ESTIMATION OF REQUIRED CAPACITY OF SHUNT TYPE ACTIVE POWER FILTER WITH A THYRISTOR CONVERTER LOAD

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Abstract – The main drawback of parallel type active power filters (APF) is the large capacity required for harmonic compensation. This paper evaluates the APF capacity requirement for harmonic/reactive power compensation for thyristor converter load. Theoretically achievable maximum power factor under partial load is evaluated. And it is shown that the APF capacity can be considerably reduced while slightly sacrificing the filtering performance by deliberately limiting the peak current of the APF.

1. INTRODUCTION

During the last decade various types of active power filter (APF) schemes have been developed [1-4]. Among them, the shunt type active power filter is the most direct way of filtering that injects unwanted harmonic current component into the utility grid to keep the line side free from undesirable effects due to the harmonic current. It requires a tight current control of an arbitrary waveform, which is met by recent progress in power device technologies in small to medium power range, along with advanced pulse-width modulation techniques such as the space vector modulation.

In spite of some successful commercialization examples, however, the shunt APF seems not to be justified in many applications because of its high required capacity and as a result high cost. The series type APF combined with conventional shunt passive filters and some variations [4] offer an economic solution to power system harmonic problems. But the shunt APF is still attractive in its inherent ability of handling actual power flow that allows reactive power compensation and flicker control, etc. [3], in addition to the harmonic elimination.

For given voltage level at the point the APF is connected, the capacity of the APF is determined by the peak current the APF provides to the lines. As the APF current is composed of harmonic components, it appears as a highly distorted waveform and its peak value may become considerably large compared to the magnitude of the fundamental component of the load current. For example, the peak current a diode rectifier with capacitive dc link draws from the lines may reach several times of the magnitude of the fundamental component. The harmonic current injection for this kind of load thus requires the APF power circuit to have a large current rating that is unacceptable in most circumstances. Therefore, the shunt APF has been usually adopted for the load that has relatively low peak current level, such as thyristor converters [1, 2, 4].

The APF capacity can be reduced by limiting the peak current the APF delivers. The current limit imposed on the APF operation leaves residual harmonics in power lines. Recognizing that the purpose of the power line filter, active or passive, is not completely eliminating the line side harmonics but suppressing the harmonics to an acceptable level [5], the appropriate current limit can be determined so that the residual harmonics do not have significant effects at the point of common coupling (PCC). In this regard, this paper examines the impact of current limiting of APF on the performance of harmonic suppression in terms of the total harmonic distortion (THD) of the line current, for a thyristor converter load.

2. APF CAPACITY WITHOUT REACTIVE POWER COMPENSATION

Fig.1 shows a schematic single-line diagram of the thyristor converter system with the shunt APF. To avoid unnecessary complication in the subsequent analysis, following assumptions are made:

1. The dc link of the thyristor converter is highly inductive to yield a constant ripple free dc current.
2. The current transition over the commutation interval of the thyristor converter is linear.
3. Current control of the APF is ideal, that is, the switching ripple in the APF output current is negligible.

First consider the case of no source inductance or as a result no commutation overlap. According to the first assumption, the load current waveform i_L is given by a six-step quasi-square waveform as shown in Fig. 2(a). The load current is decomposed into the fundamental component i_{L1} and remaining distorted component, which will be the same as the APF current i_F and the source current i_S, respectively, under the assumption 3 given above.

