Chiến lược kết nối giữa lọc tích cực và lọc thụ động để loại bỏ dòng điện bậc cao và cải thiện hệ số công suất trong hệ thống điện ba pha

A joint active filter and passive filter strategy for current harmonic cancellation and power factor enhancement in three-phase power networks

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Tóm tắt

Trong bài báo này chúng tôi trình bày một giải pháp mới trong việc xây dựng cấu trúc và phương pháp điều khiển cho bộ lọc sóng hài lai kiểu song song. Nó là sự kết hợp giữa bộ lọc tích cực và bộ lọc thụ động truyền thống, và được sử dụng cho việc loại bỏ dòng điện hài cũng như cải tiến hệ số công suất trong hệ thống điện ba pha. Thuật toán điều khiển hệ thống lọc được xây dựng trong miền tần số trên cơ sở của của phân tích Fourier. Thuận lợi của cách tiếp cận là cho phép bộ lọc có thể lựa chọn chính xác những bậc hài cần loại bỏ. Việc thiết kế và kiểm tra tính khả thi của bộ lọc trong những tình huống vận hành khác nhau của hệ thống được thực hiện trên phần mềm MATLAB/Simulink. Những kết quả đạt được cho thấy tỉ lệ dòng bù của bộ lọc của chúng tôi chỉ bằng 30% so với phương pháp chỉ dựa hoàn toàn trên lọc tích cực APF. Việc giảm đáng kể tỉ lệ dòng bù cũng đồng nghĩa với việc giảm chi phí rất lớn trong việc đầu tư so với những phương pháp cũ (chỉ có lọc tích cực được áp dụng).

Từ khóa: Bộ lọc sóng hài song song kiểu lai, lọc sóng hài tích cực, lọc sóng hài thụ động, lọc sóng hài chọn lọc, triệt tiêu sóng hài trong hệ thống 3 pha.

Abstract: This paper presents the construction and a new control method of a hybrid parallel harmonics filter (HPHF) which is used for harmonics cancellation and reactive power compensation in three-phase electrical systems. The HPHF hardware is comprised of two primary components: harmonics tuned passive filters and active power electronics filter. HPHF control algorithm makes use of Fourier analysis to facilitate accurate selective harmonics targeting allowing cooperation between passive and active components. MATLAB/Simulink is used to theoretically design and confirm HPHF operation as well as its core functionality. The obtained results show that the active component current rating in the HPHF system is only 30% of the pure active power filter rating with the same harmonics filtering performance. This reduction in rating implies a great economic advantage of the proposed HPHF compared to the traditional APF.

Keywords: Hybrid parallel harmonics filter, active power filter, passive filter, selective harmonics filtering, three-phase harmonics cancellation.

Nomenclature

Notation	Unit	Expression
Z	Ω	electrical impedance
f_{har}	Hz	tuning frequency
ω_{har}	Rad/s	tuning angular frequency
h		harmonic order
L_s	H	line parasitic inductance
L_f	H	output filter inductance
C_f	μF	output filter capacitance
Q_{filter}	VAr	electrical reactive power of passive component
X_1		result of Discrete Fourier transform
x_{k1}		result of Inverse Discrete Fourier Transform
*		reference value

Acronym

HPHF	hybrid parallel harmonics filter
PHF	passive harmonics filter
PPF	passive power filter
APF	active power filter
IGBT	insulated-gate bipolar transistor
DFT	discrete Fourier transform
PWM	pulse width modulation

1. Introduction

In recent years, in order to response to the rapid development of infrastructure, the industrial facilities are constantly being built and expanded. This leads to the increase of nonlinear loads that result in the deterioration of power quality. Electrical devices with strong nonlinear characteristic may be mentioned herein such as arc electric furnaces, induction furnaces, saturated transformers and equipment including semiconductor switches. These equipment release current and voltage harmonics [1] while consume a significant amount of reactive power [2]. Moreover, their reactive power consumption changes constantly over time resulting in sags, swells, flickers and other disturbances [3]. Because of upstream current harmonics, grid voltage harmonics is produced. The presence of voltage harmonics in the grid is harmful as additional power loss is introduced and malfunctioning of the grid components may occur [4]. Finally, reactive power is required to maintain the voltage to deliver active power. When there is not enough reactive power, the voltage sags down and it is not possible to push the power demanded by loads through the lines. Though reactive power is needed to run many electrical devices, it can cause harmful effects on electrical appliances. So the reactive power compensation is very important in electrical power system. This is why most of research works concerning the power quality reported in the literatures are interested in the matter of current harmonics cancellation and dynamic reactive power compensation [5].

