SIMULTANEOUS COMPENSATION OF REACTIVE AND HARMONIC COMPONENTS OF LINE CURRENT USING SUPERCONDUCTING MAGNET ENERGY STORAGE

by

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A Thesis

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of

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JUNE,1996

DEDICATED TO :

MY GRANDFATHER

WHOSE BLESSINGS INSPIRE ME FOREVER

DECLARATION

I hereby declare that this thesis work has not been submitted elsewhere for the award of any degree or diploma or publication.

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CONTENTS

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ABSTRACT

A simple on-line compensation scheme to compensate the reactive, harmonic and sub-harmonic components of line current is proposed in this thesis. The on-line compensation scheme is based on the fact that if a current of equal amplitude but 180 degrees out of phase with respect to the reactive, harmonic and sub-harmonic components is injected in the line then these components will be eliminated. Aimed toward this scheme a closed loop feedback control circuit has been proposed to estimate the combined waveshape of the reactive, harmonic and sub-harmonic components of line current. The approximation of this estimated wave by some available functions such as pulse width modulated wave and the stepwise function using power electronic switching circuit is also studied in this work. The study reveals that the compensation using step-wise approximation provides better performance than the approximation using pulse width modulated wave. This work proposes a power electronic switching scheme using superconducting magnet energy storage (SMES) to inject current in the line based on the estimated wave and step-wise approximation to compensate the reactive, harmonic and sub-harmonic components of line current. This thesis also includes the performance study of the proposed switching scheme using computer simulation program.

LIST OF FIGURES

Figure no.		**Title of the figure**	**Page no.**
Fig. 3.6	:	The difference between actual and estimated values of the compensating current.	35
Fig. 3.7	:	Variation of I_G with time for first 5 cycles.	37
Fig. 3.8	:	Variation of I_G with time at steady state.	38
Fig. 4.1	:	Schematic diagram of the SMES based compensation scheme.	40
Fig. 4.2	:	Switching scheme used to inject compensating current in the line.	42
Fig. 4.3	:	Schematic of the steps used in step-wise approximation.	43
Fig. 4.4	:	Time response of the SMES current.	48
Fig. 4.5	:	Switching sequence for the injection of SMES current.	50
Fig. 4.6	:	Harmonic components of the line current after compensation.	53

LIST OF TABLES

LIST OF ABBREVIATIONS

ACCD	AC Current Detector
ACVD	AC Voltage Detector
RMS	Root Mean Square
GC	Gain Controller
SMES	Superconducting Magnet Energy Storage
GTO	Gate Turn Off
LPF	Low Pass Filter
PWM	Pulse Width Modulation
PCS	Power Conversion System

CHAPTER 1

INTRODUCTION

In recent years, power electronics has consistently enjoyed rapid progress. There are two underlying reasons for this. The first is related to the ever widening field of applications. Increasingly, power is provided in a form adapted to suit a particular use. The second stems from the improvement in power semiconductor performance and the arrival of new components designed to meet specific requirements. With this increasing use of semiconductor power electronic devices the harmonics contents of a power system may reach an objectionable level. From the point of view of the supply system, the power electronic converter constitutes a non-linear load: when sinusoidal voltages are applied, it draws non-sinusoidal currents. It may be regarded as a harmonic current generator. Each harmonic current propagates in the power system like any other alternating current. The harmonic current has many adverse effects on a supply system as follows:

- Cause additional rotor and stator losses, reduce the output torque and increase the noise level in the rotating machine

- Increase the losses in the capacitors and may cause abnormal heating effects.

- Can produce malfunctions in control system by displacing the zero crossings of the voltage waves.

•Accelerate the aging process in lighting equipment using fluorescent lamps.

• May cause measuring and metering error.

Disadvantages of the presence of reactive component of line current on the utility are as follows:

•Increased KVA rating of the generators and transformers.

•Increased Cu-loss and reduced efficiency.

•Increased conductor size.

•Poor regulation due to the increased voltage drop.

•Increased burden on the installed equipment capacity.

To get rid of these adverse effects of harmonic and reactive currents we have to eliminate them. Recently much attention has been paid on the control of reactive component as well as the active component of line current in a power system. This thesis is directed towards an integrated approach to simultaneous compensation of reactive and harmonic components of line current in a power system using superconducting magnet energy storage.

1.1 Literature survey :

In the process of power conversion, rectification, inversion etc. , harmonics and subharmonics are produced on both side of the converter system. Harmonic filters consisting of passive elements are used to reduce these undesirable current harmonics. The filters, however, suffer from several disadvantages such as the requirement of large size inductor and capacitors which is a function of frequency. Some authors have dealt with solutions to some of the disadvantages of the filters[1-4].

A new method of reducing current harmonics on ac side of a converter has been proposed by Ametani [5] to modify the current waveform on the dc windings of the converter transformer by injecting a harmonic current at a particular frequency. The injected currents flow through the closed circuit which consists of a current source and dc windings and thus the original current waveform on these dc windings is deformed by the injected current. By deforming the current waveform to a suitable shape, the harmonics components of the current on the ac system are reduced. This method has been applied to a thyrister converter [6] where the third harmonic currents of the power frequency are used as the injecting currents.

The current harmonics resulting from converter operation can be greatly reduced by injecting appropriate currents in the secondary (converter side) winding of the converter transformer. A practical implementation of this principle described in a paper by Arrillaga et. al [7] , uses ripple of the rectified voltage and a single-phase feedback converter to drive the appropriate injection currents. This scheme constitutes a considerable improvement over previously described current injection technique using external sources. As compared with harmonic elimination by tuned filters, in this proposed scheme harmonics are reduced within the converter, thus avoiding the risk of resonance between the filters and as system impedances, furthermore the reinjection scheme is always locked to the system frequency avoiding problems within filter detuning.

Simultaneous control of active and reactive powers of the power system has been and still is the subject of numerous publications. In a paper by Ise et. al [8] the instantaneous control of active and reactive components has been described using SMES. An SMES, utilizing a superconducting coil as an electric energy storage element, is effective for ac power system stabilization because it provides fast response characteristics in charging and discharging electric power. Such an SMES consists of power converters and a superconducting coil must be able to regulate active and reactive powers flowing to it from ac power lines by firing angle control of the converters. Application of gate turn off converters to an SMES provides faster response and a wider range of power control characteristics. Moreover, pulse modulation control of GTO converters is effective in reducing the magnitude of the ac current harmonics of the SMES. In a recent paper by Shirahama et. al [9] a new type of gate pulse generator for GTO converters is presented which provides quick response firing angle control and PWM control. Using this gate pulse generator an instantaneous control method of active and reactive power using SMES has been proposed. In this method the harmonic contents is not taken under consideration and it may reach an undesirable level due to the control of active and reactive power by this method. But no integrated approach has been suggested to reduce these harmonics.

By virtue of its importance, the question of harmonics transmitted to the ac supply system by power electronic devices has been and still is the subject of extensive research. For this work the most importants are taken and they have been divided into three categories : (1) calculation or measurement of the harmonic values (2) propagation of harmonics in the ac system, the effects of capacitors and filters (3) unwanted effects of harmonics. Two aspects of the problems with harmonics is dealt in different publications. The first is that of the uncharacteristic harmonics. In addition to the harmonics for three phase supply, harmonic analysis of the currents actually supplied by the source to a converter shows that other harmonics are present. In general these 'uncharacteristic' harmonics [21-23] due to the imperfect nature of the source and converter are relatively small. They are mainly attributed to the following factors :

(1) The unbalance of the ac supply voltage and in some cases, the waveform distortion of these voltages.

(2) Inequality of triggering delay angles due to imperfections of control signal generator

The second is that of harmonic reduction by injecting harmonic currents of suitable value and phase which cancel out those present in the system. As the current injection technique is effective to eliminate the harmonics present in the system it must also be effective to compensate the reactive component of line current in the system. But so far, no integrated approach has been taken to compensate the reactive component of line current using current injection technique thus reducing the effective value of the current and improving the system power factor. In this thesis an integrated approach has been proposed to simultaneous compensation of the reactive and harmonic components of line current in a power system. Because of its fast response characteristics in charging and discharging electric power [10-12] a SMES, utilizing a superconducting coil as an electric energy storage has been used to generate the current to be injected in the system for compensation.

1.2 Thesis objectives:

With the consistent progress of power electronics in recent decades, the harmonic contents of a power system may reach an objectionable level. High level of harmonic contents of the power supply system is unacceptable because of their adverse effects. Power system should supply a near-sinusoidal waveform with a total rms harmonic content of not more than 5% and with no individual harmonic component greater than 3% of the fundamental value [24]. In other cases the requirements may be less stringent, none the less important. The means whereby the harmonic content can be obtained within the necessary limits represents a very important aspect of power system. Usually in order to reduce the harmonic contents of the line current of a power system the selective harmonic reduction technique is used. Phase multiplication and phase modulation techniques are also used to reduce the harmonics to an appreciable level in some cases. But no integrated approach has been taken to eliminate the harmonics of the line current of a power system. Moreover, much attention has been paid to control the reactive component of line current, another component which leads to poor system power factor. This thesis is directed toward the simultaneous compensation of reactive and harmonic components of line current of a power system by injecting current of suitable amplitude and phase. Aiming toward the design of this control scheme, a closed loop feedback control system has been designed to estimate the reactive, harmonic and subharmonic components of line current. A switching scheme has also been designed to generate and inject a current of suitable amplitude and phase based on the estimated combined waveshape of the reactive and harmonic components of line current. In this thesis computer simulation program has been used to study the performance of the feedback control system and the switching scheme.

1.3 Thesis layout :

Reduction of harmonic contents of line current plays an important role in modern power system. With the rapid progress of power semiconductor technology it has become easier to reduce the harmonics of line current of a power system to a tolerable level. Mathematical analysis presented in chapter 2 shows that harmonics can be compensated by injecting arbitrary waveshapes of the compensating current provided they fulfill certain criteria. Chapter 2 also includes the time analysis of several arbitrary functions and proposed function to be used is also described.

Chapter 3 proposes a closed loop feedback control circuit for the estimation of the current components to be compensated. This chapter also includes the study of the response of the feedback control circuit.

Chapter 4 proposes a schematic switching scheme consisting of inverters and driven by the SMES to inject current in the line for compensation purpose. This chapter includes the performance study of the switching scheme and also includes the verification of the improvement of the system power factor.

Chapter 5 concludes the thesis by summarizing the findings of the present work and includes recommendation for future work.

CHAPTER 2

HARMONIC COMPENSATION USING NON-SINUSOIDAL FUNCTION

2.1 Mathematical model :

The line current of a power system contains reactive, harmonic and sub-harmonic components along with the power component. The frequency of the reactive component is the same as the line frequency but harmonics and sub-harmonics are of different frequencies. To improve the system power factor and to reduce the effective value (rms value) of the line current the reactive, harmonic and sub-harmonic components are to be eliminated. Fortunately, the line inductance and capacitance are readily available to eliminate the higher order (components higher than 2KHz) components. To compensate the remaining components it is necessary to feed in the line, a current of equal amplitude but 180° out of phase. If the current to be compensated is F(t) then it is best to inject -F(t) in the line. But using power electronic circuits it is not possible to inject exactly -F(t) in the line. So, we have to use the most commonly used functions to attain a better approximation of the function F(t). This article proposes the mathematical basis of the fact that the function F(t) can be approximated by an arbitrary function $\xi(t)$ so that they contain equal low order fourier coefficients as our goal is to eliminate the lower order components (components lower than 2 KHz) .

Fourier co-efficient using open-ended integral:

Let us assume a function F(t) and mathematically define a quantity D_n as follows:

$$D_n = \frac{1}{t}\int_0^t F(\tau)e^{-jn\omega\tau}d\tau \qquad 2.1$$

keeping the integration limit open-ended.

Now, if t=T then

$$D_n = \frac{1}{T}\int_0^T F(\tau)e^{-jn\omega\tau}d\tau = C_n$$

If t>>T then t can be represented as follows (m is an integer):

$$t = mT + \Delta T$$

$$\therefore D_n = \frac{1}{mT+\Delta T}\int_0^{mT+\Delta T} F(\tau)e^{-jn\omega\tau}d\tau$$

$$\text{or, } D_n = \frac{1}{mT+\Delta T}\left[\int_0^{mT} F(\tau)e^{-jn\omega\tau}d\tau + \int_{mT}^{mT+\Delta T} F(\tau)e^{-jn\omega\tau}d\tau\right]$$

$$\text{or, } D_n = \frac{1}{mT+\Delta T}\left[mTC_n + \int_0^{\Delta T} F(\tau)e^{-jn\omega\tau}d\tau\right]$$

$$\text{or, } D_n = \frac{1}{mT}[mTC_n + \Delta T \Delta C_n]$$

$$\therefore D_n \approx C_n$$

where $mT >> \Delta T$ and $mTC_n >> \Delta T \Delta C_n$

So, the time limit can be kept open-ended without producing much error if t>>T. So, the value of D_n would be a close approximation of C_n if t>>T. As our aim is to compensate the harmonics and reactive components using on-line system so D_n will be a close approximation of C_n and for this reason the integral is kept open-ended in our analysis.

Relation between F(t) and ξ(t) :

Now, for low frequency harmonics the function F(t) can be approximated by an arbitrary function ξ(t) if-

$$\frac{1}{t}\int_0^t F(\tau)e^{-jn\omega\tau}d\tau = \frac{1}{t}\int_0^t \xi(\tau)e^{-jn\omega\tau}d\tau \qquad 2.2$$

To estimate ξ(t) let us take the integral of equation (2.1). The time limit of the integration can be divided into small time elements Δ as follows :

$$\int_0^t = \int_0^{\Delta} + \int_{\Delta}^{2\Delta} + \int_{2\Delta}^{3\Delta} + \ldots\ldots\ldots\ldots + \int_{t-\Delta}^{t}$$

Now if $\Delta << T/n$ we can write :

$$\int_{m\Delta}^{(m+1)\Delta} F(\tau)e^{-jn\omega\tau}d\tau = e^{-jm\omega n\Delta}\int_{m\Delta}^{(m+1)\Delta} F(\tau)d\tau \qquad 2.3$$

But for a time duration like Δ the function $F(\tau)$ can be replaced by $\xi(\tau)$ so that the integral of equation (2.3) remains same. So, the relation between F(t) and $\xi(t)$ is :

$$\int_{m\Delta}^{(m+1)\Delta} F(t)dt = \int_{m\Delta}^{(m+1)\Delta} \xi(t)dt$$

This is the required relation for $\xi(t)$. It is valid for low frequency harmonics and F(t) can be approximated by an arbitrary function so that they contain equal lower order fourier coefficients.

2.2 Available functions:

The waveshapes, those can be generated easily by power electronic switching are as follows:

1. PWM train of pulses
2. Step-wise approximation etc.

2.2.1 PWM Train of pulses:

The arbitrary function F(t) shown in figure 2.1 can be approximated by a pulse width modulated (PWM) wave as shown in figure 2.2. To determine the PWM wave a carrier signal (triangular wave) is taken. When the value of the function F(t) is greater than that of the carrier signal then the PWM wave will have a positive pulse and when F(t) is smaller then the PWM wave will have a negative pulse. In approximating the function F(t) with this PWM wave the frequency of the carrier and the amplitude of the pulse can be varied. It can be shown that among the harmonics present in the remaining function after compensation using PWM wave,

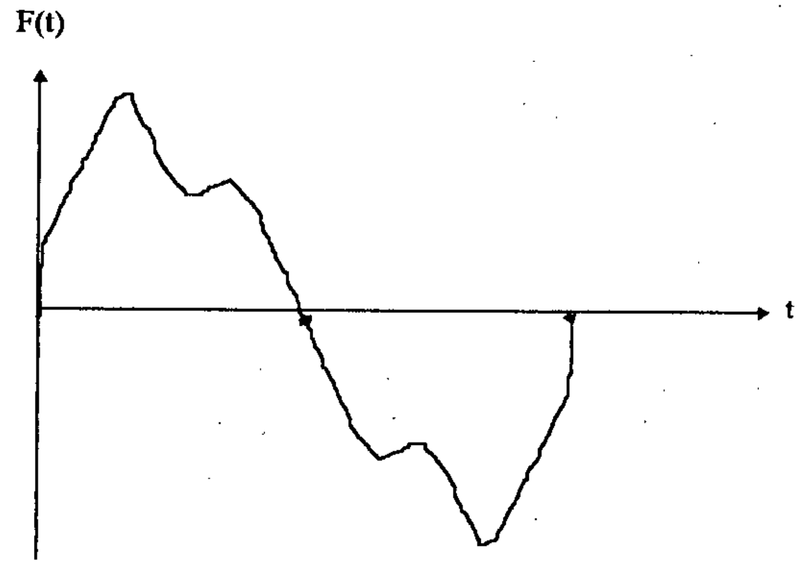

Fig. 2.1 : Graphical representation of an arbitrary function F(t).

