Three Phase Active Harmonic Rectifier (AHR) to Improve Utility Input Current THD in Telecommunication Power Distribution System

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Abstract- **Modern telecommunication power supply systems have several parallel connected switch mode rectifiers to provide -48V DC. Typical switch mode rectifier configuration includes a three phase diode rectifier followed by a DC-DC converter. Such a system draws significant harmonic currents for the utility resulting in poor input power factor and high total harmonic distortion (THD). In this paper, a three phase active harmonic rectifier (AHR) scheme is proposed. In AHR scheme, a diode rectifier module is replaced by 6-IGBT PWM rectifier to supply load harmonics as well as its own active power. Each DC-DC converter module is connected to a shared 48V dc-link. The AHR module together with parallel connected switch mode rectifiers is controlled to achieve clean input power characteristics. The VA ratings of AHR scheme is compared with an active power filter (APF) approach. The control design is based on the synchronous reference frame approach. Analysis, simulation and experimental results show that AHR offers several advantages such as lower VA rating, better current control response, efficient use of AHR dc-link, small size, and stable dc-link voltage control.**

I. INTRODUCTION

Modern telecommunication power systems require several three-phase rectifiers in parallel to obtain higher DC power with -48V DC. Such a rectifier normally employs diodes or silicon-controlled rectifiers (SCR) to interface with the electric utility due to economic reasons. The rectifier type utility interface causes significant harmonic currents resulting in poor input power factor and high total harmonic distortion (THD), which contributes to an inefficient use of electric energy. The above mentioned rectifier is referred to as nonlinear loads. The proliferation of rectifier loads deteriorates the quality of voltage and current waveforms. Further, harmonic currents can lead to equipment overheating, malfunction of solid-state equipment, and interference with communication systems [1-3]. IEEE 519 and IEC EN 61000-3 standards specify regulations governing harmonic compliance [4, 5]. Passive filter has been a viable approach because of low cost and high efficiency [6-7]. However, the performance of the passive scheme has a limitation since the addition of the passive filter interfaces with the system impedance and cause resonance with other network. Numerous active solutions which are becoming a more effective means to meet the harmonic standards by overcoming the drawback of the passive filter have been proposed [8-11].

Active power filters employing PWM voltage source inverter seem to be the most preferred scheme for canceling load harmonics. However, the general voltage source inverter topology employs a relatively large dc-link capacitor to serve as a constant dc voltage source. Therefore, this scheme suffers from a bulky electrolytic capacitor, higher switching losses, and its associated dc link voltage control issues due to reduced damping.

In this paper, three phase active harmonic rectifier (AHR) scheme based on space vector pulse width modulation (SVPWM) is proposed. The AHR module together with parallel connected switch mode rectifiers (Fig. 2 a) is controlled to achieve clean input power characteristics. AHR is compared with APF based on the analysis of VA power rating. The control system is designed on the synchronous DQ reference frame where a low pass filter to cancel harmonics offers better performance than the stationary reference frame. The converter fulfills harmonic cancellation as well as powering active power to its own load by PWM rectification [12, 13]. Therefore, the converter carries a fundamental current for active power and harmonics for the nonlinear loads. The proposed scheme provides the following advantages:

- Reduced dc-link capacitor banks
- The VA rating of AHR is lower than that of APF with rectifier current THD greater than 35%.
- The harmonic RMS current of AHR is $(N-1)/N$ times smaller than that of APF, where N is the number of DC-DC converter modules.
- Current control response is better.
- Control system is stable due to damping provided by the load.
- No additional boost stage.
- Efficient use of PWM rectifier.

II. TELECOM POWER SYSTEM

Modern telecommunication systems require a higher DC power. An example system requirement consists of -48V DC and 800A (38.4kW) [14]. All of the equipment run on DC voltage generated by AC fed redundant rectifiers of which the purpose is to supply power to the equipment. Fig.1 (a) shows a distributed rectifier system where a three-phase utility power is transferred into 48V DC [15]. The telecom rectifiers consist of a rectified stage, a dc to dc converter, and a battery backup system. The major portion of the load is the logic circuitry in board mounted power (BMP) converter units used to convert 48V to 5V and ± 12V. The purpose of the dc/dc converter is to transfer high dc-link voltage to lower voltage 48V and