Over the past few decades, the history of power filters has gone through a changing process from passive power filters (PPFs) [6] to active power filters (APFs) [7], and recently, towards hybrid active power filters (HAPFs). Different topology types of HAPF composed of active and passive equipment in series and/or parallel connection have been proposed, aiming to improve the compensation characteristics of PPFs and reduce the voltage and/or current ratings (costs) of the APFs, thus leading to improvements in cost and performance [8]. Jasmine Susila et *al.* have implemented a series topology HAPF in [9], simulation results showed improved power quality. However, their proposed topology was not adequately tested with the experimental setup. Mehdi Asadi et *al.* [10] proposed a HPAF which comprises a b-shape C-type HAPF (bCHAPF) and an active electromagnetic filter consisting of a Zig-Zag transformer and a single-leg inverter, the topology performed well with current harmonics elimination but complex in construction and difficult to implement.

In this paper, a joint strategy of active filter and passive filter for current harmonic cancellation and power factor enhancement in three-phase power networks is proposed and studied. The strategy is a parallel configuration of low order passive harmonics filter and selective shunt active power filter. Frequency domain Fourier Transform analysis and robust PI controlling methodology are used to design control algorithm. The strategy performance is verified by modeling and using Matlab/Simulink software for the simulations.

2. Shunt component power filters

2.1 Passive power filter

Single tuned topology is chosen to implement the passive component because it is simple to construct and economically viable. Along with high pass and double tuned filters, single tuned passive filter is one of the most commonly used types of harmonics filter in three-phase systems.

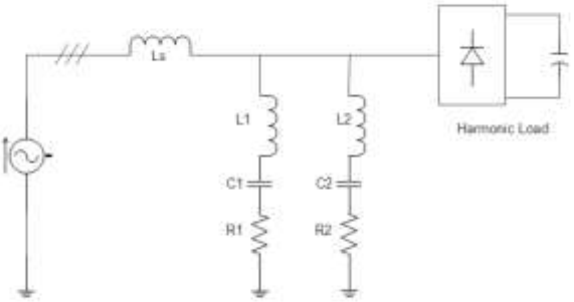


Figure. 1 *Passive power filter connection diagram*

The passive components of the joint topology are designed to eliminate the majority of the lower part of the harmonic spectrum, typically 5th and/or 7th harmonics. Essentially, the passive components are passive harmonics filters (PHF) in which a combination of inductance and capacitance is chosen so that the filters achieve almost zero impedance at specifically tuned frequencies, this characteristic provides low-impedance paths for harmonic currents preventing upstream harmonic current flow. The characteristics of the impedance curves of the PHFs not only depend on L, C values but also the quality factor of the filter which is signified by the Q value. Q often falls into the range of 20 to 100 and inversely proportional to the branch resistance.

Filter tuning frequency f_{har} and tuning angular frequency ω_{har} are calculated as,

$$f_{har} = \frac{1}{2\pi\sqrt{LC}}, \omega_{har} = \frac{1}{\sqrt{LC}}. \tag{1}$$

Filter impedance Z_{filter} and the relationship between filter inductance L and capacitance C are presented as,

$$Z_{filter} = Z_L - Z_C + R \tag{2}$$

and

$$Z_{L,har} = Z_{C,har} \rightarrow L = \frac{1}{(h\omega_{fundamental})^2 C}, \tag{3}$$

where: h is the harmonic order of the PHF branch; $Z_{L,har}$ and $Z_{C,har}$ are impedance of inductor and filter capacitor at tuning frequency; $\omega_{fundamental}$ is the fundamental angular frequency.

Filter quality factor Q is calculated as,

$$Q = \frac{Z_C}{R} = \frac{1}{R}\sqrt{\frac{L}{C}}. \tag{4}$$

It can be seen in Eq. (3) that L tends to become small as harmonic order of the filter increases. This consequently makes the filter branch become less effective in damping transient disturbance at higher harmonic order and this could damage the filter’s capacitors.