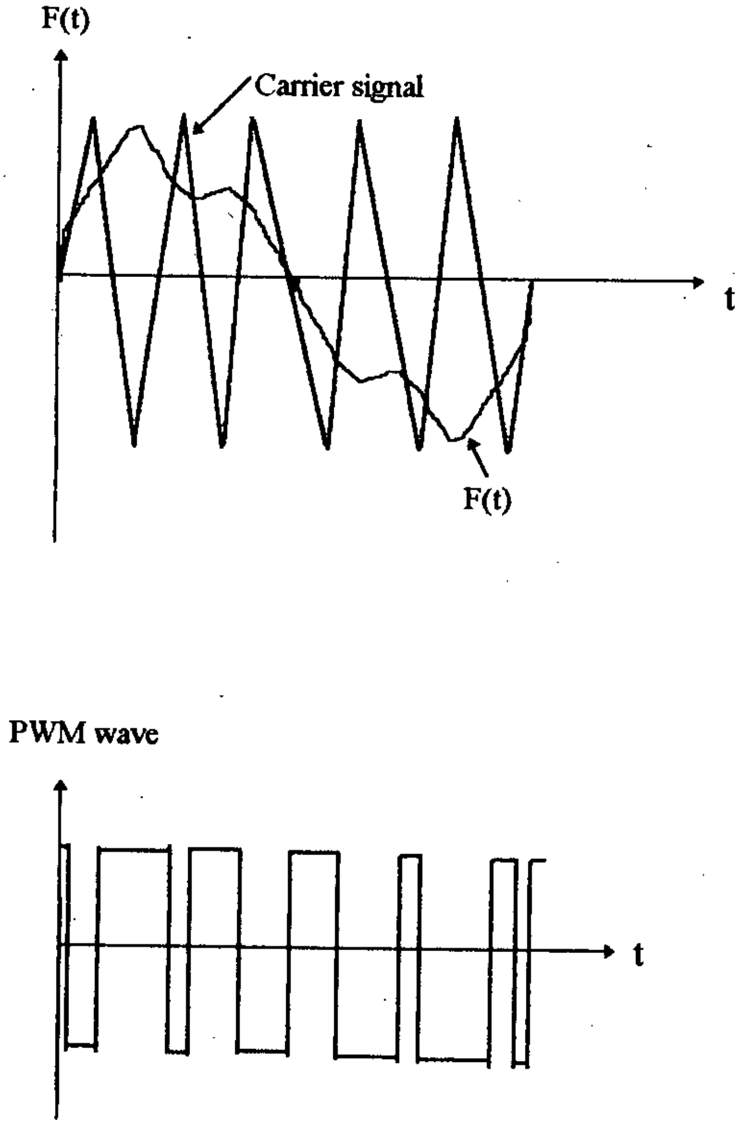

Fig. 2.2 : Graphical representation of the approximation of F(t) using PWM wave.

the harmonics of the frequency equal to the carrier frequency has the largest amplitude. So, if the carrier frequency is high then this harmonics will be eliminated automatically by the line inductance and capacitance. However if the carrier frequency is very high then the switching circuit cost to generate this carrier signal will be high, switching loss will be high and temperature of the switches may increase to an objectionable value.

2.2.2 Step-wise approximation:

A function of any waveshape can be represented by a step-wise approximation with little error so long as each step is not of such duration as to encompass an excessive variation of instantaneous value of the function. Such an approximation of the function F(t) is shown in figure 2.3. In approximating the function F(t) using step-wise approximation the number of steps and the step size can be varied. The more the number of steps the better will be the approximation. If the number of steps is very high then the cost of the switching circuit to generate the steps will be high and switching loss will be also high. Again if the stepsize can be made smaller then better approximation can be attained. However if the step size can be made variable then the approximation will be even better. In our analysis we are using uniform step size. If the value of the function F(t) crosses the midpoint of a step then the step-wise function will have the value of the next step and if F(t) is below or at the middle of a step then the approximating function will have the value of the previous step.

2.2.3: Performance comparison of PWM and step-wise approximation:

Now the performance of the above functions, available from power electronic switching, in approximating a function F(t) will be studied using computer simulation. To study the performance let us assume that a function F(t) contains the following components:

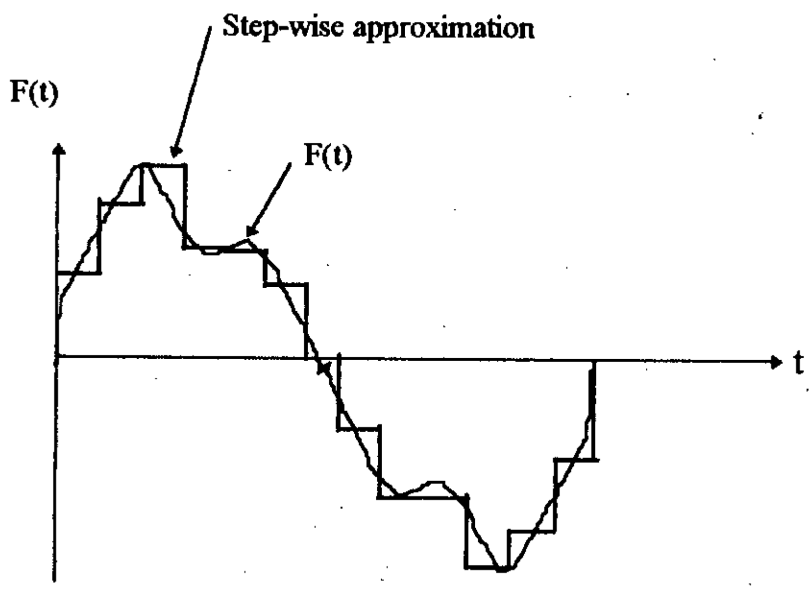

Fig. 2.3 : Graphical representation of the approximation of F(t) using stair-case function.

$$F(t) = 0.1\cos 2\pi(0.5f)t + 0.05\sin 2\pi(1.8f)t + 0.05\sin 2\pi(3f)t + 1.15\cos 2\pi ft$$

where f is the line frequency in cycles per second and the amplitudes are chosen arbitrarily. The function F(t) has been shown graphically in figure 2.4. We have to compensate the function F(t) consisting of the above components. Now the compensation performance of this function will be studied. Table 2.1 shows how the value of the function is reduced for different values of the amplitude of the PWM wave $\xi(t)$. The table reveals that F(t) is not decreased reasonably. The fact behind this is that for some positive values of F(t) the PWM wave, $\xi(t)$ has negative values and then $F(t)-\xi(t)$ will be greater than F(t). The approximation of the function F(t) by the PWM wave has been shown

Table 2.1: Approximation of F(t) using PWM wave [carrier frequency=500Hz)

	Pulse Height	$F(t) - \xi(t)$ (rms)	Actual value of F(t) (rms)
1	0.5	0.5654188	
2	0.6	0.5623140	
3	0.7	0.5760390	0.8
4	0.8	0.6054497	
5	1.0	0.7024538	

graphically in figure 2.5 using simulation program for the amplitude of the PWM wave equal to 0.5.

Table 2.2 shows how the function F(t) has been reduced after compensation using step-wise approximation with different step size. Here 8 steps has been used

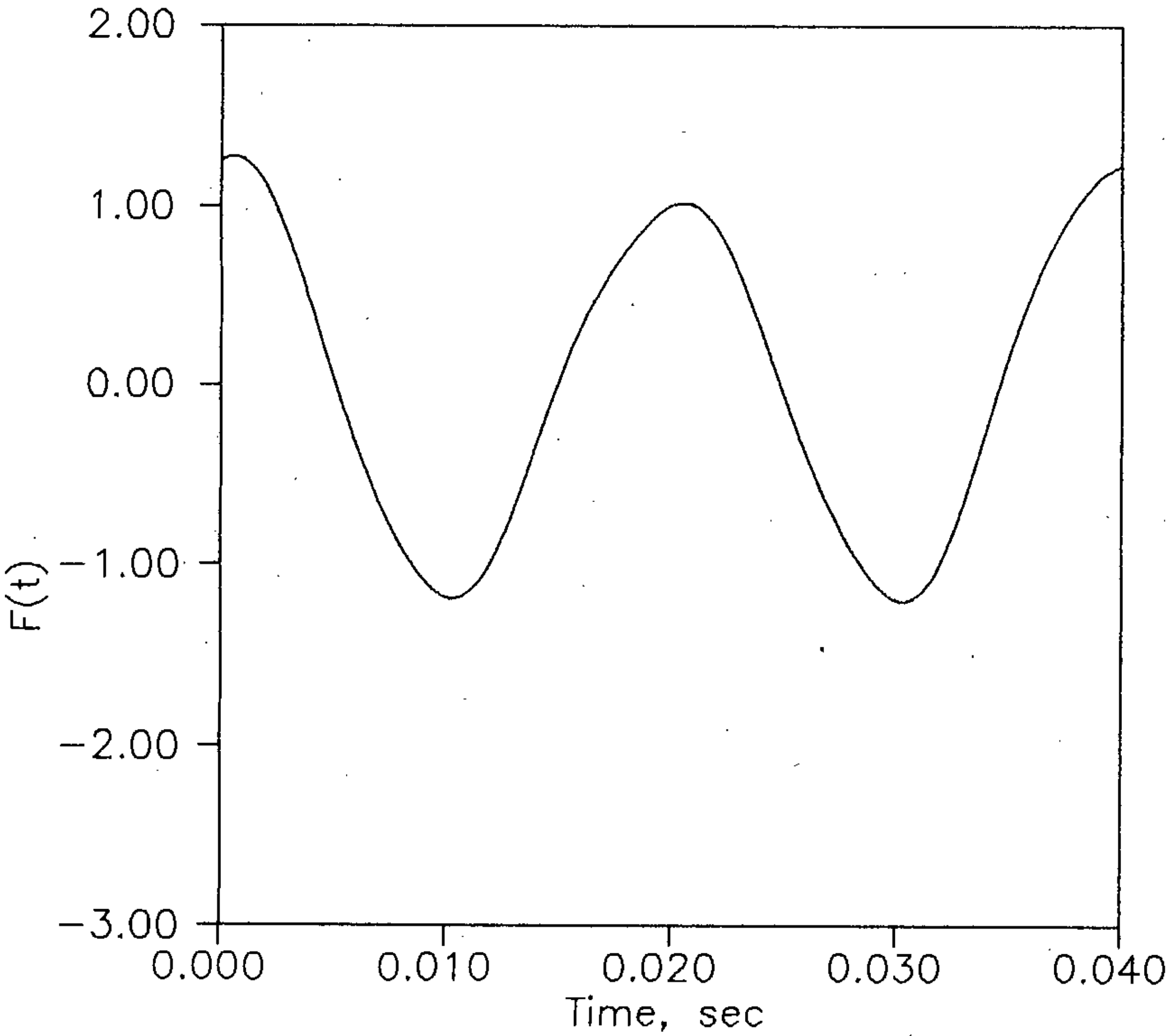

Fig. 2.4 : F(t) obtained from mathematical expression

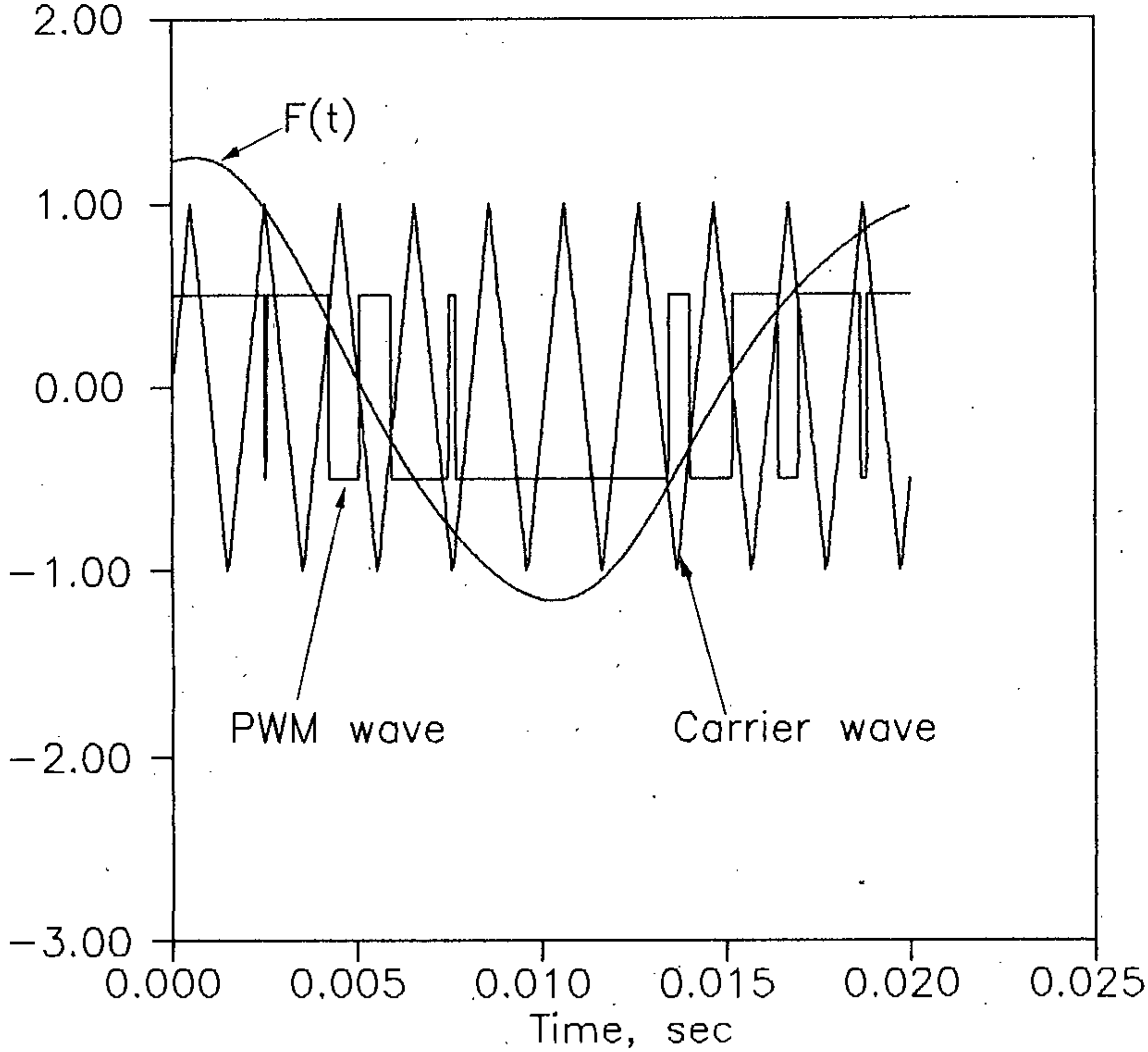

Fig. 2.5 : Approximated F(t) obtained by using PWM.

in approximating the function and the approximation using step size= 0.25 has been shown graphically in figure 2.6. A study of table 2.2 reveals that for smaller step size the reduced value of F(t) is smaller. In approximating F(t) with step-case function it has been assumed that the maximum error is half of the stepsize. So, with smaller step size error is smaller as table 2.2 reflects.