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provide isolation. Each paralleled DC-DC converter module requires current sharing mechanism to ensure even current distribution. Battery backup system on 48V dc bus is required to support the critical loads in case of utility failure. Basic topology of telecom rectifier is shown in Fig. 1 (b). The boost stage is used only to regulate dc-link voltage for wide input voltage range. Since the power supply employs diode rectifiers because of economic reason, the high power rectifiers result in more serious problems related to harmonic currents. Such a typical rectifier may have more than 30% THD of input current. Fig. 2 shows an example of a telecommunication power system. An active harmonic rectifier (AHR, Fig. 2 a) or active harmonic filter (APF, Fig. 2 b) is embedded in a rectifier slot and rack mountable so that the THD in the utility current can be improved by eliminating harmonic contents. AHR with harmonic filtering function supplies active power and harmonic currents while APF generates load harmonics and optional reactive power.

III. PROPOSED AHR SCHEME

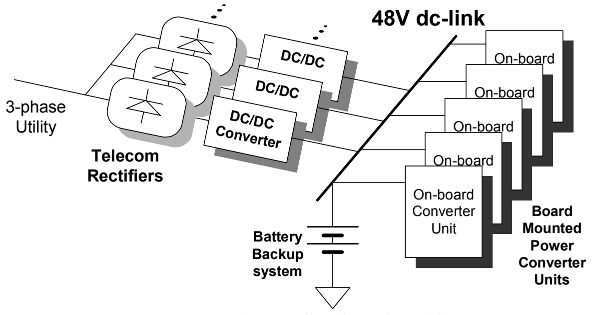
Fig. 3 shows the basic harmonic cancellation techniques using AHR (Fig. 3 a) and APF (Fig. 3 b). The proposed AHR scheme which consists of rectifier nonlinear loads, 3-leg PWM rectifier, paralleled DC-DC converters, and battery backup system. Since rectifier load produces harmonic currents such as 5th, 7th, etc., PWM rectifier with active harmonic filtering capability, called active harmonic rectifier (AHR), compensates for load harmonics as well as supplies active power to its own load. The AHR carries a fundamental current for active power and harmonics for the nonlinear loads to make the input current sinusoidal. Fig. 4 shows the current waveforms for the rectifier input, AHR, and utility currents. The reactive power of the load also can be optionally compensated to improve power factor. To control the active harmonic rectifier, bi-directional power flows are required for 5th and 7th harmonic currents. The input source current is defined as:

$$\mathbf{i}_S = N\mathbf{i}_L - \mathbf{i}_F \,, \tag{1}$$

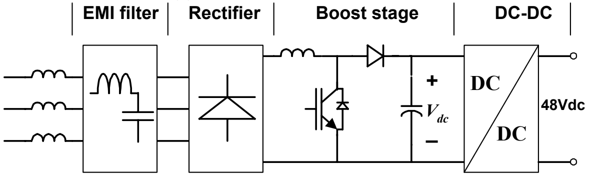
where, i_S , Ni_L , and i_F denote utility, load, and APF currents, respectively. Fig. 5 shows the fundamental 60Hz current and voltage vectors for AHR with and without reactive power compensation. Assuming no reactive power compensation (Fig. 5 a), the steady state utility current can be obtained by,

$$\begin{aligned} i_s &= \sqrt{(N-1)^2 i_{L1,I}^2 + \left(i_{F1} + (N-1) i_{L1,R}\right)^2} \\ &= i_{L1}\sqrt{(1-2N)\sin^2\varphi + N^2} \end{aligned} \,, \tag{2}$$

where, N is the number of DC-DC modules and i_{L1} denotes the fundamental load current of each rectifier module. R and I denote real and imaginary part, respectively. $i_{F1} = i_{L1}\cos\varphi$ since i_{F1} is synchronized with the utility voltage. Displacement power factor angle ξ after compensation is,

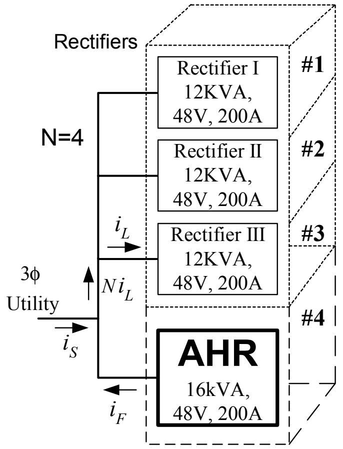


(a) Telecom distributed rectifiers

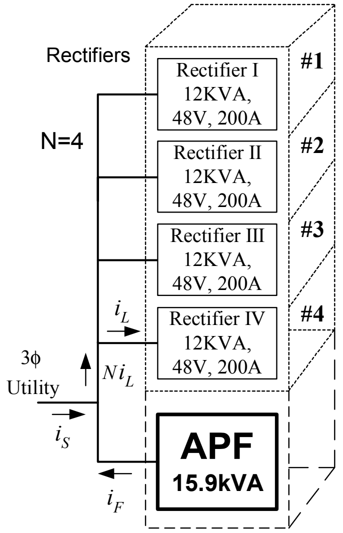


(b) Basic telecom rectifier topology

Fig. 1 Telecom rectifier power system.