As seen in Figure 1, two PHF branches are tuned at 5th (L_1, C_1, R_1) and 7th (L_2, C_2, R_2). Beside harmonics filtering functionality, the two PHF branches also provide background reactive power compensation for power factor correction.

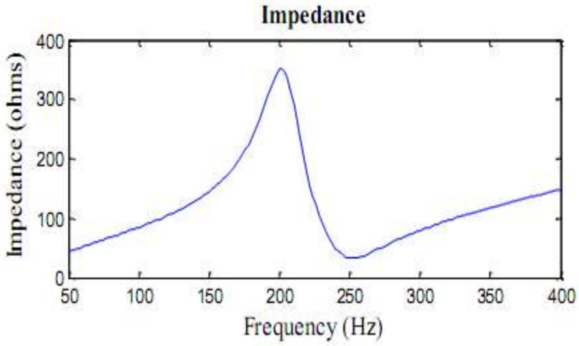


Figure. 2 *Branch Impedance with Frequency diagram of a typical single tuned passive filter*

For power factor correction from an initial PF_0 to a desired PF_1 value, the amount of reactive power produced by the passive component Q_{filter} is calculated as follow:

$$Q_{filter} = P_{load}(\tan[\text{acos } PF_0\ ] - \tan[\text{acos } PF_1\ ]). \quad (5)$$

Q_{filter} can also be calculated by

$$Q_{filter} = Q_C - Q_L = \frac{h^2 - 1}{h^2} Q_C, \quad (6)$$

where,

$$\begin{aligned} Q_C &= \frac{h^2}{h^2 - 1} P_{load}(\tan[\text{acos } PF_0\ ] - \tan[\text{acos } PF_1\ ]) \\ &= \frac{U_c^{\ 2}}{Z_c} = \omega_{fundamental} C U_c^{\ 2}. \end{aligned} \quad (7)$$

In which, U_C is the voltage applied on the capacitor. When Q_C is obtained, C and L can then be found by substituting to Eq. (3) and Eq. (7). Finally, R can be calculated via selection of quality factor Q.

Figure 2 shows the impedance response of a passive filter in which the local maximum shows a parallel resonance between the filter of grid parasitic impedance. The local maximum situates at the frequency f_{res} defined by

$$f_{res} = \frac{1}{2\pi\sqrt{(L + L_s)C}}. \quad (8)$$

The impedance response also shows that branch impedance does not entirely equal to zero at tuning frequency due to non-zero quality factor in which Z_L and Z_C cancel each other out at f_{har}, making Z_{filter} equals the internal resistance R.

2.2 Active power filter

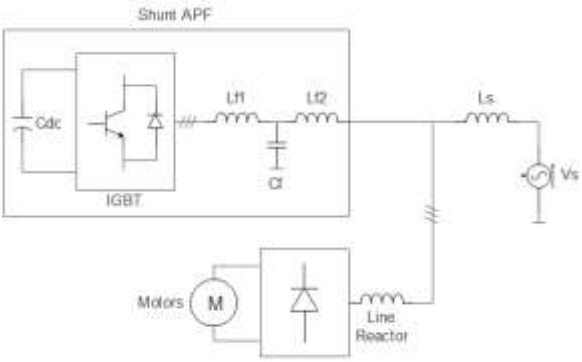


Figure. 3 *Structure and wiring diagram of a shunt active power filter*

The active component of the joint topology is a shunt APF with small compensation current rating. As the APF is placed upstream of the passive components, it will only see high order harmonics which are typically 11th, 13th, etc., harmonics as lower harmonics are eliminated by the passive component. Apart from the cancellation of harmonics, the active component also copes with minor reactive power fluctuation at the point of common coupling (PCC).