Table 2.2: Approximation of F(t) using stair-case function

	Step size	$F(t) - \xi(t)$ (rms)	Actual value of F(t) (rms)
1	0.25	0.1333410	
2	0.30	0.1444311	0.80

Figure 2.7 and 2.8 shows the function $F(t)-\xi(t)$ after F(t) has been approximated using PWM wave and the step-wise approximation respectively. It is obvious from these figures that the step-wise approximation is better and the function F(t) has decreased more due to step-wise approximation than the PWM approximation. It is also revealed from the comparison of the tables 2.1 & 2.2 that the step-wise approximation is better between the previously mentioned two schemes for the 8 steps used. It can also be mentioned here that the more the number of steps the better the approximation. Figure 2.9 shows the amplitude of different frequencies present in the function $F(t)-\xi(t)$ after step-wise approximation for step size=0.25. This figure reflects that the harmonics present in the function F(t) has been reduced reasonably.

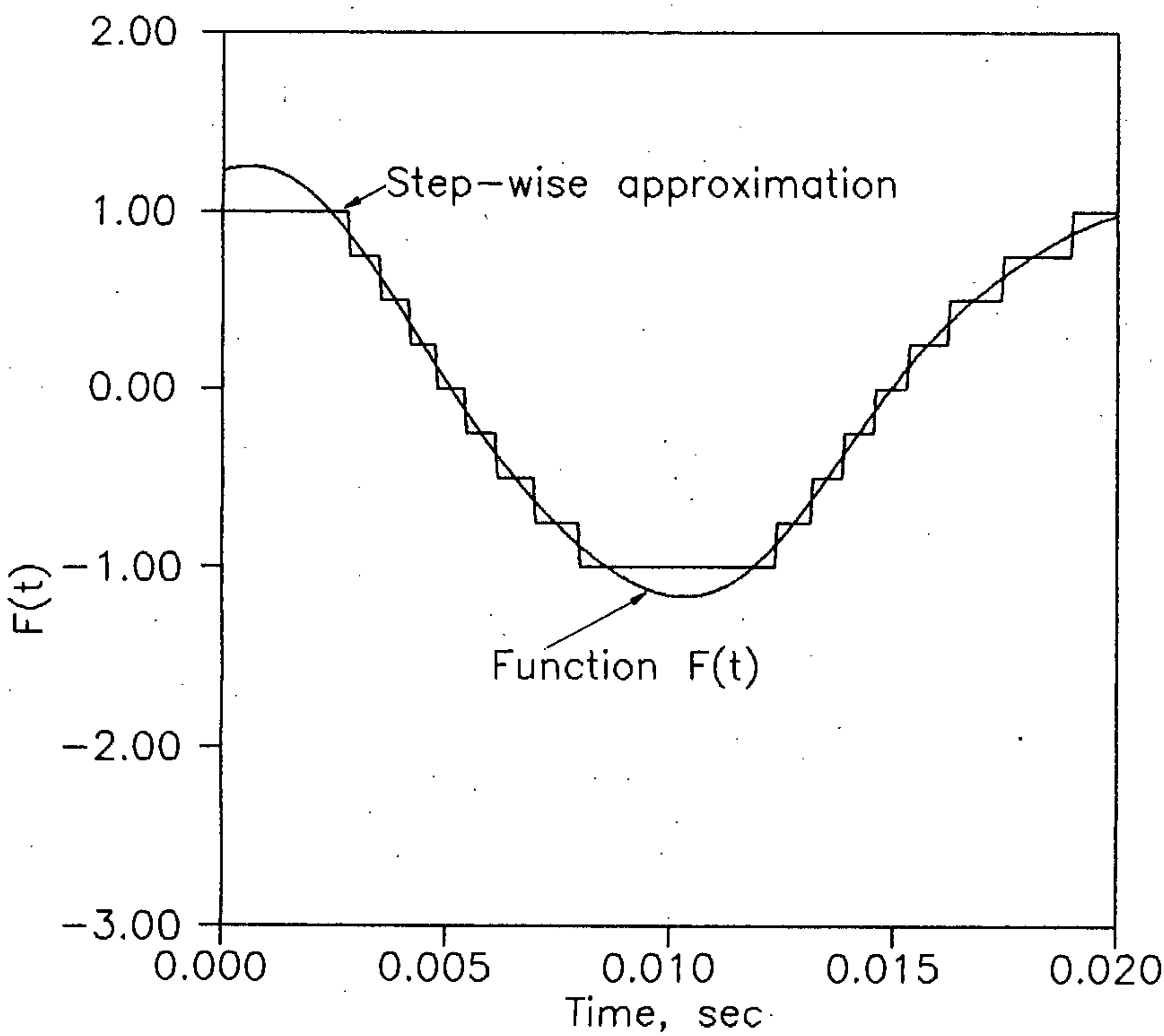

Fig. 2.6 : Approximated F(t) obtained by using step function.

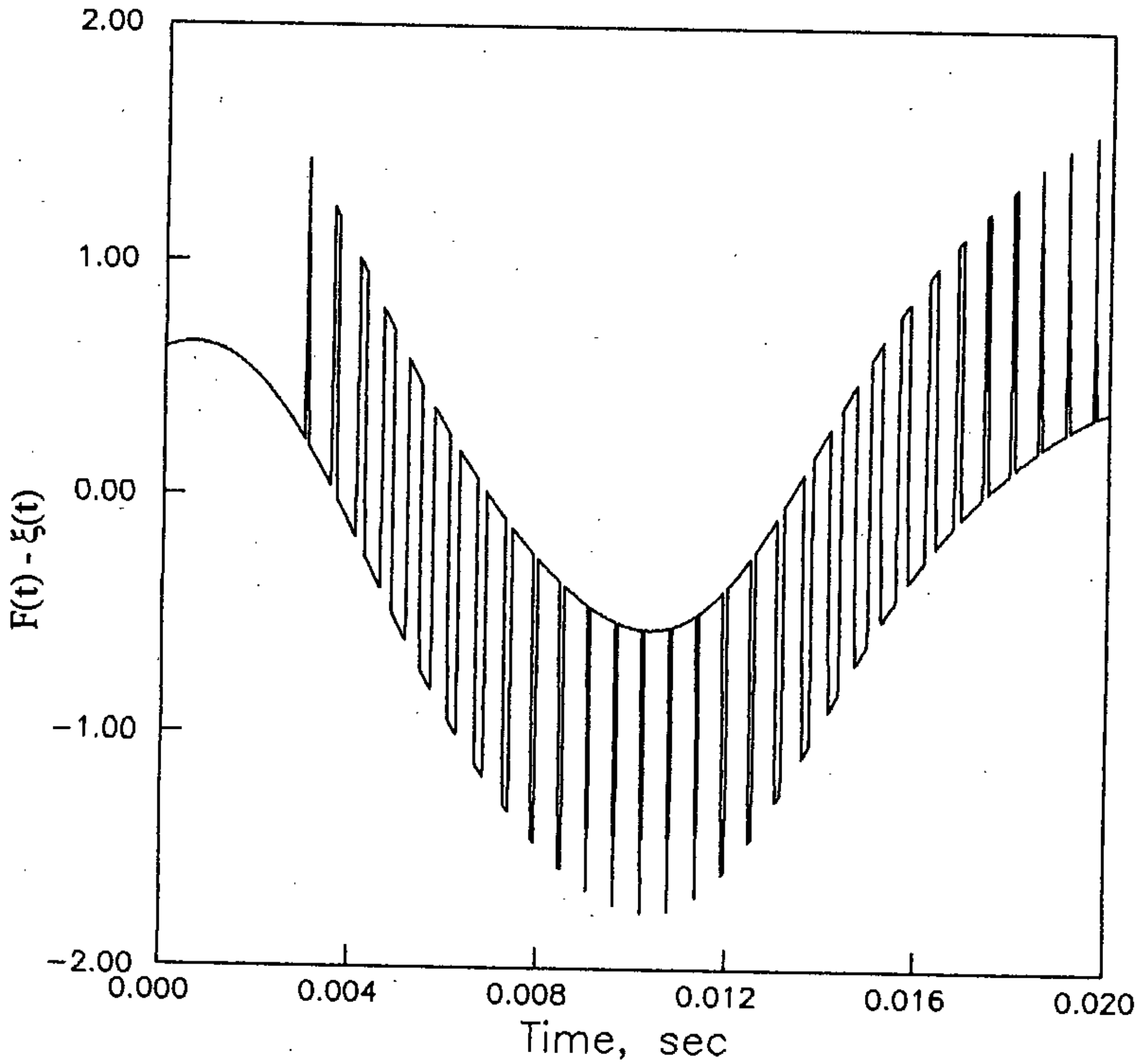

Fig. 2.7 : Time variation of the difference between F(t) and ξ(t) obtained by using PWM approximation.

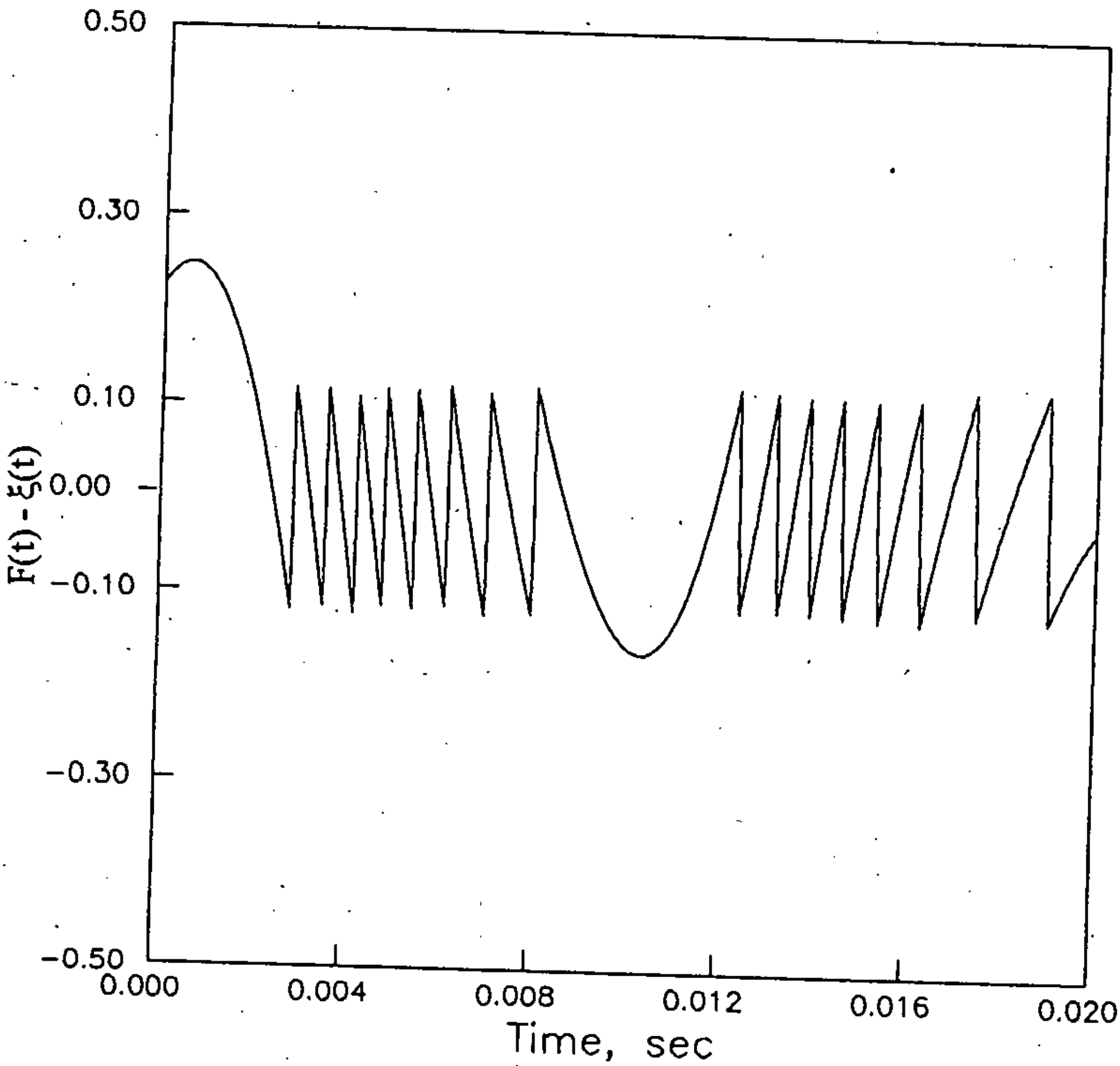

Fig. 2.8 : Time variation of the difference between F(t) and ξ(t) obtained by using step-wise approximation.

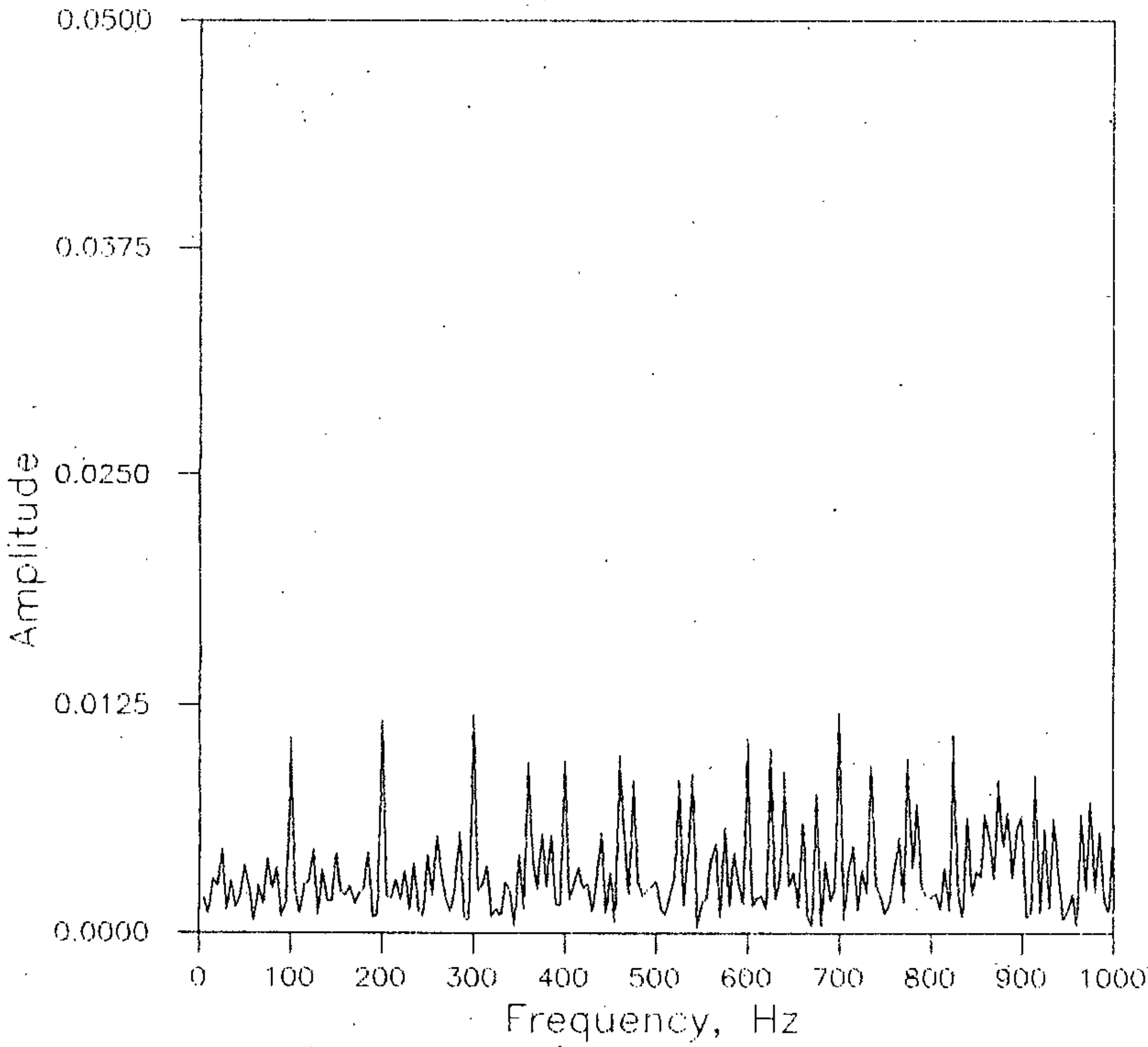

Fig. 2.9 : Harmonic content of the function F(t) - ξ(t) using step-wise approximation.

