Harmonics Compensator by Connecting Sinusoidal Voltage PWM Converters

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Abstract

We propose a harmonics compensator for the utility line voltage distortion by connecting the sinusoidal voltage generated by the PWM converters to the AC line to be compensated point. This connecting point is adjustable by changing the feed back gain k. Adjusting the gain k, the capacity of the PWM converter and the supersession characteristics become controllable.

This compensator can reduce or compensate the common utility line voltage distortion derived from the downstream utility source voltage harmonics and the upstream load current harmonics at the same time.

In this paper, we describe the basic principle of the control method, the control system of the compensator constructed by the sinusoidal PWM converter. And then, we show some operating waveforms for the both case of the downstream voltage distortion and the upstream harmonics current from the nonlinear loads by simulation analysis to verify the feasibility..

Key words: Harmonics suppression, Adjustable control.

1 Introduction

Harmonics problems by the remarkable development of static power converters with nonlinear characteristics have been one of significant subject because utilities more frequently encounter harmonic related problems. In order to suppress harmonics generation, the harmonics standards have been expressed in developed countries. So far, individual consumers producing rich harmonics in the industries sometimes install an active filter not to affect another loads connected to the common bus. Harmonics compensation, however, does not provide any direct benefit or increased productivity to the general user as described in the literature [1]. So, there is seldom any motivation for users to meet the harmonics standard by installing harmonics compensators such as active filters.

So far, the sinusoidal reference waveform for the current control has been used not to flow any harmonic currents by itself for the sinusoidal current PWM converter. But the sinusoidal current PWM converter cannot improve the distribution line voltage distortion. On the other hand, the PWM converter with active filter functions has been also reported to compensate the current harmonics from nonlinear loads [2]. In this case, the control system for the PWM converter becomes complicate and the required kVA rating becomes large for a high power harmonics. Moreover, the converter cannot improve the voltage distortion arising from the utility source line.

In this paper, we propose a new control method of the PWM converter to improve the waveform quality of the utility network system without complicating the control system and spending a lot of additional cost for harmonics compensation. The proposed PWM converter can improve the secondary line voltage waveform of the step down transformer. In the proposed system, the converter does not intend to compensate perfectly the common AC utility line voltage unlike the instantaneous line voltage compensator as presented in [3] [4].

One of the feature of the system is easy cooperation of the harmonics compensator by indirect connection to the common utility line[5].

2 Principle of Control Method

Fig.1 shows the equivalent circuit per phase of the harmonics compensator by connecting the sinusoidal voltage source to the common terminal to be compensated. The output voltage e_o contains rich voltage harmonics due to nonlinear loads current i_o and utility source line voltage e_a with distortion waveform. The series inductance L_a includes utility line impedances. The PWM converter represented by a sinusoidal voltage e_b is applied to this output terminal through coupling inductance L_b.

When the voltage e_a and the load current i_o are expressed by their fundamental components and harmonics components respectively, the output voltage e_o is also shown with their two components as next.

$$e_a = e_{a1} + e_{ah} \tag{1}$$

$$i_o = i_{o1} + i_{oh} \tag{2}$$

$$e_o = e_{o1} + e_{oh} \tag{3}$$

Where, the subscript *1* means fundamental component and *h* represents the harmonics components. When the sinusoidal voltage e_b is applied, the harmonics component of the output voltage e_{oh} is given as next.

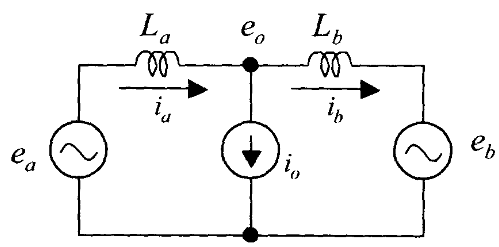

Fig. 1. Equivalent circuit per phase of the compensator.

$$e_{oh} = \frac{L_b}{L_a + L_b} e_{ah} - \frac{L_a L_b}{L_a + L_b} \frac{di_{oh}}{dt} \tag{4}$$

As can be seen, the influence to the output voltage harmonics e_{oh} due to the harmonics source voltage e_{ah} and the harmonics load current i_{oh} can be reduced in (4) expressed by the dividing relation between two inductances L_a and L_b. In this case, the compensation current i_b is shown as,

$$i_b = \int \left(\frac{1}{L_a + L_b} e_{ah} \right) dt - \left(\frac{L_a}{L_a + L_b} i_{oh} \right) \tag{5}$$

The current i_b is composed of the compensation current for the harmonics voltage e_{ah} (first term) and the harmonics current i_{oh} (second term).

When the output voltage e_o is controlled to the sinusoidal waveform by the PWM converter as presented in [3], the harmonics component e_{oh} becomes zero. Then, from (4),

$$i_b = \int \left(\frac{1}{L_a} e_{ah} \right) dt - (i_{oh}) \tag{6}$$

This means that (6) is obtained from (5) by reducing the coupling inductance L_b to zero. As the inductance L_b decreases, the compensation current i_b increases. So, the required kVA rating of the PWM converter for harmonics compensation can be adjusted by the inductance L_b. And the kVA rating of the PWM rectifier circuit or the PWM inverter circuit with the harmonics compensation functions [2] is decided by the rms value of the total sum current of the fundamental current and the harmonics compensation current.