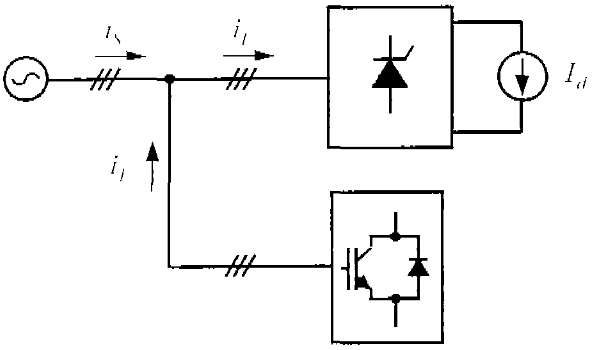


Fig. 1 Shunt active power filter with thyristor converter

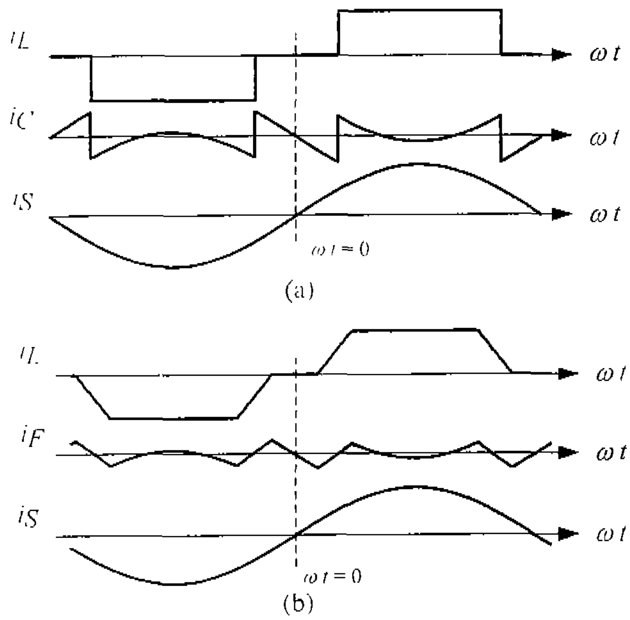


Fig. 2 Waveforms of load current, APF current, and the line current (a) without source inductance and (b) with source inductance

With the time reference point shown in the figure, the fundamental component of the load current is given by

$$i_{L1} = I_0 \sin \omega t \qquad (1)$$

where

$$I_0 = \frac{2\sqrt{3}}{\pi} I_d \qquad (2)$$

for given dc output current of the load converter, I_d. The APF current waveform shows that the peak current occurs at the point of current transition, $\theta_1 = \pi/6$ to give the peak current

$$\hat{i}_f = |i_f(\theta_1 -)| = |i_{L1}(\theta_1 -) - i_L(\theta_1 -)| = I_0 \sin\frac{\pi}{6} \qquad (3)$$

or

$$\hat{i}_f = \frac{\sqrt{3}}{\pi} I_d = 0.55 I_d \qquad (4)$$

Th above equation shows that the current rating of the power devices of a shunt APF should be as large as 55% of that of the load converter, which is called the 'base rating' hereafter. This is the worst figure, as the actual load current waveform has smoother transition due to the source inductance as shown in Fig. 2(b). To examine the effect of source inductance, it is convenient to introduce the short-circuit ratio (SCR) defined as

$$\text{SCR} = \frac{\text{System short circuit MVA}}{\text{Converter MVA}} \qquad (5)$$

The SCR is related to the system reactance X_S with

$$\text{SCR} = \frac{V_{LL}}{\sqrt{3} X_S I_{L,rated}} \qquad (6)$$

where V_{LL} is the system line voltage and $I_{L,rated}$ is the rated current of thyristor converter The commutation overlap angle u and the system reactance has the following relationship:

$$\cos(\alpha - u) = \cos\alpha - \frac{2X_s}{\sqrt{2} V_{LL}} I_d \qquad (7)$$

where α is the firing delay angle of the converter.

With the assumption of linear transition of the current, the magnitude of the fundamental component in (1) is replaced by

$$I_u = \frac{4\sqrt{3}}{\pi u} I_d \sin\frac{u}{2} = \frac{2}{u} \sin\frac{u}{2} I_0 \qquad (8)$$

As can be seen in Fig. 2(b), the peak current occurs at $\theta_1 = \pi/6 - u/2$ yielding the peak value

$$\hat{i}_f = |i_{L1}(\theta_1)| = I_u \sin(\frac{\pi}{6} - \frac{u}{2}). \qquad (9)$$