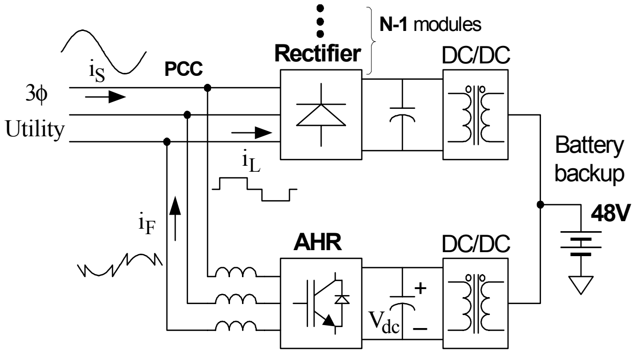


(a) Rectifier system with AHR (Po=38.4kW)

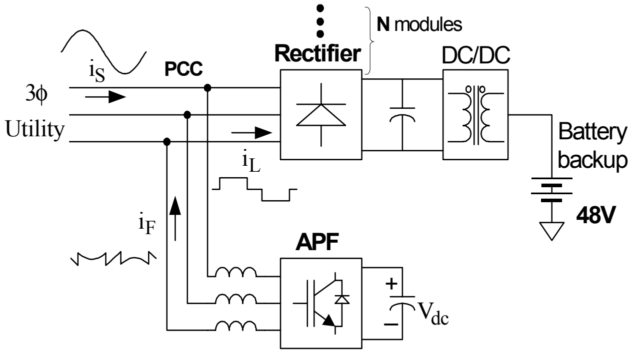


(b) Rectifier system with APF (Po=38.4kW)

Fig. 2 Example telecom power system as a plug-in rack mountable module.



(a) Active harmonic rectifier (AHR)



(b) Active harmonic filter (APF)
Fig. 3. Active harmonic filtering techniques in telecom distributed system.

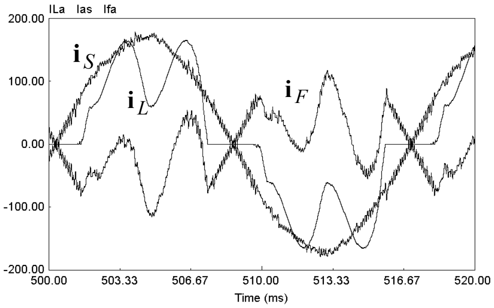


Fig. 4 Current waveforms for the proposed AHR scheme.

$$\xi = tan^{-1}\left(\frac{N-1}{N}\,tan\,\varphi\right) < \varphi\,, \tag{3}$$

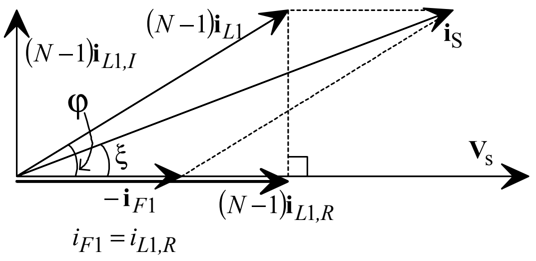
The input displacement power factor is derived without reactive power compensation,

$$cos\,\xi = \frac{N\,cos\,\varphi}{\sqrt{(1-2N)sin^2\,\varphi + N^2}}\,, \tag{4}$$

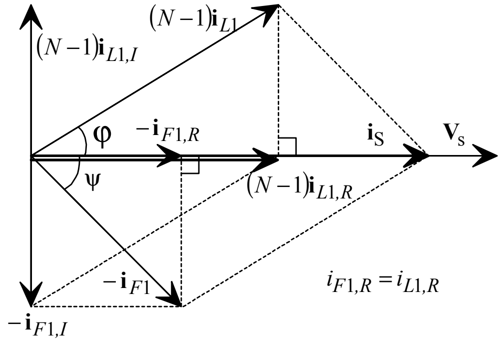
On the other hand, the fundamental utility current depends on the displacement power angle φ with reactive power compensation. Input current is similarly calculated as,

$$i_S = i_{F1,R} + (N-1)i_{L1,R} = N \cdot i_{L1} \cdot cos\,\varphi\,. \tag{5}$$

where, $i_{F1,R} = i_{L1}\,cos\,\varphi$ and $i_{F1,I} = i_{L1}\,sin\,\varphi$. The angle between the input voltage and the AHR current is,