Even if the kVA rating of the PWM converter is small, it may contribute to improvement of the utility line voltage. Therefore, many sinusoidal PWM converter connected to the common line may make the line voltage sinusoidal waveform, while the sinusoidal current PWM converter have not such compensation functions. Moreover, the control system of the proposed PWM converter is very easy as compared with the conventional PWM converter because the current control loop is not basically required to construct the system.

As shown in (4), the coupling inductance L_b is proportional to the compensation factor not only for line voltage distortion but also for load current harmonics, and the inductance value L_b is selected enough to reduce the pulsation current by the PWM switching. So, the inductance value is decided from their trade off relations.

3 Modified Control Method

On the other hand, the direct improvement of the utility line waveform can be performed by the PWM control based on the terminal voltage detection as presented in [3] to compensate satisfactory. But the required kVA rating becomes too large and the voltage detection at the terminal apart from the power circuit compensator is needed to construct the control system.

If the modified voltage e_b' subtracted by the inductance drop proportional to L_b' instead of the pure sinusoidal voltage e_b ($=e_{b1}$) is applied, (see Fig.2)

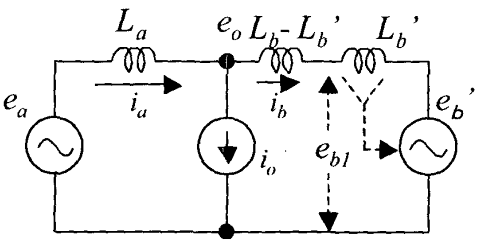

Fig. 2. Equivalent circuit for modified voltage control.

$$e_b' = e_{b1} - L_b' \frac{di_b}{dt} = e_{b1} - kL_b \frac{di_b}{dt} \tag{7}$$

where, the L_b is the total coupling inductance and the L_b' is the detection inductance of the total voltage drop. And k is the ratio of them. Equation (4) and (5) can be rewrote as next.

$$e_{oh} = \frac{(1-k)L_b}{L_a + (1-k)L_b} e_{ah} - \frac{L_a (1-k) L_b}{L_a + (1-k)L_b} \frac{di_{oh}}{dt} \tag{8}$$

$$i_b = \int \left(\frac{1}{L_a + (1-k)L_b} e_{ah} \right) dt - \left(\frac{L_a}{L_a + (1-k)L_b} i_{oh} \right) \tag{9}$$

When k is zero, these equations are the same as (4) and (5). Equation (9) becomes (6) as the k becomes unity.

The harmonics e_{oh} of the output voltage become small according to the equivalent series inductance $(1-k)L_b$ as shown in (8). And if L_b' is the same as the total series inductances L_b, the harmonics component e_{oh} becomes zero. So, by using the modified voltage reference e_b' the terminal voltage can be improved without directly detecting the terminal voltage e_o and it becomes easy to design the compensation level of the PWM converter.

The compensation current ratio K_{ib} of I_b (for k) to I_{b0} (for k=0) is expressed as

$$K_{ib} = \frac{I_b}{I_{b0}} = \frac{L_a + (1-k)L_b}{L_a + L_b} \tag{10}$$

As shown, the required current rating of the PWM converter is adjustable between that of (k=1) and (k=0). The rating varies from half to full rating in the case of La=Lb. The remained harmonics e_{oh} in the output voltage is given by (8).

The compensation current i varies depend on the harmonics of the AC line voltage and the load current.

So, the PWM converter can be operated as the compensator to reduce the harmonics of the terminal voltage within the current rating by adjusting the k.

4 Controlled Terminal Voltage

Fig.3 shows the basic equivalent circuit for fundamental component of the output voltage. The series inductance La is important role to compensate the harmonics and it composed of the reactance including the step down transformer in addition to the external inductance if it is required.

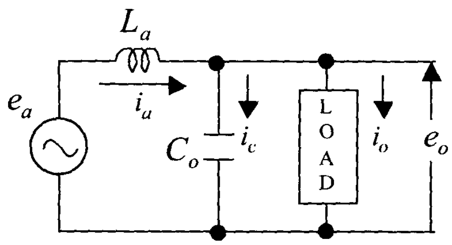

Fig. 3. Equivalent circuit for terminal voltage control.

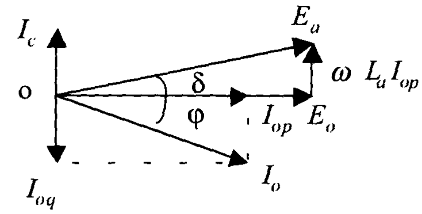

Fig. 4. Voltage relation between E_a and E_o

The capacitor C is also used for capacitor bank to improve the power factor of the factory AC supply line.