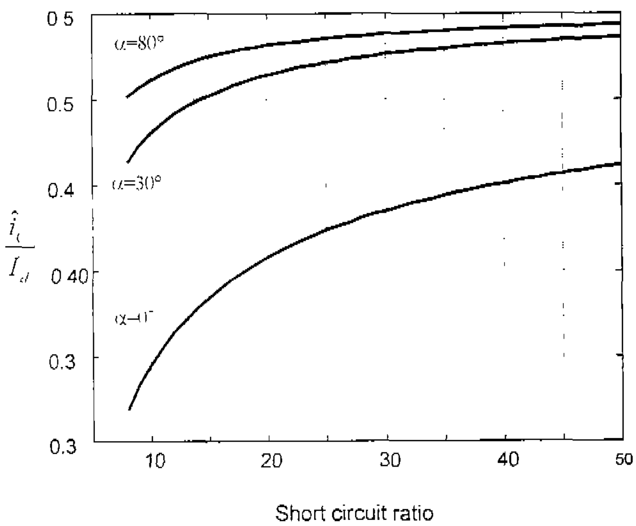


Fig. 3 Peak current with short circuit ratio

With (6)-(9), the variation of the peak current with short-circuit ratio and the firing delay angle of the thyristor converter is calculated and plotted in Fig. 3. The figure shows that the source inductance does not have significant effect on the peak current of the APF while constraining the firing delay angle, although not practical in most thyristor converter applications, may result in considerable reduction of the required current capacity.

3. APF CAPACITY WITH REACTIVE POWER COMPENSATION

The shunt APF can be used for compensating the reactive power by superimposing the reactive current component on the harmonic current injection. The fundamental component load current can be expressed as

$$i_{l1} = I_0 \cos\alpha \sin\omega t + I_0 \sin\alpha \sin(\omega t - \frac{\pi}{2}) \tag{10}$$

The first term in the above equation, the active component, is provided by the lines, while the second term, the reactive component, is partially or fully compensated by the shunt APF. Let the compensated line current be

$$i_S = I_0 \cos\alpha \sin\omega t + k I_0 \sin\alpha \sin(\omega t - \frac{\pi}{2}) \tag{11}$$

where k generally takes the value from 0 to 1 according to the degree of reactive power compensation, and is given by a function of the resultant power factor seen from the line side as

$$k = \frac{1}{\tan\alpha} \frac{\sqrt{1 - \mathrm{PF}^2}}{\mathrm{PF}} \tag{12}$$

Fig. 4 shows a typical waveform with reactive power compensation assuming no commutation overlap for simplicity. As the peak current occurs at the point of commutation, following four current magnitudes are of interest.