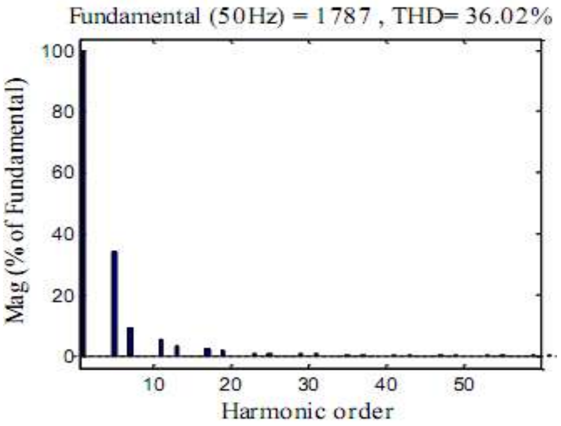


Figure. 4 *Harmonics spectrum of a typical 6-pulse DC drive*

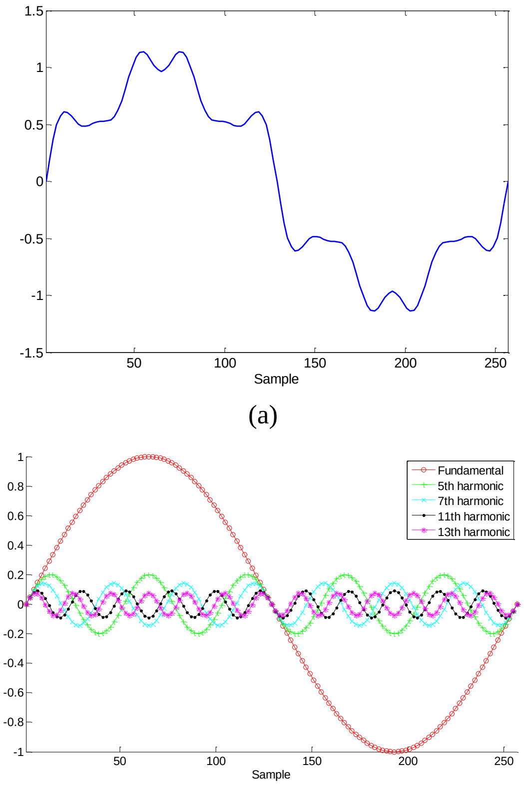
In many harmonic load configuration, especially in DC and AC drive applications, 11th, 13th and high order harmonics are much less in amplitude than lower harmonics (e.g. 5th, 7th harmonics) due to the fact that harmonic current is inversely proportional to its order.

In principle, the active filter stores electrical energy in its DC bus, which is a high voltage DC capacitor, and convert this DC voltage into three phase AC voltage and current. The control algorithm for the active power filter decides how much reactive power is being supplied to the grid by varying the output current phase and amplitude. This can be achieved to estimating the correct amount of reactive power needed by the non-linear load using voltage and current feedback signals measured at PCC and DC bus. Details about the control algorithm will be discussed further in the next section.

3. Filter control technique in frequency domain

3.1 Harmonics filtering using frequency domain transformation

Fourier Transform is used to analyze load feedback signal to provide flexible selective harmonic current generation.



(a)

(b)

Figure. 5 *(a) Nonlinear harmonic waveform, (b) Visual representation of the Fourier Transform of the harmonic waveform in (a)*

Fourier Transform and Inverse Fourier Transform are versatile tools to decompose a measured harmonic feedback signal into multiple harmonic subcomponents as seen in Figure 5a and Figure 5b. This allows the selection of high order harmonics while omitting lower components. According to Fourier Transform, load current can be represent as

$$i_{load}\ t = i_{load,\,fundamental}\ t + \sum_{h=2}^{\infty} i_{load,h}(t), \tag{9}$$

where, $i_{load,\,fundamental}(t)$ is the fundamental component and $i_{load,h}(t)$ is the function of harmonic components.

Discrete Fourier Transform (DFT) is the digital form of Fourier Transform. DFT of a discrete signal sampled N times in a cycle is defined as