(a) Without reactive power compensation



(b) With reactive power compensation
Fig. 5 Fundamental 60Hz current vector diagrams.

$$\psi = tan^{-1}\left(\frac{i_{F1,I}}{i_{F1,R}}\right) = tan^{-1}(tan\,\varphi)\,, \tag{6}$$

$$\psi = \varphi$$

The rms harmonic currents of AHR and APF is relatively given as,

$$i_{F,har} = (N-1) \cdot i_{L,har}\,, \tag{7}$$

$$i_{F,har} = N \cdot i_{L,har}\,. \tag{8}$$

The harmonic current of AHR is $(N-1)/N$ times APF harmonic currents. The VA ratings of proposed AHR with and without reactive power compensation are respectively,

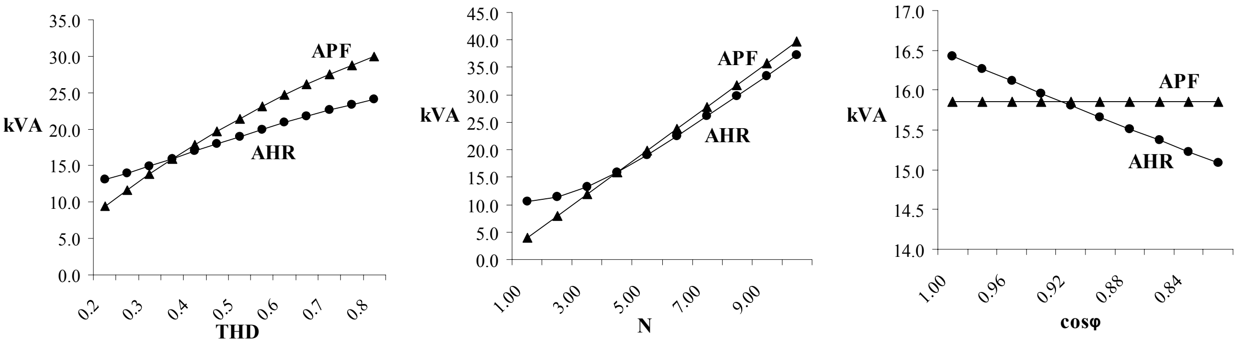
$$VA_{AHR} = \sqrt{\frac{(N-1)^2\left(sin^2\,\varphi + THD_{NL}^2\right) + cos^2\,\varphi}{1 + THD_{NL}^2}} \cdot VA_{NL}\,, \quad \text{(with)} \tag{9}$$

$$VA_{AHR} = \sqrt{\frac{cos^2\,\varphi + (N-1)^2\,THD_{NL}^2}{1 + THD_{NL}^2}} \cdot VA_{NL}\,, \quad \text{(without)} \tag{10}$$

where, the subscript NL denotes a nonlinear load. In case of APF, the VA rating is given by,

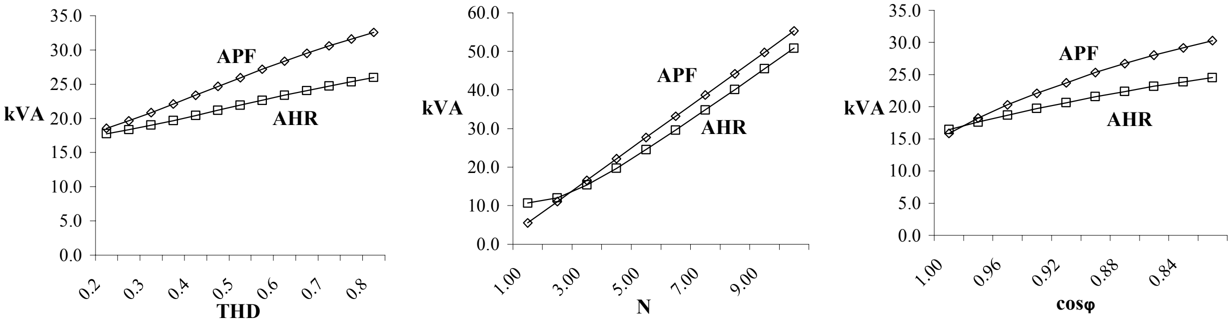
$$VA_{APF} = \sqrt{\frac{THD_{NL}^2 + sin^2\,\varphi}{1 + THD_{NL}^2}} \cdot N \cdot VA_{NL}\,, \tag{11}$$