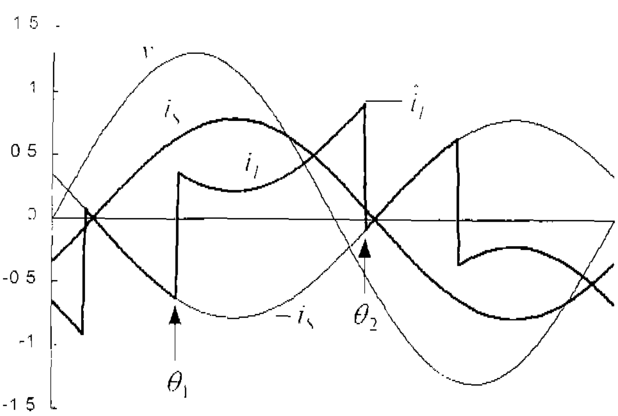


Fig. 4 Typical APF current waveform with reactive power compensation

$$I_{1-} = i_F(\theta_1 -) = -i_S(\theta_1) \tag{13}$$

$$I_{1+} = i_F(\theta_1 +) = I_d - i_S(\theta_1) \tag{14}$$

$$I_{2-} = i_l(\theta_2 -) = I_d - i_S(\theta_2) \tag{15}$$

$$I_{2+} = i_l(\theta_2 +) = -i_S(\theta_2) \tag{16}$$

where

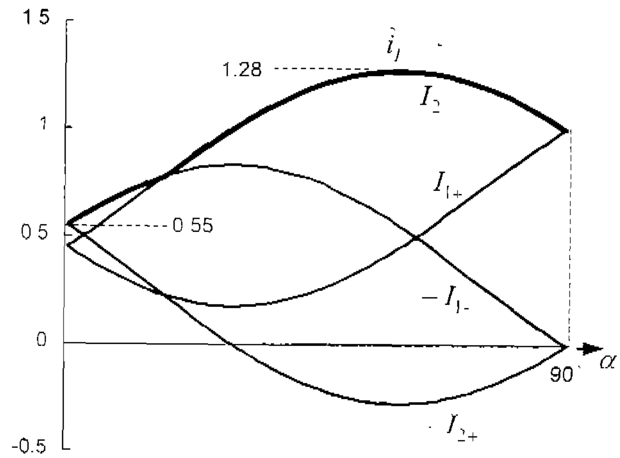
$$\theta_1 = \alpha + \frac{\pi}{6} \tag{18}$$

$$\theta_2 = \alpha + \frac{5\pi}{6} \tag{19}$$

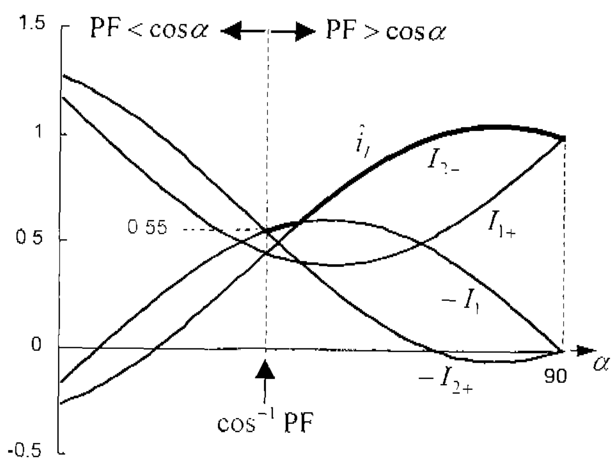
And the peak current over a cycle is

$$\hat{i}_l = \max(\pm I_{1-}, \pm I_{1+}, \pm I_{2-}, \pm I_{2+}) \tag{20}$$

Fig. 5(a) shows the variation of the current at the switching instants as a function of the firing delay angle when the reactive power is fully compensated to give



(a) PF=1



(b) PF=0.8

Fig. 5 Peak current variation with firing angle nity power factor seen from the lines. The thick line indiates the peak APF filter current. The peak current may each $1+\sqrt{3}/2\pi$ or 1.28 times the dc output current of he thyristor converter at $\alpha = 60°$. which corresponds to .3 times the base current rating.

When the reactive power is partially compensated to ;ive resultant power factor less than unity, the peak curent characteristics changes, as shown in Fig. 5(b). It hould be noted that the reactive power compensation is ıecessary only when the resultant power factor is greater han the displacement power factor, that is, over the range vherein $PF > \cos\alpha$, as indicated by the dotted boundary ine in the figure. It is interesting that the boundary coinides the crossing point of $-I_{1-}$ and $-I_{2+}$ curves. This :an easily proved by equating (14) and (17), which yields $k = 1$ or $PF = \cos\alpha$.

As can be observed in the figure, the partial compenation clearly reduces the peak current level. If I_d is naintained constant at its rated value over the entire range of firing angle, however, the peak current always exceeds he base rating of the APF. The reactive power compensaion is possible only when the converter draws less voltampere than rated. In particular, if the dc output current level decreases as the firing angle increases, and its profile can be drawn as in Fig. 6(a), the reactive compensation limit, or achievable maximum power factor that does not exceed the APF rating can be determined as shown in Fig. 6(b). In Fig. 6(b), the APF is assumed to be rated at the base rating. The monotonically increasing solid line represents the reciprocal of the curve in Fig. 6(a), which gives the APF current limit in per unit. In general, the limit curve is expected to lie under the dotted line that represents the pure resistive load of the thyristor converter, being inversely proportional to the cosine of the firing angle. From the figure, the peak APF current curve that meets the given limit curve can be determined. and the associated power factor will be the maximum achievable power factor that can be maintained over the entire range of converter operation.