CHAPTER 3

ESTIMATION OF THE CURRENT COMPONENTS TO BE ELIMINATED

3.1.1 Block diagram of the control circuit :

The fundamental component of the current which is in phase with the supply voltage of the power system is known as power component. It is the component which carries the real power. The component of current in quadrature with the supply voltage is the reactive component of line current and the components with frequencies other than the supply fundamental frequency are the harmonic components. The reactive and harmonic components of line current do not carry mean power so long the line voltage remains perfectly sinusoidal. It is assumed that the line voltage does not contain any harmonics. Elimination of these components at first involve their estimation. This work proposes the feedback control circuit shown in figure 3.1 to estimate the reactive and harmonic components.

3.1.2 Description of the control circuit :

The feedback control circuit to estimate the undesirable components of

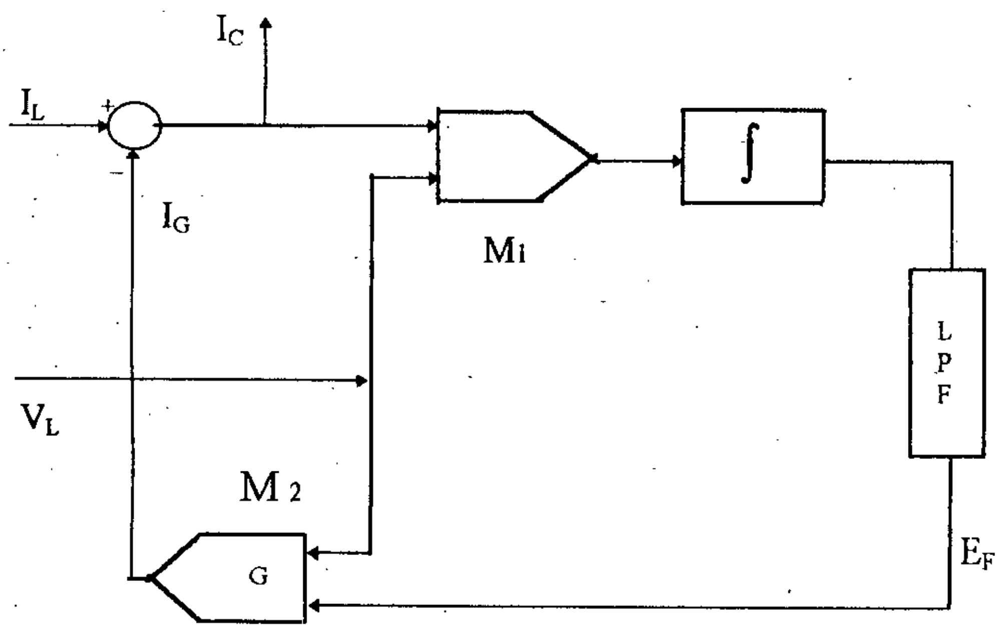

Fig. 3.1: Block diagram of the feedback control circuit.

line current consists of :

- samples of line voltage and current
- a subtractor
- two multipliers
- an integrator and
- a low pass filter (LPF)

The first multiplier, M_1 multiplies the line voltage with the line current to be compensated to find the power content. The power at the output of the multiplier is then integrated to find the energy which is then filtered out through the low pass filter LPF to find the dc component. The low pass filter, LPF, is an averaging filter. It gives the average value of the alternating quantity which is used as the input. A digital low pass filter can be represented as follows:

$$[LPF] = a(LPF) + b(I)$$

where, [LPF] = present output of LPF
LPF = previous output of LPF
I = input to the filter LPF
$a<1$ and usually around 0.9
$b<1$ and usually around 0.1

The dc component of energy is then multiplied with the line voltage, V_L by the second multiplier, M_2 of gain factor G. The gain factor, G can be varied. It can be used to attain faster or slower response of the feedback control circuit to estimate the compensating component of the line current. If G is higher then I_c will attain a value equal to the compensating current more quickly than when G is lower. With larger values of G the settling time, Ts of the feedback control system will be lower but there may appear peak overshoot in the time response of the feedback control circuit. So, with larger values of G there is some possibilities of over-compensation. The output of this multiplier I_G is then subtracted from the line current to find the components to be compensated.

Let the line voltage be a sinusoidal voltage be as follows:

$$v_L = V_L \sin \omega t$$

Then the line current can be expressed as

$$i_L = I_P \sin \omega t + I_R \cos \omega t + i_h$$

where I_P = amplitude of power component

I_R = amplitude of reactive component

i_h = harmonic component

From the block diagram :

$$I_G = GE_F V_L \sin \omega t$$

$$\therefore I_C = I_L - I_G$$

$$= I_P \sin \omega t + I_R \cos \omega t + i_h - GE_F V_L \sin \omega t$$

$$= (I_P - GE_F V_L) \sin \omega t + I_R \cos \omega t + i_h$$

Now if $I_P = GE_F V_L$ then

$$I_C = I_R \cos \omega t + i_h$$

So, if the value of E_F is such as to make $I_P = GE_F V_L$ then the output of the control circuit I_c will be proportional to sum of the reactive and harmonic components of line current to be compensated. When I_c is equal to the reactive, harmonic and subharmonic components of line current then the output of the multiplier, M_1 will be zero and the filter output, E_F will remain fixed. So, no overshoot will arise in the response of the proposed feedback control circuit. The output of the feedback control circuit gives an indication of the amplitude and waveshape of the reactive and harmonic components of the line current. It is the output based on which we have to inject a current in the line which is a good approximation of the line current to be compensated. To inject this current we shall use a power electronic circuit consisting of inverters and driven by a SMES. The injected current will be 180 degrees out of phase so as to cancel the reactive and harmonic components of line current and improve the system power factor.

3.2 Transfer function for the control circuit:

The transfer function for the control circuit can be defined as the ratio of the output current $I_c(s)$ and the input current $I_L(s)$.

Transfer function for the integrator : K_1/s ; K_1 is a gain factor

Transfer function for low pass filter : $K_2/(1+Ts)$; K_2 is a gain factor and T is time constant

Then,

$$I_G(s) = I_c(s)V_L^2(s)\frac{K_1K_2G}{s(1+Ts)}$$

Again, $I_C(s) = I_L(s) - I_G(s)$

$$\Rightarrow \frac{I_C(s)}{I_L(s)} = \frac{s(1+Ts)}{Ts^2 + s + K_1K_2GV_L^2(s)}$$

which is the required transfer function.

3.3 Response of the control circuit :

In order to demonstrate the estimation capability of the feedback control circuit we have to know the response of the control circuit. To study the time response we shall simulate the control scheme with a computer program (Appendix A) . To study the response let us assume the line voltage and the line current to be as follows :

$$v_L = \sin 314t$$

$$i_L = 0.1 \sin 157t + 0.5 \sin 314t + 0.2 \cos 314t + 0.2 \cos 628t$$
$$+0.15\sin 942t+0.1\sin 1256t+0.2\sin 1570t+0.1\cos 1884t+\ldots\ldots\ldots$$

where the compensating current consists of fundamental , sub-harmonics, higher order harmonics and the reactive component. Here,

$I_p=0.5$, $I_r=0.2$

$$i_h=0.1\sin 157t+ 0.2 \cos 628t + 0.15\sin 942t +0.1\sin 1256t+0.2\sin 1570t$$
$$+0.1\cos 1884t$$

The variation of line current, line voltage and the reactive, harmonic and subharmonic components of line current to be compensated is shown in figure 3.2, figure 3.3 and figure 3.4 respectively. As the current of the control circuit is the difference of the line current and the current to be compensated so it should be in phase with the line voltage. This is obvious from the figure 3.3 that they are in phase. Figure 3.5(a) and Figure 3.5(b) shows the actual value of current to be compensated and the estimated value of this current estimated by the control circuit. It is revealed from figure 3.5(b) that at steady state the actual and estimated values of the compensating current are same. So, it can be said that the estimation circuit reliably estimates the combined waveshape of the reactive, harmonic and sub-harmonic components of the line current. Figure 3.6 shows the difference

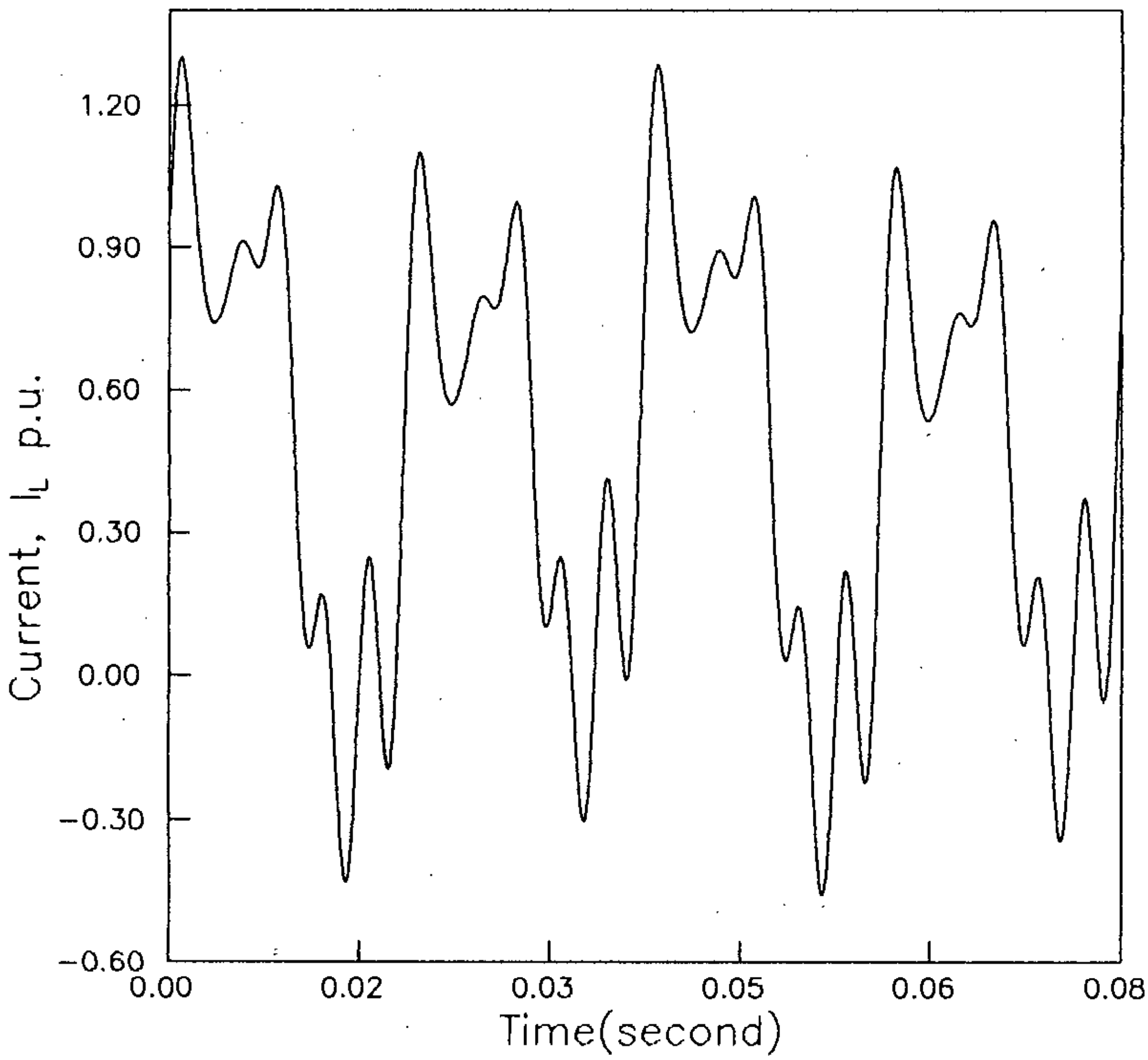

Fig. 3.2 : Schematic representation of load current I_L.

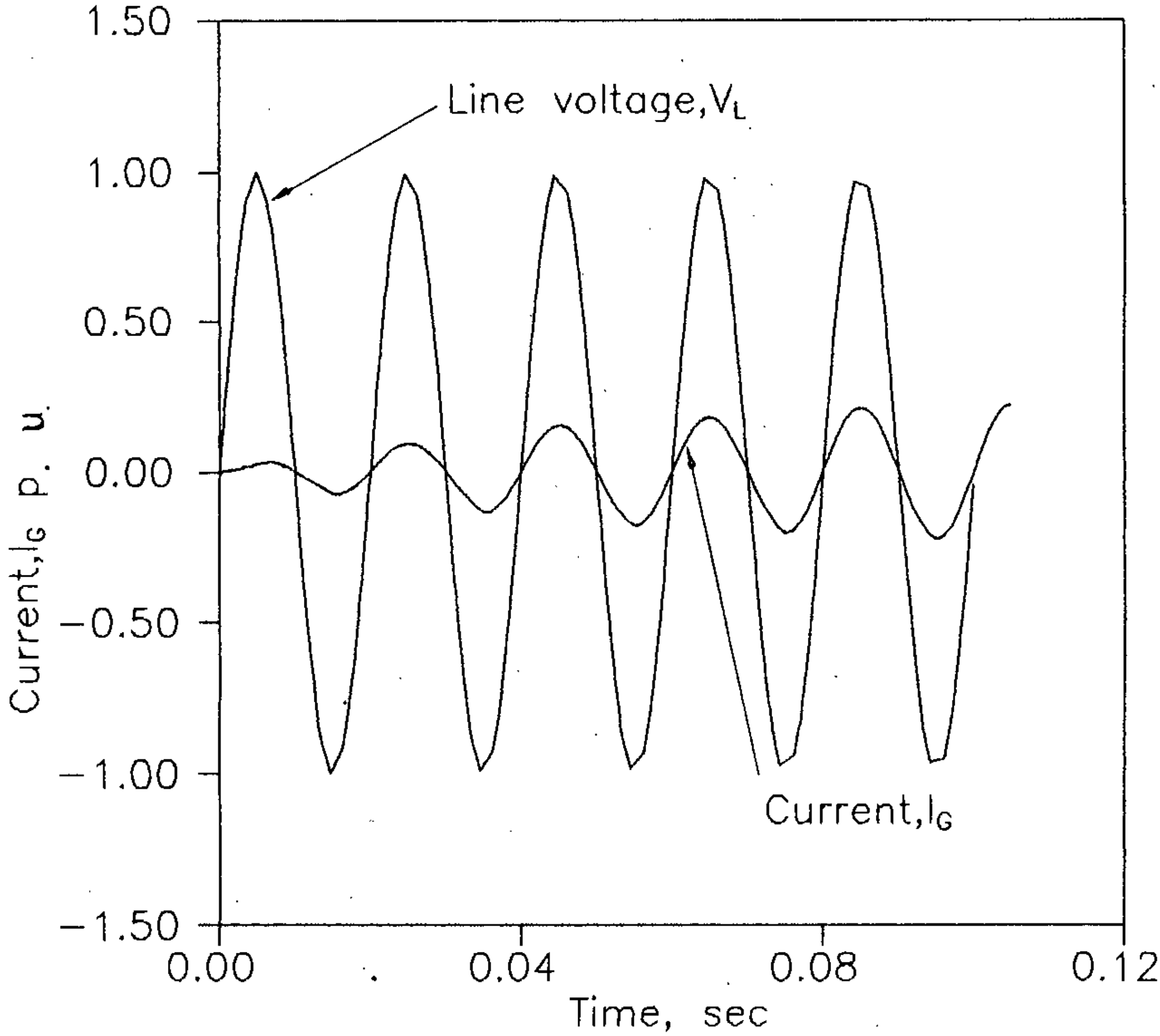

Fig. 3.3 : Schematic representation of V_L and I_G.