If the reactive power is not compensated, $\varphi = 0$. Fig. 6 shows the VA rating comparison between APF and AHR without reactive power compensation assuming THD=35%, N=4, and cosφ=0.94. The VA rating of AHR is smaller than that of APF if THD is greater than 35%, N is greater than 4, and displacement power factor is less than 0.92. Similarly, the



(a) THD: variable (b) N: variable (c) $\cos\varphi$: variable

Fig. 6 VA ratings without reactive power compensation (Pin=48kVA, Po=38.4 kW).



(a) THD: variable (b) N: variable (c) $\cos\varphi$: variable

Fig. 7 VA ratings of AHR and APF with reactive power compensation (Pin=48kVA, Po=38.4 kW).

VA rating of AHR is shown in Fig. 7 when reactive power is compensated.

IV. CONTROL SYSTEM

To control the proposed active harmonic rectifier, a harmonic reference current generator is required. Fig. 8 shows several techniques to generate harmonic reference currents on the synchronous reference frame (SRF). A low pass filter can eliminate certain harmonic currents except dc component since the certain frequency is far enough from DC component on the frequency domain. That is the reason why the low pass filter provides better performance on the SRF.

A. Without Reactive Power Compensation

In steady state, the harmonic reference currents contain only load harmonic components such as 5th, 7th, etc. assuming that reactive power is not compensated (Fig. 8 a). Reactive power is optionally compensated since the power rating of active power filter is increased by adding fundamental current for reactive power compensation. DQ transformation results are tabulated in Table I for fundamental current, negative/positive sequences of harmonics, and zero sequence. Three phase balanced currents are transferred into a d-component with a certain dc quantity and a q-component with zero. Negative sequence harmonic (6h-1) components include 5th, 11th, 17th, etc. while the positive sequence harmonics (6h+1) 7th, 13th, 19th, etc. DQ transformations of negative and positive

TABLE I. DQ TRANSFORMATION FOR SEVERAL COMPONENTS.

Input (i_{Labcs})	Output (i_{Ldqns})
Fundamental with power angle $I_1\begin{bmatrix} sin(\omega t-\varphi) \\ sin(\omega t-\varphi-2\pi/3) \\ sin(\omega t-\varphi+2\pi/3) \end{bmatrix}$	$I_1\begin{bmatrix} cos\,\varphi \\ -sin\,\varphi \\ 0 \end{bmatrix}$
Negative Sequence $I_{6h-1}\begin{bmatrix} sin\{(6h-1)\omega t\} \\ sin\{(6h-1)(\omega t-2\pi/3)\} \\ sin\{(6h-1)(\omega t+2\pi/3)\} \end{bmatrix}$	$I_{6h-1}\begin{bmatrix} -cos(6h\omega t) \\ sin(6h\omega t) \\ 0 \end{bmatrix}$
Positive Sequence $I_{6h+1}\begin{bmatrix} sin\{(6h+1)\omega t\} \\ sin\{(6h+1)(\omega t-2\pi/3)\} \\ sin\{(6h+1)(\omega t+2\pi/3)\} \end{bmatrix}$	$I_{6h+1}\begin{bmatrix} cos(6h\omega t) \\ sin(6h\omega t) \\ 0 \end{bmatrix}$
Zero Sequence $I_{6h-3}\begin{bmatrix} sin(6h-3)\omega t \\ sin(6h-3)\omega t \\ sin(6h-3)\omega t \end{bmatrix}$	$\frac{I_{6h-3}}{\sqrt{2}}\begin{bmatrix} 0 \\ 0 \\ sin(6h-3)\omega t \end{bmatrix}$