$$X_1 = \sum_{k=0}^{N-1} x_k e^{\frac{j2\pi k}{n}}. \tag{10}$$

Inverse DFT of X_1 is defined as

$$x_{k1} = \frac{1}{N} X_1 e^{-\frac{j2\pi k}{N}}. \tag{11}$$

3.2 Reference current calculation for APF compensation control

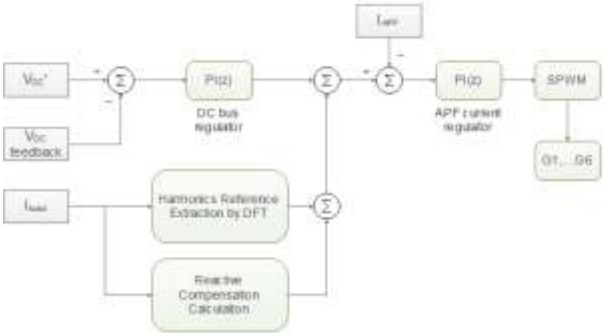


Figure. 6 *Control algorithm for the active component*

Figure 6 illustrates the control algorithm for the active component. Assuming sampling rate is 12800 Hz, which is 256 samples per an electrical cycle. The amount of frequency bin obtained by DFT is 256 bins representing 128 frequency domain components of load current (since the transformation is symmetric), including DC and fundamental components. Reference current is computed by first extracting high order harmonics from DFT analysis of load feedback current, namely 11th to 128th frequency components, and then takes the inverse DFT of this frequency range.

A DC bus voltage PI regulator is added in order to keep DC bus stable at a reference value. Output of the DC bus regulator is then added to harmonics reference current along with reactive power compensation reference current to take into account IGBT loss. Another PI controller is used to generate pulse width modulation signals and regulate APF output compensation current. The PWM generation module is a Sinusoidal PWM which creates PWM pulses by comparing the PI controller output, which is also PWM modulation index, with a triangle wave oscillating at a specific switching frequency, normally from 8 kHz to 15 kHz.

4. Simulation results

4.1 Case studies

For the purpose of demonstrating the performance of the joint topology, a case study shown in Figure 7 at Station 6 - Ba Na Hills mountain resort (Danang city, Vietnam) is conducted. The case of Ba Na Hills harmonics pollution exemplifies the harmonics generating characteristic of DC drives in industrial application. The electrical system at Station 6 consists of a pair of 575 kW DC motors driven by 2 ABB DCS800 DC drives, supplied by a 2 MVA 22kV/0.4kV Delta/Wye Transformer.

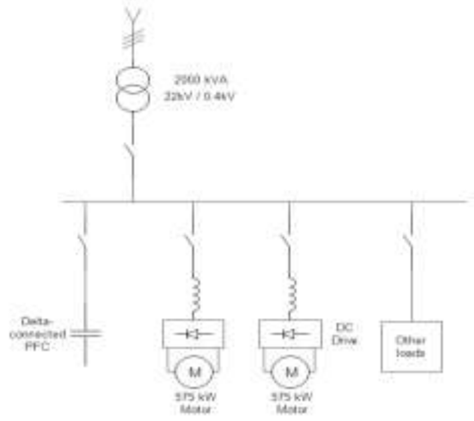


Figure. 7 *Ba Na Hills Station 6 Basic electrical diagram*

The motors are used to lift a cable car system which can accommodate up to 1500 peoples each hour. These nonlinear loads have been causing severe harmonics with current THD fluctuates between 26.7% and 113.4%. Voltage THD is also high, consistently above 12% and peaks at 25.7% in one measurement (see Figure 8).

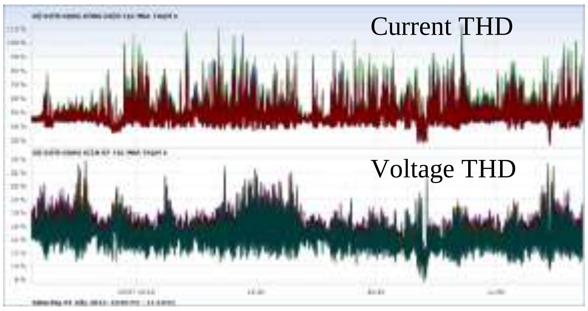


Figure. 8 *Measurement report shows high THDi and THDu*

High harmonic current and voltage have dealt significant damages to the cable car system, interrupting the chair lifting operation of the motors and creating considerable business downtime at Ba Na Hills.

