connected shunt hybrid active power filters operating at different switching frequencies for improved performance', *IEEE Trans. Ind. Electr.*, 2012, **59**, pp. 4007–4019

[6] Yilmaz, I., Ermis, M., Cadirci, I.: 'Medium-frequency induction melting furnace as a load on the power system', *IEEE Trans. Ind. Appl.*, 2012, **48**, pp. 1203–1214

[7] Yilmaz, I., Durna, E., Ermis, M.: 'Design and implementation of a hybrid system for the mitigation of PQ problems of medium-frequency induction steel- melting furnaces', *IEEE Trans. Ind. Appl.*, 2016, **52**, pp. 2700–2713

[8] Durna, E., Yilmaz, I., Ermis, M.: 'Suppression of time varying interharmonics produced by medium-frequency induction melting furnaces by a HAPF system', *IEEE Trans. Power Electron.*, 2017, **32**, pp. 1030–1043

[9] Tan, A., Bayindir, K.C.: 'Modeling and analysis of power quality problems caused by coreless induction melting furnace connected to distribution network', *Electr. Eng.*, 2014, **96**, pp. 239–253

[10] Srianthumrong, S., Akagi, H.: 'A medium-voltage transformerless ac/dc power conversion system consisting of a diode rectifier and a shunt hybrid filter', *IEEE Trans. Ind. Appl.*, 2003, **39**, pp. 874–882

[11] Tangtheerajaroonwong, W., Hatada, T., Wada, K., *et al.*: 'Design and performance of a transformerless shunt hybrid filter integrated into a three-phase diode rectifier', *IEEE Trans. Power Electron.*, 2007, **22**, pp. 1882–1889

[12] Corasaniti, V.F., Barbieri, M.B., Arnera, P.L., *et al.*: 'Hybrid power filter to enhance power quality in a medium-voltage distribution network', *IEEE Trans. Ind. Electron.*, 2009, **56**, pp. 2885–2893

[13] Zobaa, A.F.: 'Optimal multiobjective design of hybrid active power filters considering a distorted environment', *IEEE Trans. Ind. Electron.*, 2014, **61**, pp. 107–114

[14] Tan, A., Bayındır, K.Ç., Cuma, M.U.: 'Multiple harmonic elimination-based feedback controller for shunt hybrid active power filter', *IET Power Electron.*, 2017, **10**, pp. 945–956

[15] Luo, Z., Su, M., Sun, Y., *et al.*: 'Analysis and control of a reduced switch hybrid active power filter', *IET Power Electron.*, 2016, **9**, pp. 1416–1425

[16] He, Z., Ma, F., Li, M., *et al.*: 'Multi-functional hybrid active power converter and its industrial application for electrolytic copper-foil', *IET Gener. Transm. Distrib.*, 2016, **10**, pp. 3985–3994

[17] Valdez-Fernandez, A., Escobar, G., Martinez- Rodriguez, P.R., *et al.*: 'Modelling and control of a hybrid power filter to compensate harmonic distortion under unbalanced operation', *IET Power Electron.*, 2017, **10**, pp. 782–791

[18] Corasaniti, V.F., Barbieri, M.B., Arnera, P.L., *et al.*: 'Hybrid power filter to enhance power quality in a medium-voltage distribution network', *IEEE Trans. Ind. Electron.*, 2009, **56**, pp. 2885–2893

[19] Lam, C.-S., Wong, M.-C., Han, Y.-D.: 'Hysteresis current control of hybrid active power filters', *IET Power Electron.*, 2012, **5**, pp. 1175–1187

[20] Wang, L., Lam, C.-S., Wong, M.-C., *et al.*: 'Non-linear adaptive hysteresis band pulse-width modulation control for hybrid active power filters to reduce switching loss', *IET Power Electron.*, 2015, **8**, pp. 2156–2167