* h=1,2,3…

sequences result in 6h harmonics (6th, 12th, etc.). Zero sequences (6h-3) such as 3rd, 9th, 15th, etc. are transformed into their own components. It is noted that 5th and 7th harmonics cause a 6th harmonic component while 11th and 13th harmonics generate 12th harmonic current on the SRF. Therefore, even harmonics of the SRF are affected on the harmonic reference currents. Harmonic reference currents can be obtained by using low pass filters (LPFd, LPFq) which eliminate the even harmonics except dc component. The cut-off frequency of the low pass filter is set to from 1 to 50[Hz]. Higher cut-off frequency allows fast control response, but results in distorted utility currents. On the SRF, dc quantity, i^e_{Ldq1}, represents the fundamental current of the phase current. Final expected utility current can be estimated via an inverse DQ transformation after compensating for the harmonics,

$$\mathbf{i}_{abcs} = \mathbf{T}^{-1}(\theta)\begin{bmatrix} i^e_{Ld1} \\ i^e_{Lq1} \\ 0 \end{bmatrix} = \mathbf{i}_{L1}, \qquad (12)$$

where transformation matrix is given as,

$$\mathbf{T}(\theta) = \frac{2}{3}\begin{bmatrix} \sin\theta & \sin(\theta - \frac{2}{3}\pi) & \sin(\theta + \frac{2}{3}\pi) \\ \cos\theta & \cos(\theta - \frac{2}{3}\pi) & \cos(\theta + \frac{2}{3}\pi) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}. \qquad (13)$$

The input current vector is the same as that of the load fundamental current $\mathbf{i}_{L1}$. Harmonic reference currents i^*_{Fdqsh} are obtained from the even harmonics as,

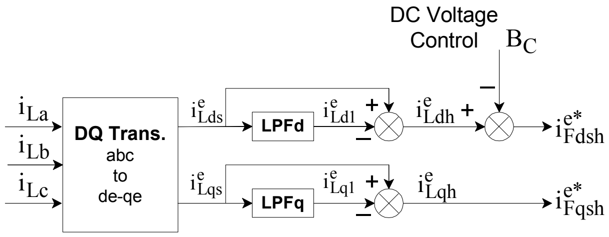
$$\mathbf{i}^{e*}_{Fdqsh} = \begin{bmatrix} i^*_{Fdsh} \\ i^*_{Fqsh} \end{bmatrix} = \begin{bmatrix} i^e_{Ldh} - B_c \\ i^e_{Lqh} \end{bmatrix}, \qquad (14)$$

$$\mathbf{i}^e_{Ldqh} = \begin{bmatrix} i^e_{Ldh} \\ i^e_{Lqh} \end{bmatrix} = \begin{bmatrix} i^e_{Lds} - i^e_{Ld1} \\ i^e_{Lqs} - i^e_{Lq1} \end{bmatrix}, \qquad (15)$$

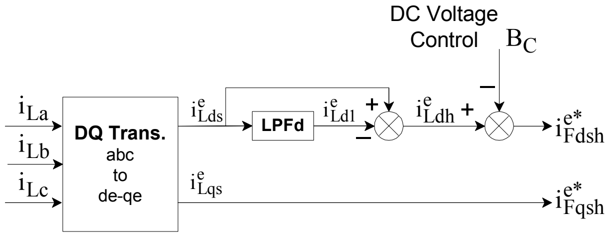
where, $\mathbf{i}^e_{Ldqh}$ denotes the even harmonics and B_c is obtained from dc bus voltage control. The AHR current due to the dc-link voltage control is expressed as,

$$\mathbf{i}_{Fabcs} = -\mathbf{T}^{-1}(\theta)\begin{bmatrix} B_c \\ 0 \\ 0 \end{bmatrix}. \qquad (16)$$

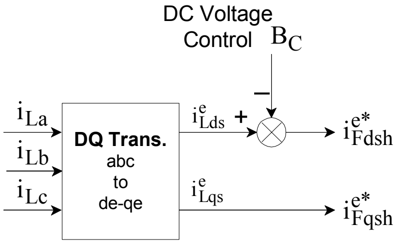
Thus, dc bus voltage control factors can be simply added into the reference currents since dc bus voltage depends on the fundamental AHR current of which magnitude is controllable. Fig. 9 shows the current waveforms on the synchronous reference frame based upon the load currents. The harmonic reference currents i_{Fdqsh} contain 6h harmonics mainly having 6th harmonic component.



(a) Without reactive power compensation



(b) With reactive power compensation



(c) Simple block diagram for reactive power compensation

Fig. 8 Harmonic reference current generators.