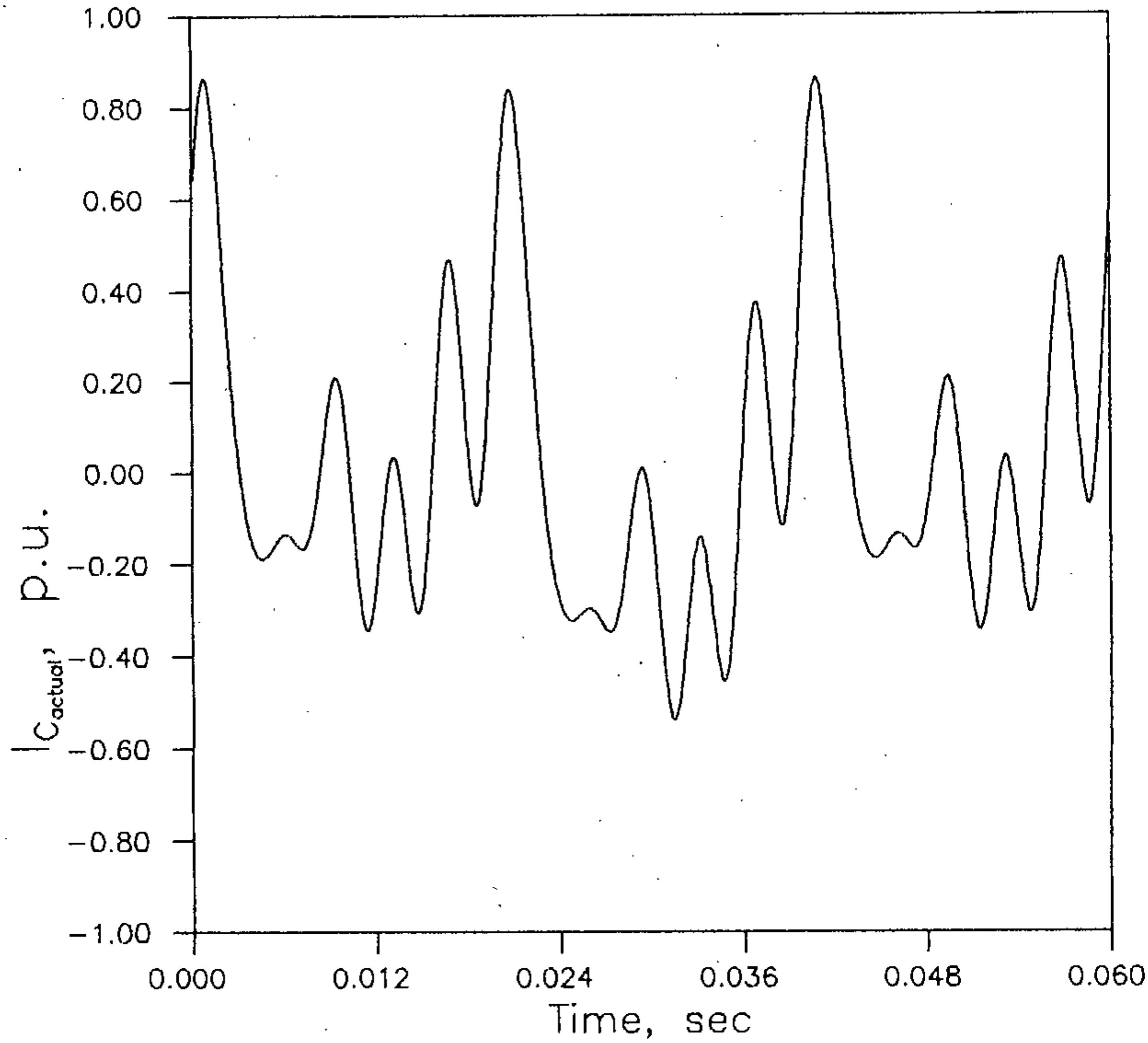

Fig. 3.4 : Actual value of the compensating current I_C.

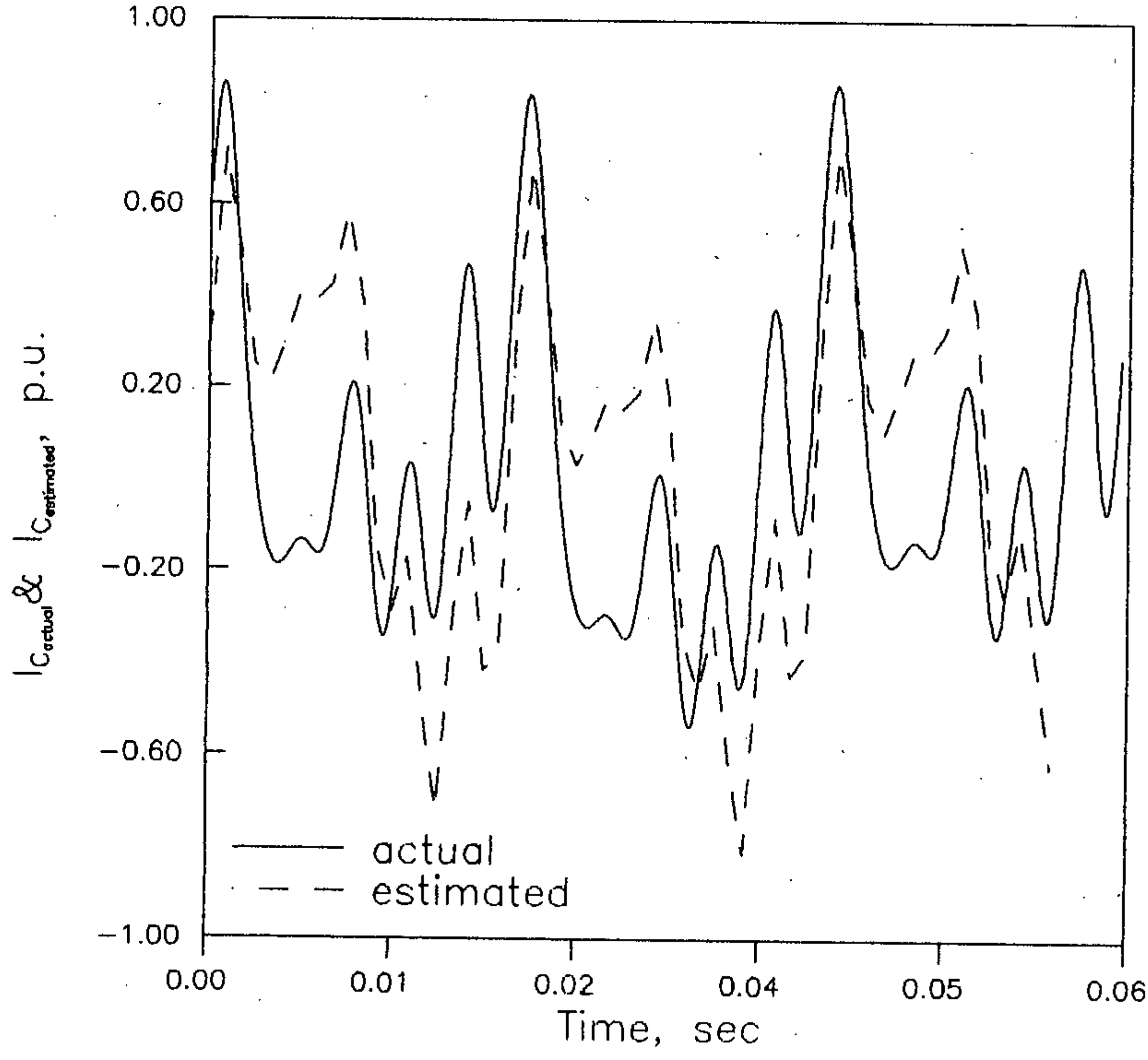

Fig. 3.5(a): Comparison between the actual and the estimated values of compensating current for the transient condition.

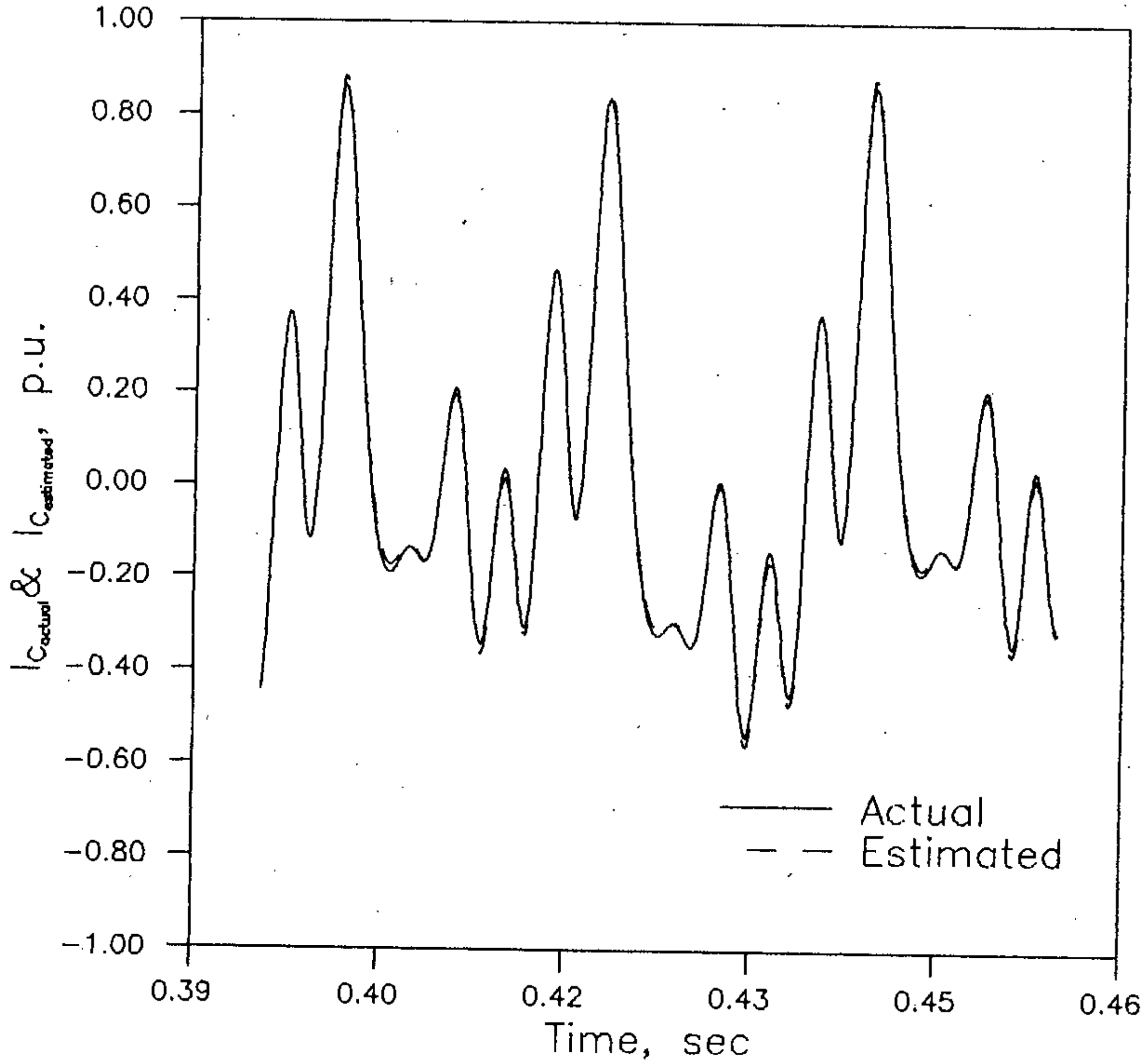

Fig. 3.5(b) : Comparison between the actual and the estimated values of compensating current at steady state.

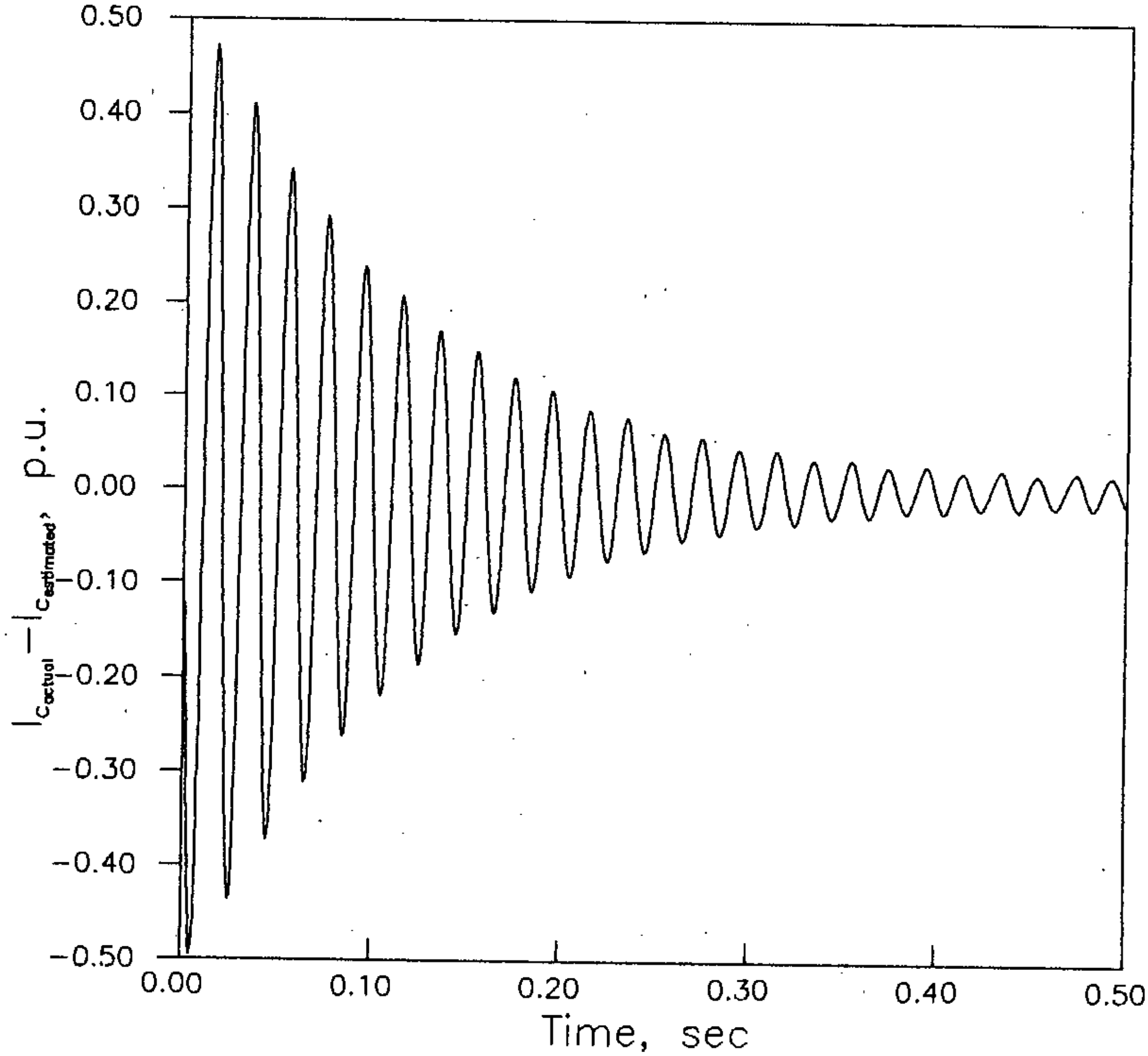

Fig. 3.6 : The difference between actual and estimated values of the compensating current.

between the actual value and the estimated value of the current to be compensated. It is obvious that the difference decreases to a reasonable value within 10 cycles.