To obtain the maximum achievable power factor when the load converter is partially loaded, the APF is assumed to be designed at its base rating. Fig. 7 shows the theoretical limit of the power factor improvement for various firing angles. Analysis shows that the load current level is divided into three ranges: For the per unit converter current less than 0.42, it is always possible to get the unity power factor. For the per unit converter current greater than 0.42 and less than 0.707, the maximum power factor is determined by I_{2-} . And for the converter current greater than 0.707 pu, it is determined by I_{2-} or either one of I_2 or $-I_{1-}$, according to the firing angle and converter current level, which causes the breakpoints in the curves for the firing angle of $30°$ and $45°$. The breakpoint does not appear in the curves for $\alpha > 60°$.

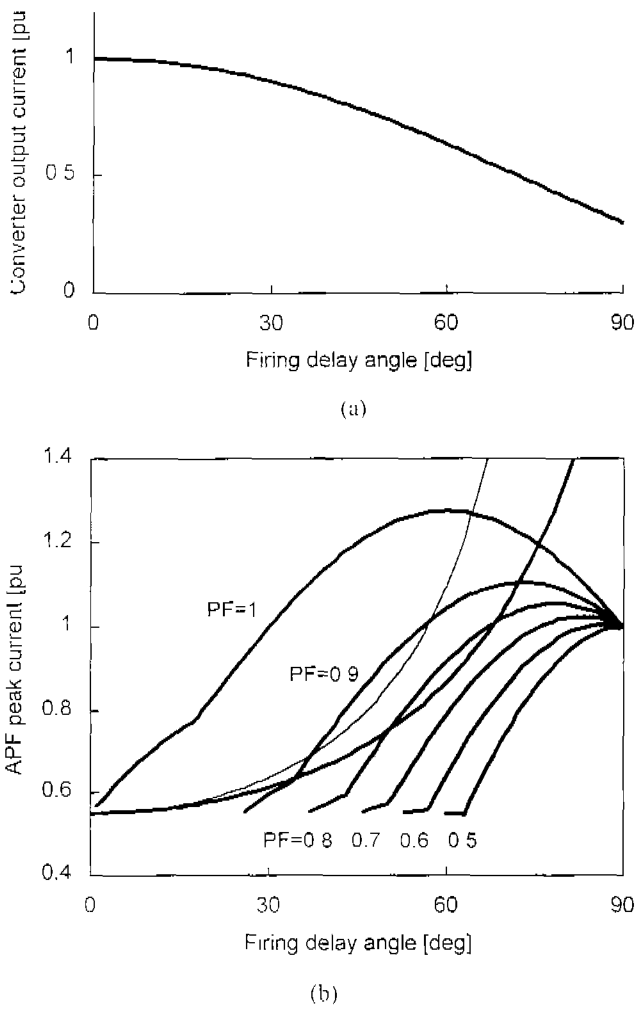


Fig. 6 load current profile and APF peak current

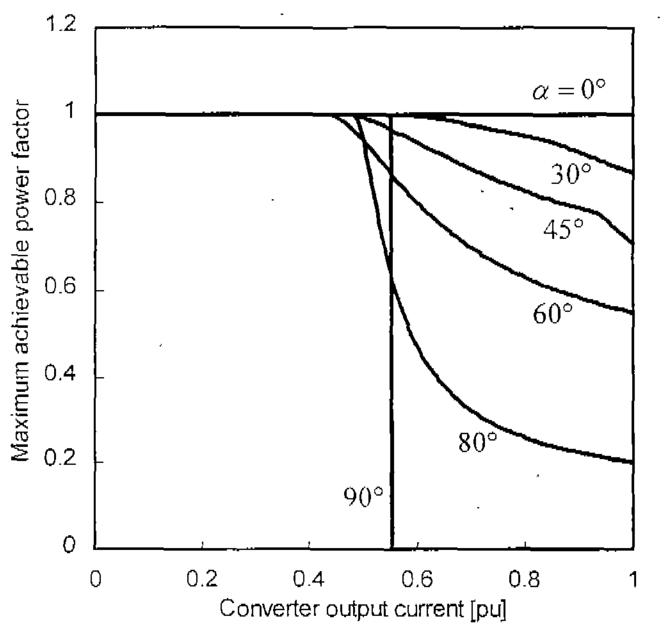


Fig . 7 Maximum achievable power factor with APF for partially loaded load converter