B. With Reactive Power Compensation

On the other hand, the power factor angle between utility voltage and rectifier load current is calculated from Fig. 10,

$$\varphi = \tan^{-1}\left(\frac{i^e_{Lq1}}{i^e_{Ld1}}\right). \qquad (17)$$

To compensate for the reactive power as well as the load harmonics, the expected utility current is,

$$\mathbf{i}_{abcs} = \mathbf{T}^{-1}(\theta)\begin{bmatrix} i^e_{Ld1} \\ 0 \\ 0 \end{bmatrix}, \qquad (18)$$

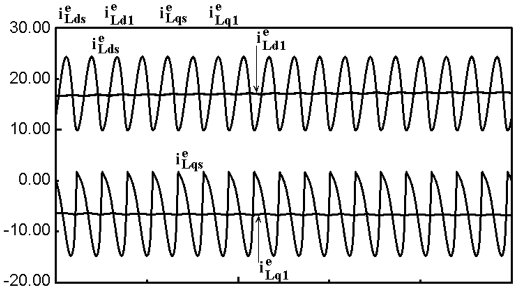
$$i^e_{Ld1} = i_{L1}\cos\delta, \qquad (19)$$

$\mathbf{i}^e_{Lq1}$ must become a fundamental AHR current. $\mathbf{i}_S$ is synchronized with the utility voltage so that the unity power factor can be achieved. Therefore, i^e_{Lqs} becomes q-axis AHR reference current i^{e*}_{Fqsh} which has dc and even harmonics,

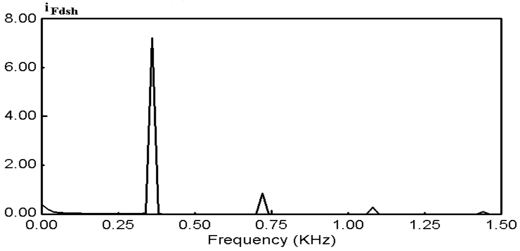
$$i^*_{Fqsh} = i^e_{Lqs}, \qquad (20)$$

while d- component i^{e*}_{Fdsh} is calculated from (14). The dc component i^e_{Lq1} in i^e_{Lqs} represents phase angle φ. Fig. 8 (b) shows the block diagram of harmonic reference current generator to compensate for reactive power as well as load harmonics. The final fundamental current of AHR is generated from the dc quantity i^e_{Lq1},

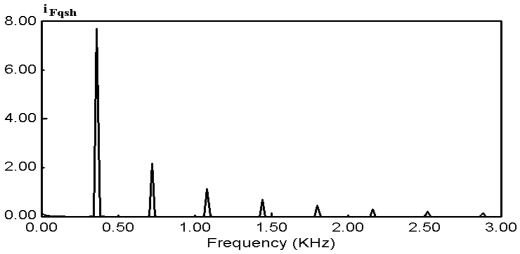
$$\mathbf{i}_{Fabcs} = \mathbf{T}^{-1}(\theta)\begin{bmatrix}0\\ i^e_{Lq1}\\ 0\end{bmatrix} = \sin\varphi\cdot I_{L1}\begin{bmatrix}\cos\theta\\ \cos(\theta-\frac{2}{3}\pi)\\ \cos(\theta+\frac{2}{3}\pi)\end{bmatrix}, \tag{21}$$



(a) DQ axis currents



(b) Spectrum of i_{Fdsh}



(c) Spectrum of i_{Fqsh}

Fig. 9 Current waveforms on synchronous reference frame.

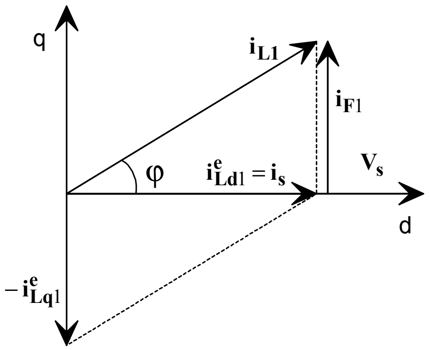


Fig. 10 Current vectors with power angle φ.

where, $i^e_{Lq1} = \sin\varphi\cdot i_{L1}$, and the current flowing out of the AHR has a leading angle $\pi/2$. Fig. 11 shows the current waveforms in terms of reactive power compensation on the stationary reference frame. It is clear that the expected utility current with reactive power compensation is synchronized with the utility voltage. The AHR current I^*_{Fa} is calculated by an inverse DQ transformation of harmonic reference current i^*_{Fdqsh}. Two APF currents are differentiated from the fundamental component. The simplified block diagram including reactive power is shown in Fig. 8 (c).