As from the control scheme $I_C = I_L - I_G$ and I_c is the total of the reactive, harmonic and subharmonic components of line current so the current I_G will be in phase with the line voltage V_L. The variation of I_G with respect to time, t is shown in figure 3.7 and 3.8. From the figures we can conclude that the control circuit can estimate the combined wave shape of the reactive and harmonic components of the line current.

Since it is required to generate a current wave similar to the compensating current which is estimated by the control circuit described before, its time response should be first enough to follow the line current very closely. From figure 3.7 the current I_G reaches its maximum value gradually and within 6 cycles it reaches a reasonable value close to the maximum value of the current component in phase with the supply voltage. From figure 3.7 it can be calculated that the peak of the current I_G reaches 5% error margin after 6 cycles. So, the settling time of the control circuit (for the multiplier gain, G=8) is T_s = 6T sec where T is the time period of the fundamental component. Also no peak overshoot is generated.

Figure 3.8 shows that the current wave reaches its steady state value and obviously it is a pure sine wave of fundamental frequency. As we have assumed the supply voltage V_L is a sine wave so the current I_G which is in phase with V_L represents the power component of the line current. As the feedback control system designed for the estimation of compensating current is an on-line system it must be capable of working effectively under changing voltage and current because the voltage and current in a power supply system may vary frequently. From the block diagram of the feedback control system it is seen that the system is workable under fluctuating voltage and current due to its closed loop control criterion.

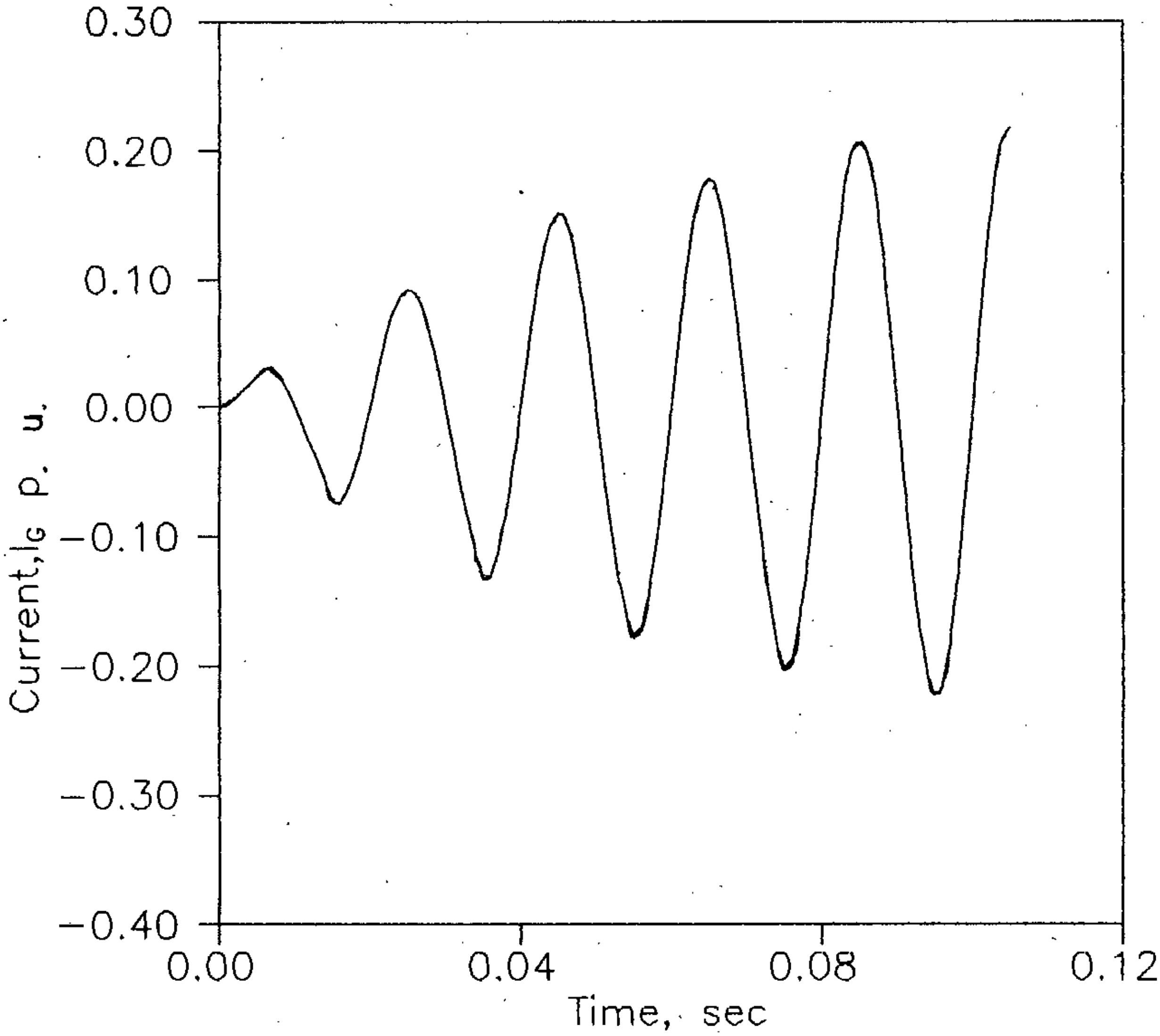

Fig. 3.7 : Variation of I_G with time for first 5 cycles.

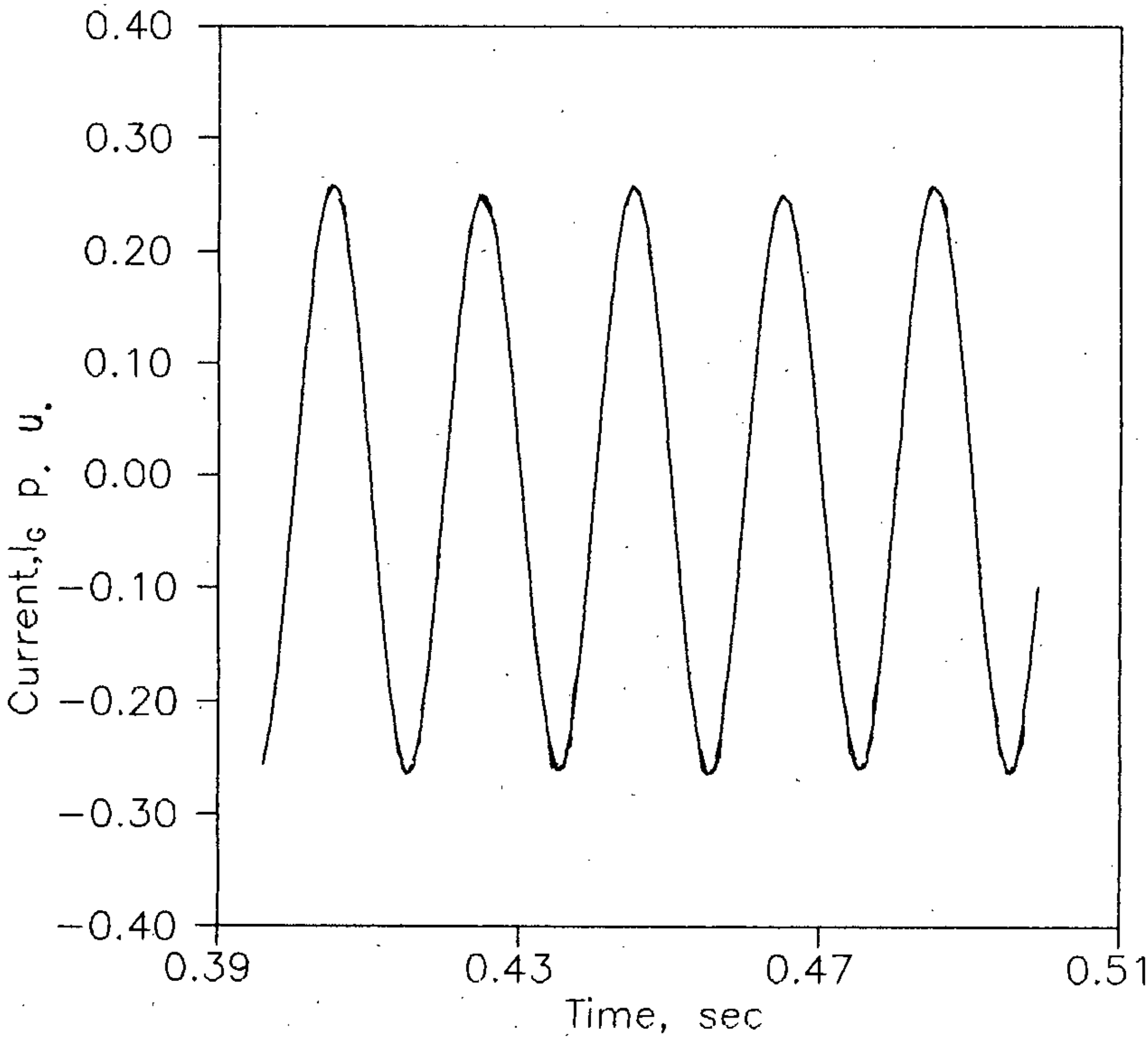

Fig. 3.8 : Variation of I_G with time at steady state.

CHAPTER 4

POWER ELECTRONIC SWITCHING SCHEME FOR CURRENT COMPENSATION

4.1 Switching scheme :

The feedback control system described in chapter 3 is used to estimate the combined waveshape of the reactive and harmonic components of the line current. The design of a power electronic switching scheme is presented here to generate a current that will be injected in the line to compensate the reactive and harmonic currents based on this estimated combined waveshape. The switching scheme consisting of a superconducting magnet energy storage and inverter circuit driven by this SMES is shown in the figure 4.1.

4.2 Description of the switching scheme :

The power electronic switching circuit proposed in this chapter to inject current in the line consists of -

- two transformers
- a SMES
- two inverters

Due to the rapid development in the techniques of high temperature superconducting materials, the application of superconducting coils become an

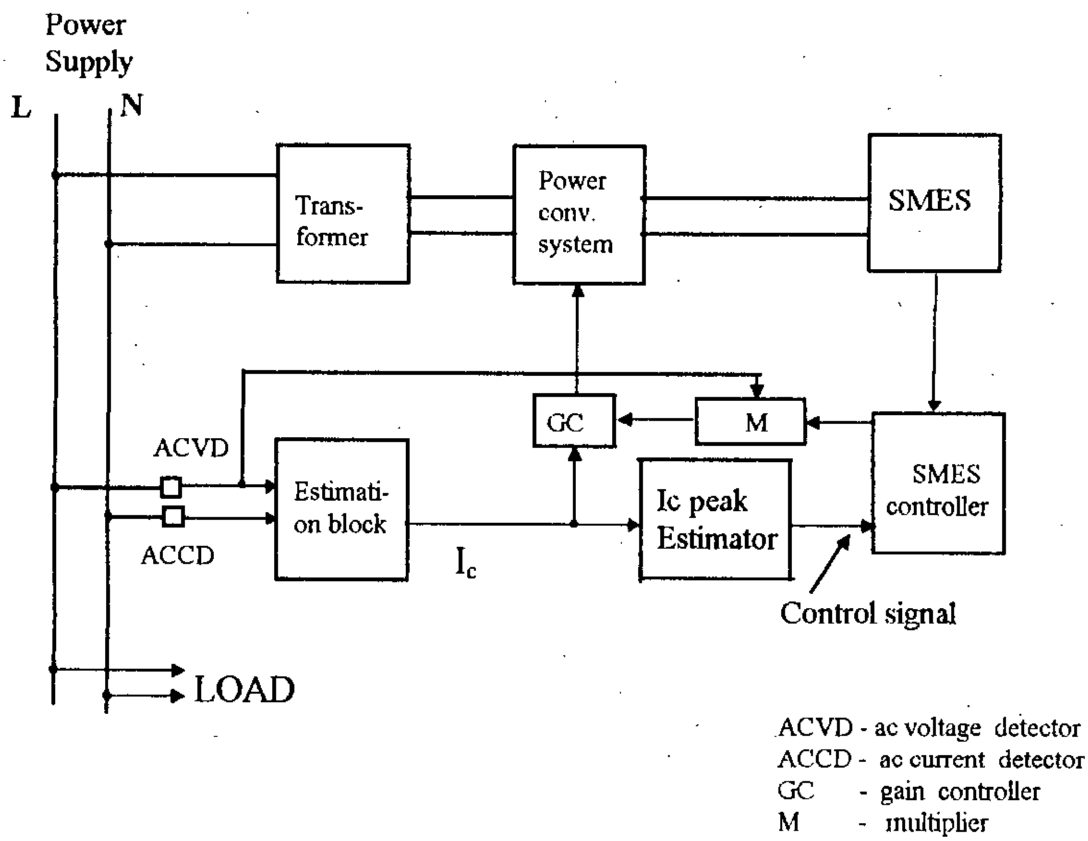

Fig. 4.1 : Schematic diagram of the SMES based compensation scheme.

important issue in electrical engineering. The SMES unit is designed to store electric power in a loss less superconducting magnetic coil. Power can be stored by or released from the coil according to the system requirement at high efficiency(>90%) [25]. The SMES is characterized by fast response and high efficiency. It has both a high power rating and storage capacity.

Fig. 4.1 shows the basic configuration of a SMES unit that can be used in a power system. The dc magnetic coil is connected to the utility grid through a power conversion system which includes two inverters. The power conversion system along with the superconducting coil is shown in figure 4.2. Once charged, the superconducting coil conducts current, which supports an electromagnetic field with virtually no losses. The inverters are driven by the superconducting magnet energy storage. The secondaries of the transformers are connected with line of the power system. The turn ratios of the two transformers are a and b. A constant current flows through the superconducting magnet energy storage and the primaries are connected in series with the SMES through the power electronic switches of the inverters. So, the current through all the primary windings are constant. Obviously the secondary currents are also constant. Moreover by changing the switches we can change the direction of the secondary current. So the available current levels obtained in the secondary are :

a, b, a-b, a+b, 0, -a, -b, -(a+b) and -(a-b)

Therefore by using combination of the above available current levels and based on the estimated waveshape of the reactive and harmonic components of line current a stair-case function to be injected in the power system can be generated.

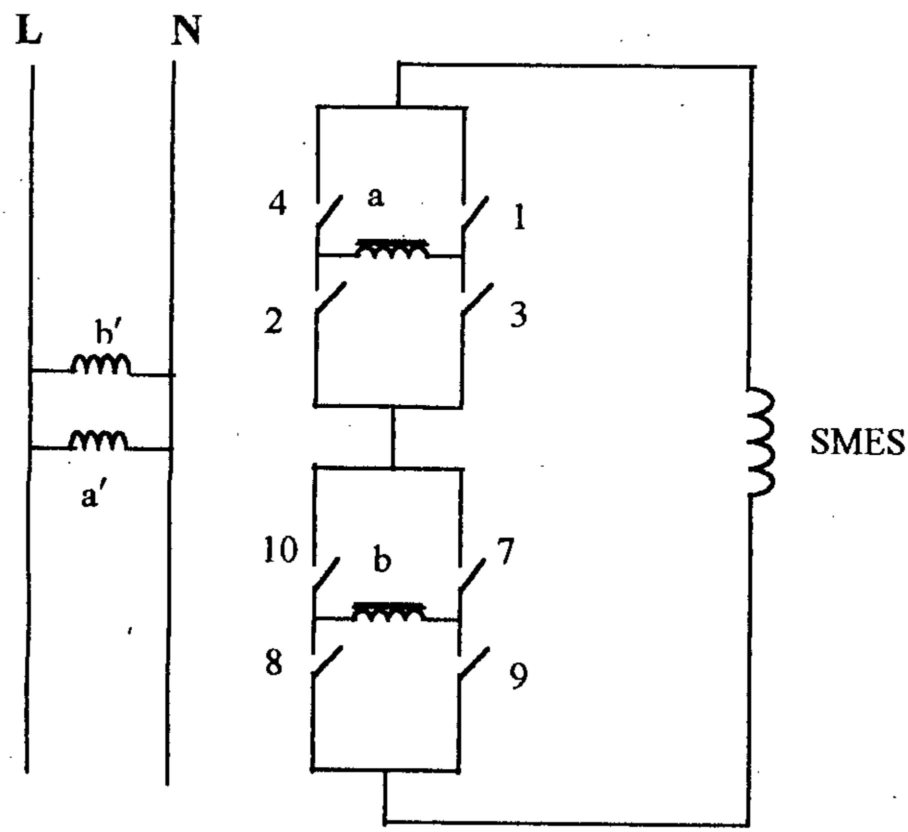

Fig. 4.2 : Switching scheme used to inject compensating current in the line.