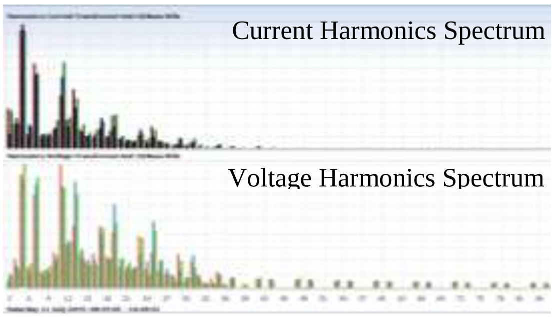


Figure. 9 *Measured harmonics spectrum shows significant harmonics at 5^{th}, 7^{th}, 11^{th} and 13^{th} orders*

4.2 Proposed topology in Ba Na Hills case

In order to face these problems, we propose in this situation a topology in which both passive filter component for 11th and 13th order and active filter component are added and presented in Figure 10.

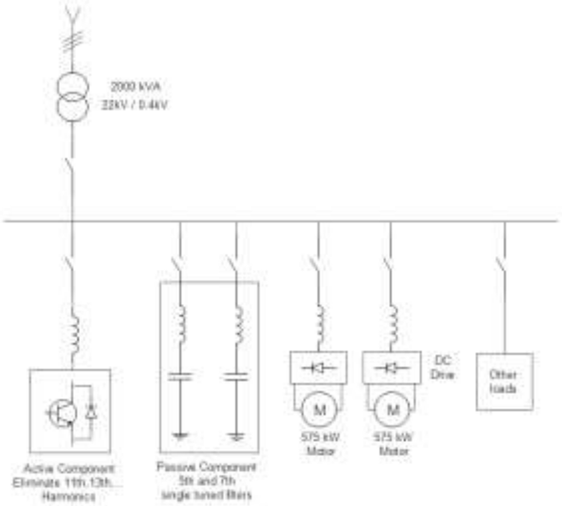


Figure. 10 *Joint topology with active and passive components installed*

The existing power factor correction capacitor bank is removed because it was producing parallel resonance in the system, making 11th and 13th current harmonics unusually high as seen in Figure 9.

As initial power factor is 0.85, the amount of reactive power needed by the 1200 kW DC motors and other loads could be calculated as follows:

$$Q_{total} = 1200\ \tan\left[\operatorname{acos}\ 0.85\right] - \tan\left[\operatorname{acos}\ 0.95\right]$$
$$= 350\ kVAr,$$

$$Q_{c,5^{th}} = \frac{5^2}{5^2-1} Q_{filter,5^{th}} = 182\ kVAr,$$

$$Q_{c,7^{th}} = \frac{7^2}{7^2-1} Q_{filter,7^{th}} = 178\ kVAr,$$

$$Q_{filter,5^{th}} = Q_{filter,7^{th}} = \frac{1}{2} Q_{total},$$

where: $Q_{c,5^{th}}$ and $Q_{c,7^{th}}$ are the reactive power of 5th and 7th PHF branches capacitors, respectively; $Q_{filter,5^{th}}$ and $Q_{filter,7^{th}}$ are the reactive power of 5th and 7th PHF branches, respectively.

The active component harmonics rating is selected to be 200Arms due to the fact that it only works with harmonics of orders 11th, 13th, and above. The DC bus is regulated at 600V with capacitance $C_{DC} = 4000\mu F$. Output filter inductance $L_{interface} = 0.4mH$. The IGBT switches are driven by a 10 kHz PWM pulse generator.

The passive component reduces effectively current THD from 33% to 13% by cancelling 5th and 7th harmonics as shown in Figure 11. Due to the fact that 5th and 7th filter branches are not designed to resonance at exactly 250 Hz and 350 Hz but rather 247.5 Hz and 347.5 Hz to avoid PHF overload. The transient occurs at 1s is characteristic of capacitor switching. Transient-free capacitor switching requires peak grid voltage detection and zero grid current detection.

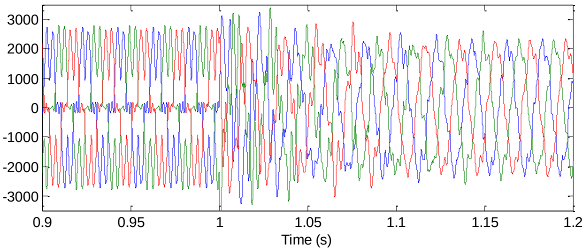


Figure. 11 *Nonlinear current being compensated with the passive component*

In Figure 12, the active component is connected at 1.3s after the passive component is stable. It is obvious that the result current is not perfectly sinusoidal because the control algorithm ignores 5th and 7th harmonics.