V. DESIGN EXAMPLE

An active harmonic rectifier design is based on the telecommunication rectifier system shown in Fig. 2 (a). The total rectifier VA rating (VA_{NL}) is 48kVA, total output power 38.4kW, THD 35%, efficiency 90%, N=4, and $\cos\varphi = 0.94$. AHR design specifications are as follows,

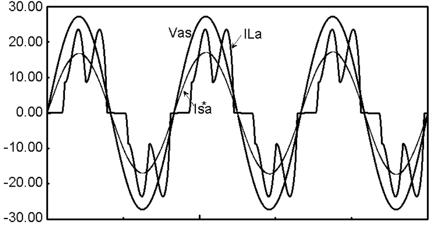
Input voltage : 208V
Input current : 38A
Dc bus voltage : 380V
Rectifier current THD : 35%
Input inductor : 1[mH]=0.12 [p.u]
Output capacitor : 5.8[mF]= 6.7[p.u]
Switching Frequency : 16.4 kHz

The VA rating of AHR from (9) and (10) is,

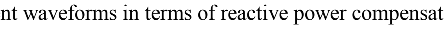
$$\begin{aligned} VA_{AHR} &= 16kVA \quad (without) \\ &= 19.7kVA \quad (with) \end{aligned}, \tag{22}$$

The VA rating of APF from (11) is,

$$\begin{aligned} VA_{APF} &= 15.9kVA \quad (without) \\ &= 22.1\,kVA \quad (with) \end{aligned}. \tag{23}$$

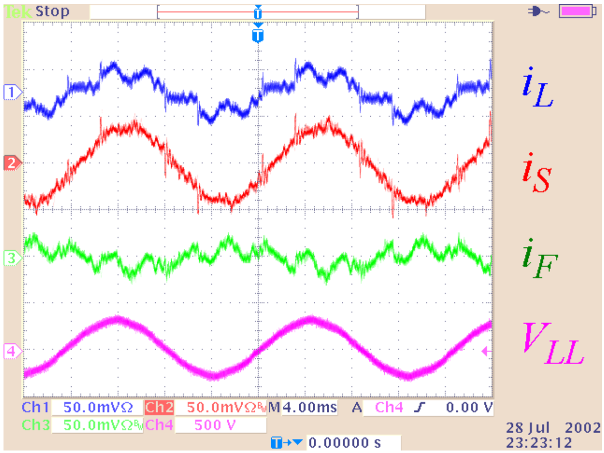


(a) Without reactive power compensation

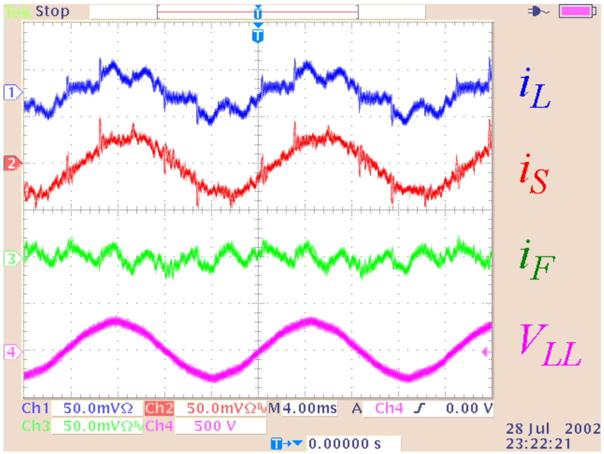


(b) With reactive power compensation

Fig. 11 Current waveforms in terms of reactive power compensation.



(a) AHR



(b) APF

Fig. 12 Experimental results.

VI. EXPERIMENTAL RESULTS

The proposed three phase active harmonic rectifier system is implemented on a fixed point DSP, TMS320LF2407. Fig. 12 (a) shows the control performances of the proposed scheme from experimental results without reactive power compensation. AHR compensates for load harmonics and supplies active power. APF results are shown in Fig. 12 (b). AHR current contains a fundamental component and load harmonics while APF generates only load harmonic currents.

VII. CONCLUSIONS

In this paper a three phase active harmonic rectifier (AHR) scheme has been presented for telecommunication power distribution system. AHR is able to compensate for rectifier harmonics as well as supply active power. Harmonic reference current generators are shown. From the VA rating analysis of AHR and APF, it is shown that AHR scheme in telecom power system provides less VA power rating including several advantages such as better current control response, efficient use of AHR dc-link, small size, and stable dc-link voltage control. The experimental results verify the performance of the proposed AHR system.

VIII. REFERENCES

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