4. LIMITTING THE APF PEAK CURRENT

Most shunt APF operates with high-speed current feedback that gives inherent current limiting ability. This can be deliberately used in order to limit the peak current of the APF. As can be observed in Fig. 2, the APF current is usually accompanied by repetitive narrow peaks. Thus it is expected that cutting out the sharp peaks does not seriously affect the performance of the APF.

The current limiting can be implemented with the hardware or the control software. In either way, it should be recognized that the phase current of a three-phase APF power circuit cannot be limited independently–limiting the current of one phase causes the deterioration of the currents of the other phases. Following discussion assumes the software implementation.

The current limiting can be represented with the hexagon shown in Fig. 8. Each side of the hexagon corresponds to the positive or negative limit for three phase currents. If the space vector of the APF current command falls outside the hexagon, it is properly scaled down to be constrained within the hexagon, as shown in Fig. 8. Fig. 8 assumes that the current vector is in the region I, one of the six regions divided by dashed lines. In this case, the q- and d-axis components of the adjusted current vector are represented by

$$
\begin{aligned}
i'_{Iq} &= I_{limit} \\
i'_{Id} &= \frac{i_{Id}}{i_{Iq}} i'_{Iq} = -\frac{1}{\sqrt{3}} \frac{i_{Ia} + 2i_{Ib}}{i_{Ia}} I_{limit}
\end{aligned}
\tag{21}
$$

where non-dashed variables represent the quantities before adjust. Converting the dq quantities to phase quantities yields

$$
\begin{aligned}
i'_{Ia} &= I_{limit} \\
i'_{Ib} &= \frac{i_{Ib}}{i_{Ia}} I_{limit} \\
i'_{Ic} &= -i'_{Ia} - i'_{Ib}
\end{aligned}
\tag{22}
$$

Similar relationships can easily be derived when the current vector is in the region other than the region I, and they are not given here.

Fig. 9 shows a waveform under current limiting. As can be seen in Fig. 9, the current limiting causes residual harmonics in the line current. The IEEE standard allows the total harmonic distortion of the line current to be 5% when the short circuit ratio is less than 20, and up to 8% when the short circuit ratio is less than 50 [5]. An example of the effect of the current limiting is shown in Fig. 10 wherein the current is limited to 70% of the base current rating. The figure clearly shows that in spite of significant decrease of the APF current rating, the residual harmonic distortion remains well within the allowable limit, over the entire range of the converter's firing delay angle.