An optimum relationship between a and b:

The steps can be represented by the diagram of figure 4.3:

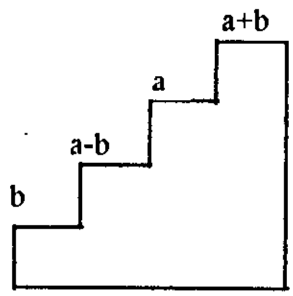

Fig. 4.3 : Schematic of the steps used in step-wise approximation.

For better approximation and to minimize the error the steps should be equal . So,

$$
\begin{aligned}
&(a-b)-b = b-0 \\
&\text{or, } a-2b = b \\
&\text{or, } a = 3b \\
&\therefore\ b = a/3
\end{aligned}
$$

By increasing the number of inverters used in series with the SMES the number of available current level to be used in approximation can be increased. With these increased number of levels it is possible to attain a better performance in compensating the objectionable components of the line current. The switching scheme is also workable if only one inverter is used. But in that case the compensation using PWM wave is to be used which also provides reasonable performance as described in chapter 2.

Change of SMES current :

When there is a change in the amplitude of the compensating current, estimated by the estimation circuit the SMES controller takes initiation to charge the coil to the new set point. The estimation block as described in chapter 3, estimates the compensating current, Ic. This current is used by the power conversion system in selecting the switching sequence and by the SMES controller to control the current to be injected. The SMES controller controls the current of the superconducting coil i.e. the SMES current according to the control signal obtained and the existing SMES current. The control signal is to be derived from the compensating current, Ic estimated by the feedback control circuit (estimator) described in the previous chapter. The maximum value of the sustained compensating current , Ic_{peak} gives an indication of the amplitude of current to be compensated. In stead of Ic_{peak} if the effective value is used as control signal for the SMES controller then in some cases it may not be possible to attain the peak value by step-wise approximation and the compensation performance will be poor. Moreover, in case of the high value current spikes, they can not be sustained in a practical power system. So, it is reasonable to use the peak value of Ic as control signal of the SMES controller instead of the effective value of the compensating current. The peak estimator will estimate the peak value of the compensating current i.e. the control signal for the SMES controller. When there is a change in the amplitude of the compensating current estimated by the feedback control estimator the SMES controller takes initiation to charge the superconducting coil to the new set point required for the compensation of the new compensating current using governor and other mechanisms. But if the SMES current is changed quickly to attain the new set point then the released or absorbed power in the line may have an adverse effect on the alternators in the system which may drive out of synchronization. For this reason the power is to be released in the line slowly. To define the gain factor, G_I and to show the governing equation in reducing the current to a new set point let us assume that,

present value of SMES current = I_s
desired value of SMES current = I_{sd}
peak value of compensating current = I_{cp}
present value of SMES energy = E_{smes}
SMES energy at desired current= E'_{smesd}

Then, the current to be added with Ic is, $I_{pc} = G_I(I_s - I_{cp})V_L$ 4.1

The energy to be released in the system in small time Δt is:

$$E_r = \int_0^{\Delta t} P_r\, dt$$
$$= \int_0^{\Delta t} (I_c + I_{pc})V_L\, dt$$

Now from energy balance equation :

$$E'_{smesd} = E_{smes} - E_r$$
$$\text{or, } \frac{1}{2}L I_{sd}^2 = \frac{1}{2} L I_s^2 - E_r$$
$$\text{or, } I_{sd} = \sqrt{I_s^2 - 2E_r / L}$$
$$\therefore I_{sd} = \sqrt{(I_s^2 - 2E_r/L)} \qquad 4.2$$

For changing the SMES current, as mentioned earlier energy is to be released to or absorbed from the line. To absorb or release energy through the power conversion system the signal obtained from the estimator, based on which switching is done, should be changed. As shown in the above analysis a fraction of power component of line current (the fraction is determined by I_{pc} of equation 4.1) is to be added or subtracted from this signal so that equation 4.2 is valid. When the SMES current reaches the new value then I_{pc} will be zero.

With the use of proper SMES current better compensation performance can be obtained. Table 4.1 shows how the rms value of the line current and system power factor has been changed after compensation using simulation program (Appendix-B) for different values of SMES current.

Table 4.1 : Effect of different values of SMES current on compensation performance.

SMES current	Before compensation		After compensation	
I_s (p.u)	Load current (p.u)	Power factor	Load current (p.u)	Power factor
0.5	0.7	0.6	0.4885460	0.8596940
1.0	0.7	0.6	0.4265470	0.9846511
0.5	1.0	0.6	0.7572035	0.7923895
0.8	1.0	0.6	0.6579869	0.9118723
1.0	1.0	0.6	0.6190300	0.9692584

As for an example, let us assume that at present the SMES current is 1.0 per unit but the value of the compensating current is such that its peak value is

0.8 per unit. Then if the SMES current I_{SMES} = 1.0 p.u. is used in injecting current in the system then the compensation performance will be poor as listed in table 4.1. For this reason the SMES current is to be changed to a new set point I_{SMES} = 0.8 p.u. and this is to be done slowly so that the alternators in the system do not go out of synchronization. As shown in the basic configuration of the SMES system in figure 4.1 when SMES current is to be reduced then the value of the signal input to the switching circuit is increased by a fraction of the power component so that real power is released in the supply system. A plot of SMES current with time shown in figure 4.4 shows how the SMES current is changed from 1.0 p.u. to 0.8 p.u for SMES inductance L=0.264H [26] at different gain factor, G_I.

The compensating current, I_c is used in switching the PCS switches to inject a current in the line. The current, Ic is processed by a gain controller so that output of the GC which is to be used in switching the PCS always has a constant maximum value. The power conversion system used is required to convert the dc current from the superconducting coil to ac at the utility grid. The PCS must also function to charge the coil from the utility grid.

4.3 The switching sequence :

The sequences in which the switches are to turn ON and OFF in order to generate a stair-case current function to be injected in the power

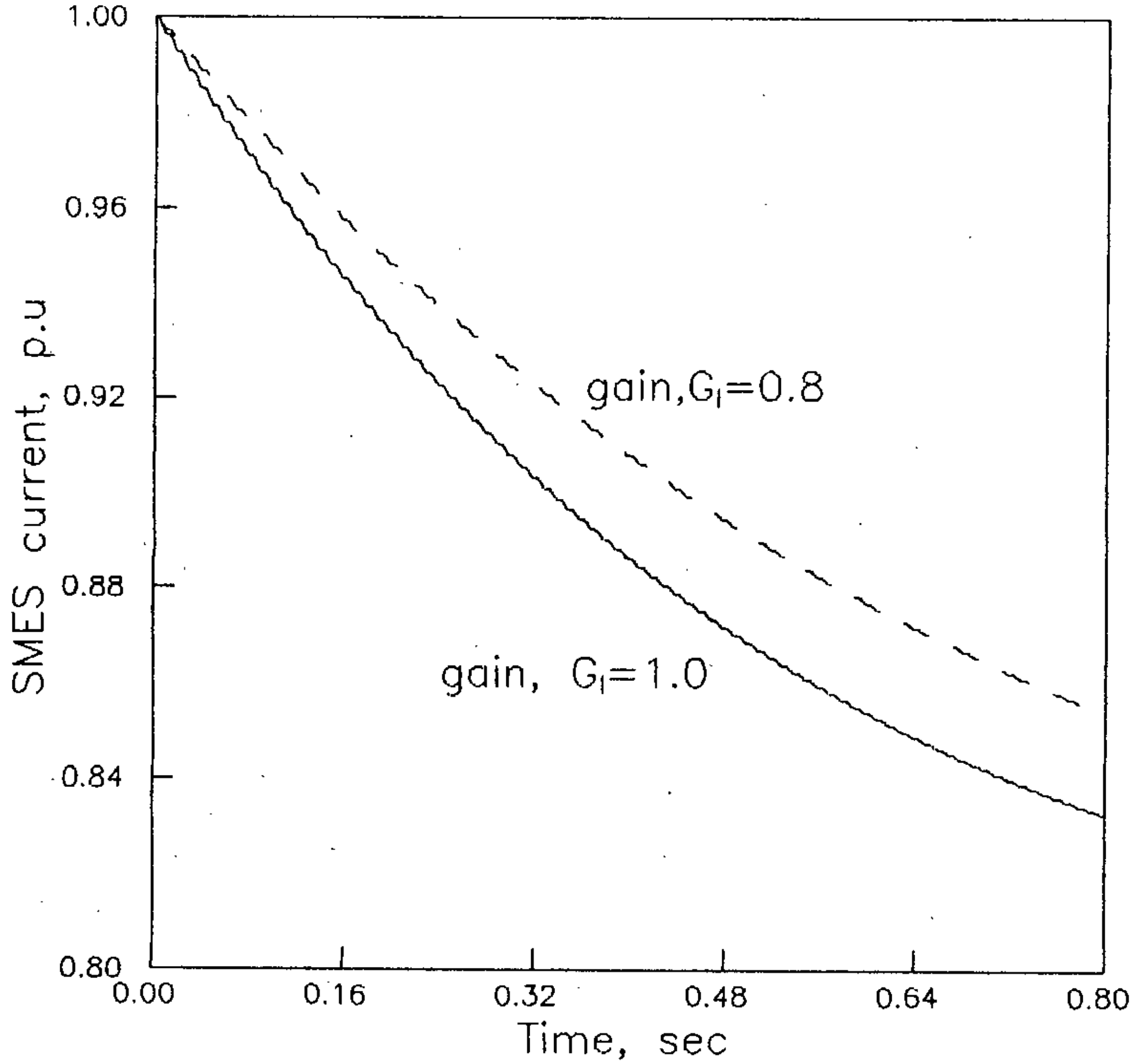

Fig. 4.4 : Time response of the SMES current.

system line to compensate reactive and harmonic components are given in table 4.2.

Table 4.2 : Switches to be turned ON for step-wise current injection in the system.

Current level	Switches to turn ON
a	1, 2, 7, 9
-a	3, 4, 7, 9
b	7, 8, 1, 3
-b	9,10, 1, 3
a-b	1, 2, 9,10
-(a-b)	3, 4, 7, 8
a+b	1, 2, 7, 8
-(a+b)	3, 4, 9,10

As for an example the switches of figure 4.2 to be turned on is shown in the diagram 4.5 for a compensating current Ic where the amplitude is taken arbitrarily.

4.4 Performance Calculation:

In order to demonstrate the compensation capability of the switching circuit described in this chapter we have to study the performance of the scheme. To study the performance we shall calculate the effective (rms) value of the line current after compensation. As the line current after compensation posses mainly the power component, the power factor of the system should be improved. As a

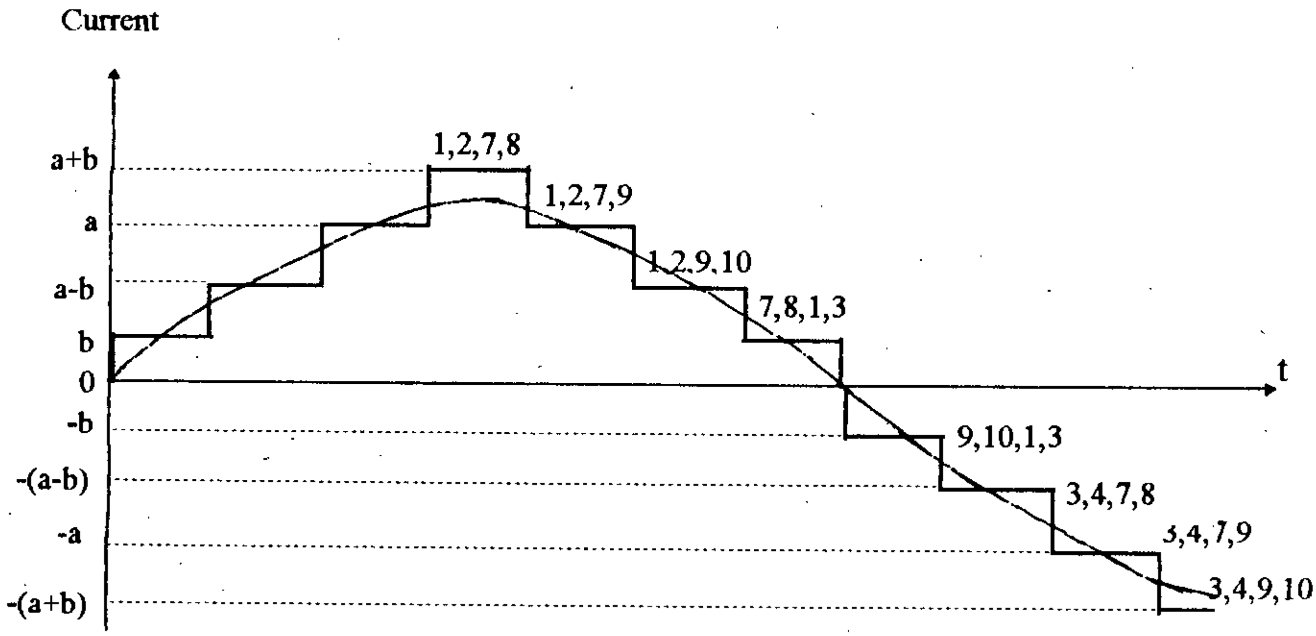

Fig. 4.5 : Switching sequence for the injection of SMES current.

performance study we shall also calculate the system power factor after compensation. To perform this study let us assume a power system having the following characteristics :

harmonic contents = $0.1 \cos 2\pi (0.5 f)t + 0.05 \sin 2\pi (1.8f)t + 0.05 \sin 2\pi(3f)t$

where f is the frequency in cycle / sec.

Now in order to show the compensation capability of the switching scheme let us simulate the scheme with a simulation program given in Appendix B. The output of the program using required SMES current is shown in table 4.3.

Table 4.3 : Compensation performance of the SMES system shown in fig. 4.1

Before compensation				After compensation	
Power factor	Load current (p.u)	Real current (p.u)	Reactive current (p.u)	Power factor	Load current (p.u.)
0 .4	0.6	0.24	0.55	0.9533040	0.2517559
0.4	1.0	0.40	0.92	0.9556382	0.4185684
0.5	0.6	0.30	0.52	0.9640235	0.3111957
0.5	1.0	0.50	0.87	0.9820384	0.5091469
0.6	0.6	0.36	0.48	0.9842041	0.3657778
0.6	1.0	0.60	0.80	0.9923631	0.6046174
0.8	0.6	0.48	0.36	0.9805385	0.4895270
0.8	1.0	0.80	0.60	0.9951783	0.8038759

It has been found from the above result that after compensation the line current of the system has reduced from its previous value to an appreciable value. As the reactive and harmonic components of the line current has been eliminated from the total current so the effective value of the line current after compensation is reduced. After compensation of the reactive and harmonic components of the line current the remaining current is the power component and it should be in phase with the system line voltage. So the system power factor should be near to unity after the elimination of the objectionable components of the line current. It has been found from the above study that the system power factor has been improved and it has been raised very close to unity. Figure 4.6 shows the relative effective values of all the frequency components after compensation. The figure shows that the harmonics are reduced reasonably.