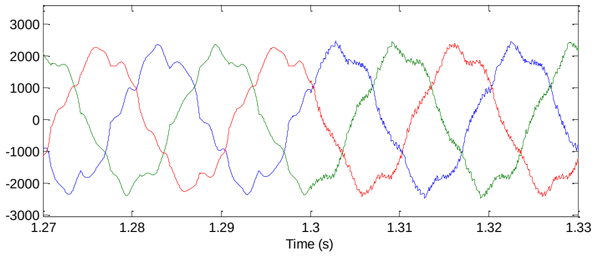


Figure. 12 *Nonlinear current being compensated with the passive component and active component*

High frequency fluctuation is considerable reduced since 11th and 13th are eliminated. Current THD is improved to 10.3%. The residual harmonics are primarily consisted of 5th and 7th harmonics. This reflects the performance of the passive component rather than the active component. Active component could be used to filter out the remaining harmonics by setting target spectrum at 5th and 7th as well 11th and 13th harmonics, but this will tradeoff the rating and cost of active component itself.

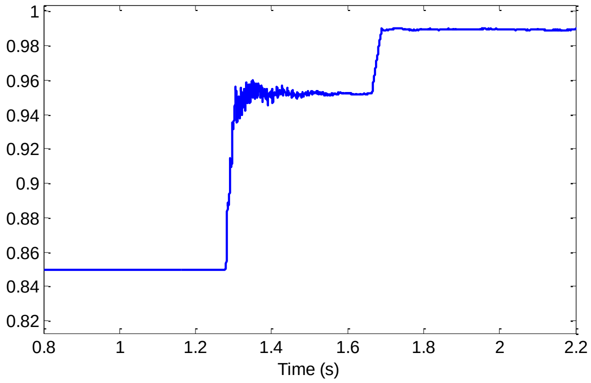


Figure. 13 *Power factor correction of the joint topology, active component connected at 1.7 s*

Figure 13 shows power factor correction from 0.85 to 0.95 just by connecting the passive component which is connected at 1.3s. At 1.7s, the active component is connected and improves the power factor to 0.98. A comparison between a typical shunt APF and the joint topology is done by measuring the amount of compensating current produced by each type of device. Figure 14 shows the reduction of RMS current rating of the active component when the active component only needs 30% of a shunt APF (200 Arms compared to 650 Arms) for the Ba Na Hills case study.

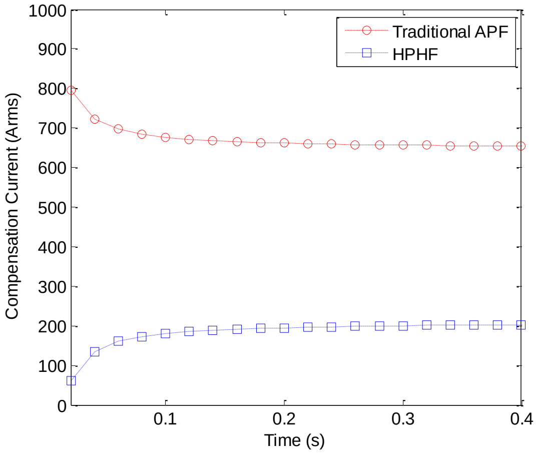


Figure. 14 *RMS comparison of compensation current between pure shunt APF and active component in joint topology*

5. Conclusion

The paper demonstrates the effectiveness of the proposed HPHF in the harmonics cancellation and the dynamic reactive compensation. The obtained results show that the active component current rating in the HPHF system is only 30% of the traditional active power filter rating with the same harmonics filtering performance. This reduction in rating implies a great economic advantage of the proposed HPHF compared to the traditional APFs. Moreover, the proposed HPHF shows significant potential in installation footprint, which is important in space constraint sites such cruise ships, oil rigs, etc.

Future works involve thermal design for the active component and a detailed transient analysis of HPHF systems. Furthermore, an electrical prototype will also be developed to real-world settings.

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