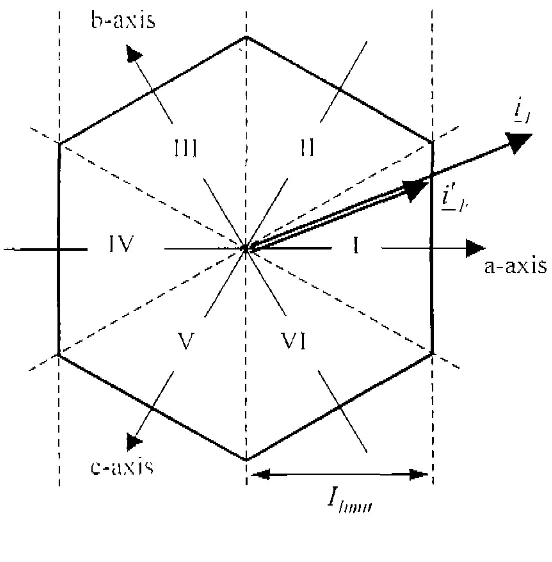


Fig. 8 Current limiting

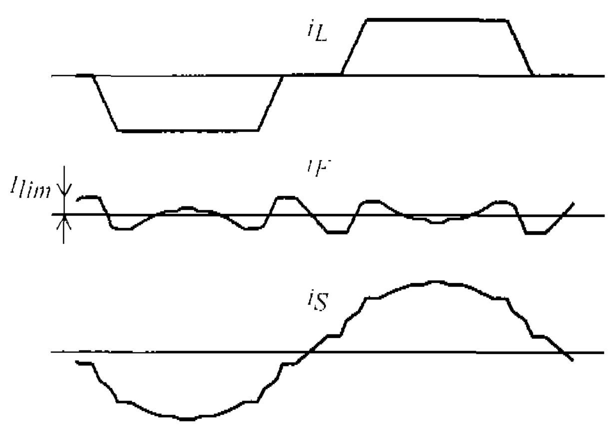


Fig. 9 Limited current waveforms

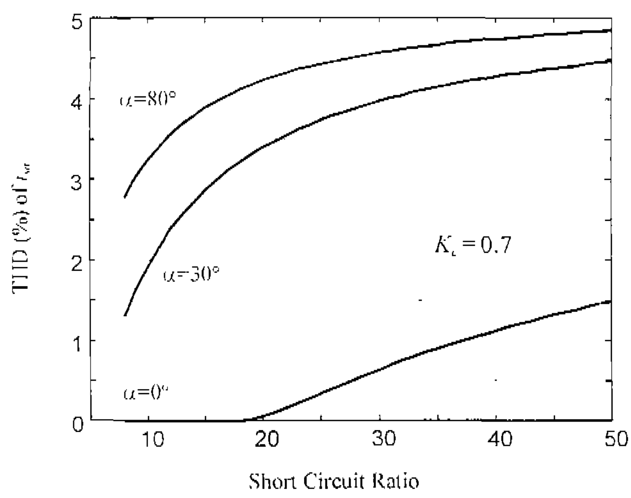


Fig. 10 THD of line current with current limiting

5. CONCLUSION

The thyristor converter is one of the most frequently met applications of shunt APFs. For complete cancellation of the harmonic current generated by the converter, the APF is required to have 55% of the dc current rating of the converter. The waveform improvement due to the line side inductance does not show considerable effect on the required capacity of the APF.

When the APF is used for reactive power compensation, in addition to the harmonic compensation, the required capacity further increases, even resulting in a larger current rating of the APF than that of the load converter. When the load converter is partially loaded, however, the reactive power compensation is possible to give an additional advantage of the shunt type APF. Analysis carried out in this paper gives achievable maximum power factor as a function of the converter load current, which shows that when the converter operates below about 40% of the rated load the unity power factor operation is always possible with the APF of the base current rating.

The concept of current limiting is introduced and the impact of the current limiting of the APF on the residual harmonic characteristic is evaluated. Theoretical investigation shows that a considerable saving in the capacity of the APF is possible while not exceeding the allowable line current distortion limit.

REFERENCES

[1] L. Gyugyi and E. C. Strycular, "Active ac power filters," in Proc. IEEE-IAS Annual Meeting, pp.529-535, 1976.

[2] H.Akagi, N. Nabae, and S. Atoh, "Control strategy of active power filters using multiple voltage-source PWM converter," IEEE Trans. on Industry Applications. vol. IA-22, no. 3, pp.460-465, May/June 1986.

[3] B. Acharya, D. M. Divan, R. W. Gascoigne, "Active power filters using resonant pole inverters," IEEE Trans. on Industry Applications, vol. IA-28, no. 6, pp.1269-1276, Nov./Dec. 1992.

[4] F. Z. Peng, H. Akagi, and A. Nabae, "A New Approach to Harmonic Compensation in Power Systems", IEEE/PESC, 1988.

[5] ANSI/IEEE Std. 519-1981, IEEE Guide for Harmonic Control and Reactive Power Compensation of Static Power Converters