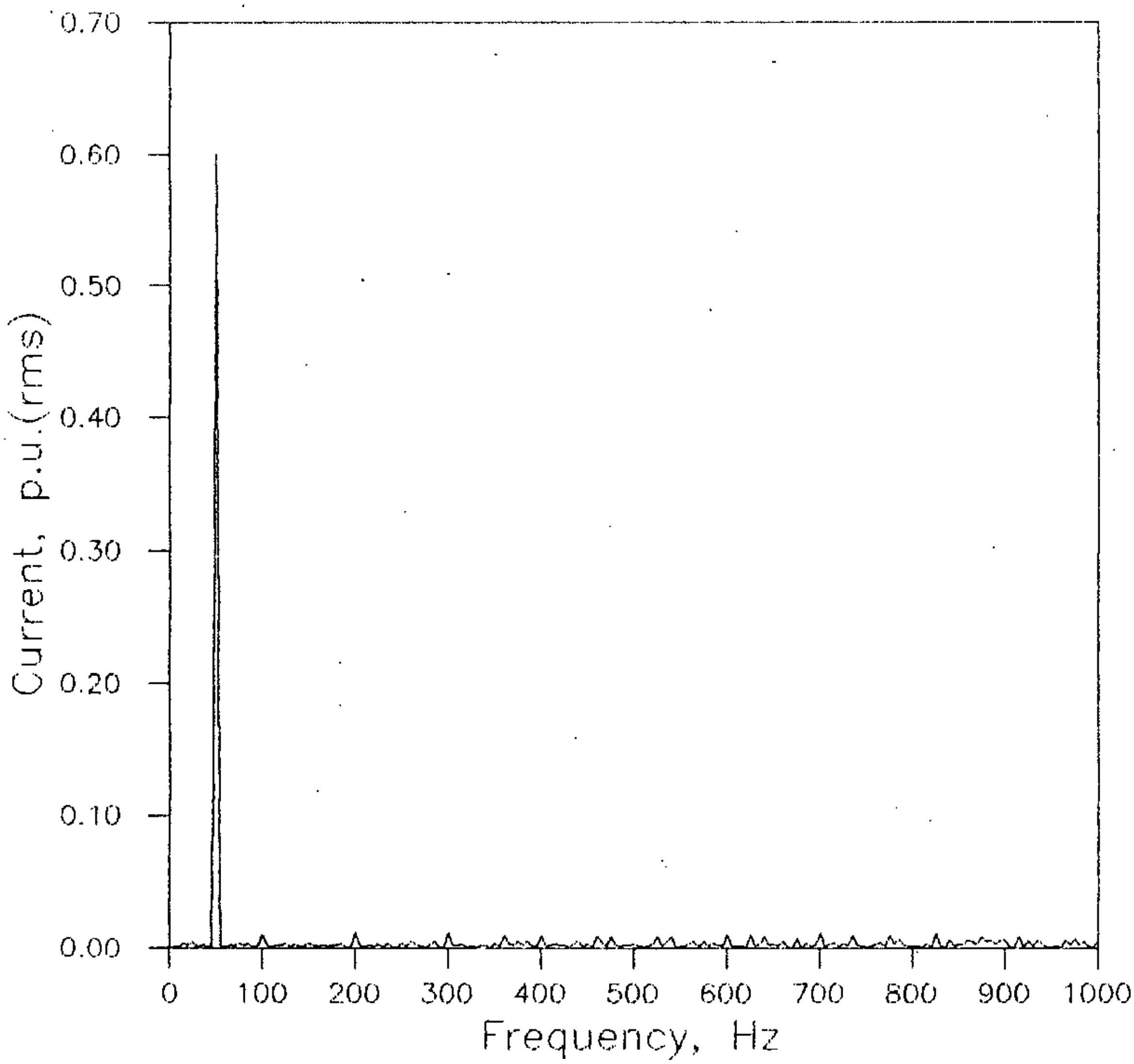

Fig. 4.6 : Harmonic components of the line current after compensation.

CHAPTER 5

CONCLUSIONS

5.1 Discussions :

This chapter concludes the work of the simultaneous compensation of reactive, subharmonic and harmonic components of line current using SMES. The computer simulation of the compensating current estimation control circuit has been carried out and its performance has been studied for different load currents and power factors. A brief discussion on this feedback control system and the switching scheme is provided in this chapter. This chapter also provides some possible future research on this work.

On line simultaneous compensation scheme of reactive, subharmonic and harmonic components of line current of a power system has been proposed in this work. The compensation scheme using SMES, for different power factor and load has been studied using computer simulation. The compensation scheme performance study has been carried out in three steps as follows:

i) Sense the line current and the line voltage

ii) Separate the current in (i) into

-the power component

-the compensating current component

iii) Based on the compensating current waveshape in (ii) inject current in the line with 180 degrees phase shift using power electronic switching circuit.

The line current has been separated into above mentioned two components using a feedback control estimation circuit. It has been assumed that the line voltage remains perfectly sinusoidal but this may not be 100% correct. The scheme has been simulated by a computer program to study its time response as mentioned in chapter 3. The scheme suffers from a limitation that the feedback control estimation circuit takes about 6 cycles to settle in separating the compensating current whereas for an on-line compensation scheme the settling time should be ideally zero. But for a practical power system the value of Ts = 6T as mentioned in chapter 4 is reasonable. It has been shown that the system power factor can be improved and the effective value (rms value) of the line current can be reduced by appropriate current injection so as to eliminate the reactive, subharmonic and harmonic components in the line current. The feedback control system time response can be improved using better control circuit.

In the compensation performance study using computer simulation the step-wise approximation with eight levels has been used. The power factor has been raised very close to unity and the rms value of the line current has been reduced considerably. It is obvious that with increased number of steps the approximation will be better and better performance will be achieved. But the use a large number of steps in the approximation will not be economically viable because the increased number of switches will increase the cost, switching loss will be high and the temperature of the switches will increase. In this work only eight steps has been used. By increasing the number of inverters in series (including transformers) as shown in the switching scheme, the number of steps used can be increased. After compensation the high frequency harmonics may go up. Hopefully this high frequency components have very small effect due to the presence of line capacitance and inductance.

It is obvious from figure 3.1 that when there is a sudden increase in the load current then the compensating current I_c will increase suddenly and the SMES may be overloaded and reach saturation. For this reason there should be some arrangement so that the change in I_c does not change the switching sequence instantaneously (say within 4 cycles).

The compensation scheme described in chapter 4 does not consider current spikes. In practical power system the current spikes in the line can not sustain. So, the switching scheme should perform all right. However, the compensation switching scheme performance will be poor if high value spikes are present.

5.2 Conclusions:

The approximation of a function F(t) using PWM wave and step-wise approximation has been studied using simulation program. The study reveals that step-wise approximation is the better of the two and it has been used in all analysis. For better approximation the number of steps should be increased and the step size is to be decreased. The time response of the reactive, harmonic and subharmonic components estimation circuit is depended on its overall gain and for high value of gain the system may become unstable. The schematic switching scheme has been simulated and its performance has been studied which provides a significant improvement of the power factor and reduction of harmonic contents of the system under consideration. So, the scheme is capable of eliminating reactive and harmonic components of line current.

5.3 Future work :

Much attention has recently been paid on the simultaneous control of the active and reactive components of line current using SMES [8, 26] but no integrated approach has been taken to compensate the harmonic and subharmonic components of the line current. Future work may include the development of an integrated scheme to control the active, reactive, harmonic and subharmonic components of the line current of a power system simultaneously using superconducting magnet energy storage in their theoretical and practical studies. In this work the compensation of reactive, harmonic and sub-harmonic current has been studied in the load end. So, the compensating current is still present in the other portion of the power system and it will cause the adverse effects as mentioned earlier in chapter 1. Future work may also include the study of the location of the SMES system to optimize the compensation performance of the proposed scheme. Future work may also include the study to modify the switching circuit of chapter 4 so that it can work to inject zero current in the secondary.

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APPENDIX

APPENDIX-A

```
CC***   SIMULATION PROGRAM OF THE FEEDBACK CONTROL CIRCUIT***

        REAL VL,IL,IG,IC,T,P,AI,A,LPF
        OPEN(3,FILE='BL.DAT')
        IG=0
        H=0.0001
        A=0
        T=0
        L=0
   30   LPF=0
        DO 10 K=1,1500
        VL=SIN(314*T)
        IL=0.1*SIN(157*T)+0.5*SIN(314*T)+0.2*COS(628*T)
      1   +0.15*SIN(942*T)+0.1*SIN(1256*T)+0.2*SIN(1570*T)
      2   +0.1*COS(1884*T)
        IC=IL-IG
   CC   FIRST MULTIPLIER
        P=VL*IC
   CC   INTEGRATION  STARTS
        AI=P*H
        A=A+AI
   CC   FILTERING ACTION STARTS
        LPF=.99*LPF+.01*A
        IG=8*LPF*VL
        WRITE(3,*) T,IG
        PRINT*,T,LPF
        T=T+H
  10    CONTINUE
        STOP
        END
```

APPENDIX B

```
***************PROGRAM TO CALCULATE PERFORMENCE*******************

      REAL F,T,TP,P,FT,TG,IM,IMS,IP,H,IRMS,PF,IC,IIP,FC,I
      READ *, F,I,PF,IS
      P=0
      T=0
      IIP=I*PF
      H=.00005
      TP=1/F
10    FC=1.4142*I*PF*SIN(6.28*F*T)
     1   +SQRT(2*I*I-2*I*I*PF*PF-0.015)*COS(6.28*F*T)
     2   +0.1*COS(6.28*F*0.5*T)
     3   +0.05*SIN(6.28*F*1.8*T)+.05*SIN(6.28*F*3*T)
      FT=SQRT(2*I*I-2*I*I*PF*PF-0.015)*COS(6.28*F*T)+
     1   0.1*COS(6.28*F*0.5*T)+0.05*SIN(6.28*F*1.8*T)+
     2   0.05*SIN(6.28*F*3*T)
      IF(FT.LT.0.125*IS.AND.FT.GT.-0.125*IS) TG=0
      IF(FT.LT.0.375*IS.AND.FT.GE.0.125*IS) TG=0.25*IS
      IF(FT.LT.0.625*IS.AND.FT.GE.0.375*IS) TG=0.5*IS
      IF(FT.LT.0.875*IS.AND.FT.GE.0.625*IS) TG=0.75*IS
      IF(FT.GE.0.875*IS) TG=1*IS
      IF(FT.LE.-0.125*IS.AND.FT.GT.-0.375*IS) TG=-0.25*IS
      IF(FT.LE.-0.375*IS.AND.FT.GT.-0.625*IS) TG=-0.5*IS
      IF(FT.LE.-0.625*IS.AND.FT.GT.-0.875*IS) TG=-0.75*IS
      IF(FT.LE.-0.875*IS) TG=-1*IS
      IM=FC-TG
      IMS=IM*IM
      IP=IMS*H
      P=P+IP
      T=T+H
      IF(T.LE.TP) GOTO 10
      IRMS=SQRT(P/TP)
CC    IC=SQRT(IRMS*IRMS-IP*IP)
      PFP=IIP/IRMS
      PRINT*,'RMS VALUE OF CURRENT, IRMS=',IRMS
      PRINT*,'POWER FACTOR, PF=',PFP
      STOP
      END
```

APPENDIX C

```
CC   ***** PROGRAM FOR PWM  APPROXIMATION *****

      REAL A,AI,T,H,TW,FT,FC,PW,PWM,RMS,F,TP,PF,I,NPF,IP
      READ*,F,PF,I
      OPEN(3,FILE='PWM.DAT')
      OPEN(4,FILE='AA.DAT')
      OPEN(5,FILE='TW.DAT')
C     READ*, F, PF, I
      A=0
      AI=0
      T=0
      TW=0
      TP=1/F
      H=TP/800
      IP=PF*I
10    FT=1.414*I*PF*SIN(6.28*F*T)+
     +    SQRT(2*I*I-2*I*I*PF*PF-.015)*COS(6.28*F*T)
     +    +0.1*COS(6.28*.5*F*T)
     +    +0.05*SIN(6.28*F*T*1.8)+.05*SIN(6.28*3*F*T)
      FC=SQRT(2*I*I-2*I*I*PF*PF-.015)*COS(6.28*F*T)
     +    +0.1*COS(6.28*.5*F*T)
     +    +0.05*SIN(6.28*F*T*1.8)+.05*SIN(6.28*3*F*T)
      T=T+H
      IF(TW.LT.1.0)THEN
        TW=TW+40/TP*H
        WRITE(5,*)T, TW
      ELSE
        GOTO 20
      ENDIF
      IF(TW.LE.FC.AND.FC.GT.0)PWM=.5
      IF(TW.LE.FC.AND.FC.LT.0)PWM=+.5
      IF(TW.GT.FC.AND.FC.GT.0)PWM=-.5
      IF(TW.GT.FC.AND.FC.LT.0)PWM=-.5
      WRITE(3,*) T, PWM
      WRITE(4,*) T, FC
      PW=FT-PWM
      AI=PW*PW*H
      A=A+AI
      IF(T.GT.TP)THEN
         GOTO 30
      ELSE
         GOTO 10
      ENDIF
```

```
20    TW=TW-40/TP*H
      WRITE(5,*)T,TW
      FT=1.414*IP*SIN(6.28*F*T)
     +  +0.1*COS(6.28*.5*F*T)+
     +   SQRT(2*I*I-2*IP*IP-.015)*COS(6.28*F*T)+
     +   0.05*SIN(6.28*1.8*F*T)+0.05*SIN(6.28*3*F*T)
      FC=SQRT(2*I*I-2*IP*IP-.015)*COS(6.28*F*T)+
     +   0.1*COS(6.28*.5*F*T)+
     +   0.05*SIN(6.28*1.8*F*T)+0.05*SIN(6.28*3*F*T)
      T=T+H
      IF(TW.LE.FC.AND.FC.GT.0)PWM=.5
      IF(TW.LE.FC.AND.FC.LT.0)PWM=.5
      IF(TW.GT.FC.AND.FC.GT.0)PWM=-.5
      IF(TW.GT.FC.AND.FC.LT.0)PWM=-.5
      WRITE(3,*)T, PWM
      WRITE(4,*)T, FC
      PW=FT-PWM
      AI=PW*PW*H
      A=A+AI
      IF(T.GT.TP)GOTO 30
      IF(TW.LE.-1.0)GOTO 10
      GOTO 20
30    RMS=SQRT(A/TP)
      NPF=IP/RMS
      PRINT*,'RMS=', RMS
```

APPENDIX-D

```
CC ****** PROGRAM FOR HARMONIC ANALYSIS *******

      DIMENSION A(205),B(205),C(205)
      INTEGER P,L,Y
      OPEN(3,FILE='AZIZ1.DAT')
      PRINT*,'TP,N'
      READ*,TP,N
      H=0.000025
      M=(TP/H)*10.0
      DO 10 K=1,N
      A(K)=FINT1(H,K,M)
      B(K)=FINT2(H,K,M)
      C(K)=1.414*SQRT( A(K)**2+B(K)**2)/(10*TP)
      PRINT*,K
      WRITE(3,*) 5*K,C(K)
10    CONTINUE
      STOP
      END

      FUNCTION FINT1(H,K,M)
      INTEGER L
      REAL IM
      T=0
      A=0
      OPEN(28,FILE='\WATFOR\CN1.DAT')
      DO 20 L=1,M
      READ(28,*)IM
      FTT=IM*COS(K*31.4*T)
      T=T+H
      AI=FTT*H
      A=A+AI
      FINT1=A
20    CONTINUE
      CLOSE(28)
      RETURN

      FUNCTION FINT2(H,K,M)
      INTEGER P
      REAL IM
      T=0
      A=0
      OPEN(28,FILE='\WATFOR\CN1.DAT')
      DO 30 P= 1,M
      READ(28,*)IM
```

```
      FTT=IM*sin(31.4*K*T)
      T=T+H
      AI=FTT*H
      A=A+AI
      FINT2=A
30    CONTINUE
      CLOSE(28)
      RETURN
      END
```