In this case, the power factor becomes approximately unity. Fig.4 shows the relation between the output voltage E_o and the supply voltage E_a under the unity power factor operation. The output voltage is given as next.

$$E_o = \sqrt{E_a^2 - (\omega L_a I_a)^2} = E_a \left\{1 - (\omega L_a I_a / E_a)^2\right\}^{1/2} \quad (11)$$

$$\cong E_a (1 - X_a[\%]^2 / 200) \quad (12)$$

where, $X_a[\%]$ is the percent reactance drop of the series inductance La. As can be seen from this equation, the voltage regulation is not so large even if an additional series inductance is connected in series.

The voltage sag for the transient load variations is also small because the considerably large capacitors C_o are installed across the factory AC line [5].

5 System Configuration

Fig.5 shows the main circuit configuration and control system of the proposed harmonics compensator. The system is constructed by the series inductances composed of L_s, L_b (divided by L_{b1} and L_{b2}), the three phase PWM converter circuit with DC capacitor C_d and the capacitor C_o across the factory AC power line. The L_S is the series inductance of the step down transformer, the capacitor C_o is considerably large enough to compensate the reactive current in the factory AC line. The series resistances rc are very small value and used to prevent oscillations.

The upper side block represents the R-L linear load and non linear load composed of the rectifier circuit. They are connected to the common utility AC line in the factory.

The control system for the PWM converter are shown in the lower side block enclosed by the dotted line. The PWM control signal is basically generated from next two control loops.

1) **Modulation index M** is generated by the reactive current control loop not to flow it.
2) **Operating phase θ** is adjusted by the DC voltage control loop to the reference voltage E_{dr}.

Fig.6 shows the PWM switching pulse generating block diagram. The PWM switching signals are generated by the comparison between the three phase control signals and a triangular carrier wave. As show in (7), the three phase control signals are modified by the feed back loop from the voltages across the series inductances. They are subtracted by ($L_{b2}di_b/dt$). The cut off frequency of the low pass filters (LPF) are less than the switching frequency but higher than

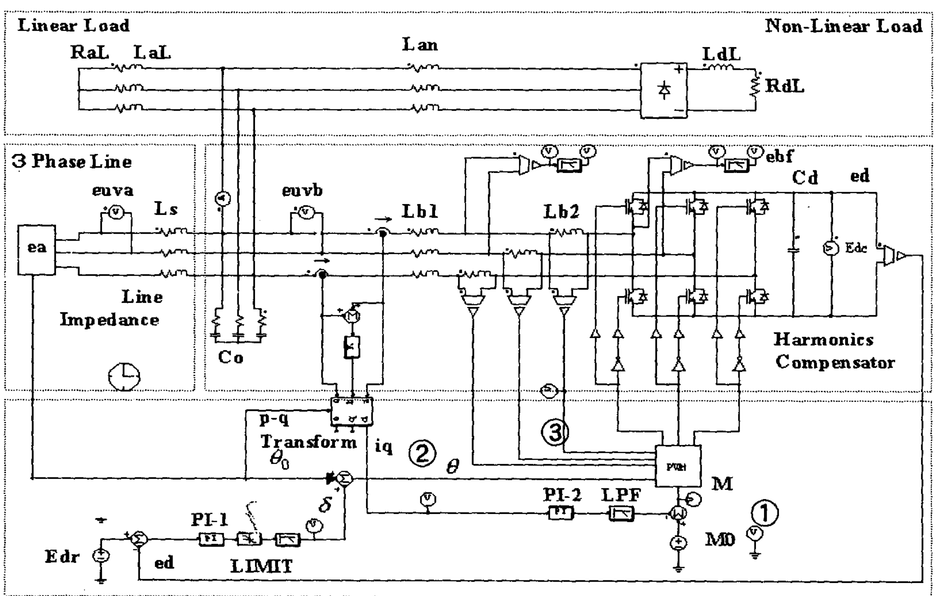

Fig. 5 Proposed harmonics compensation system.

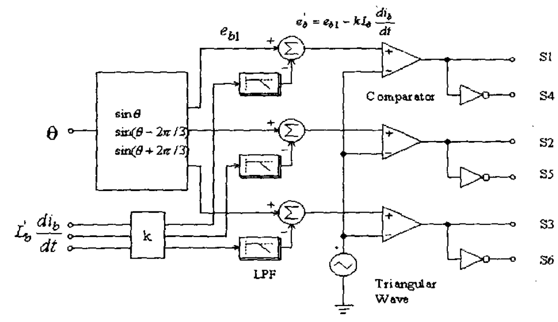

Fig.6. PWM signal generating circuit.

the several multiple fundamental frequency.

3) **Feed back coefficient k** decides the compensation accuracy and the current rating of the PWM converter. The harmonics compensation point can be adjusted by the coefficient constant k of the inductance voltage detected. The coefficient k is selected by their trade off relations.

6 Simulation Results

Table 1 shows the rating of the harmonics compensator and the circuit parameters. The proposed system is installed in the factory AC utility line. We suppose that the step down transformer from 6600 V to 200 V has 3% reactance which corresponds with the 0.03185mH inductance L_s=L_a. The Var capacity of the capacitor bank connected to the utility line is 20% of the system power rating of 100kW. In this case, the capacitance C_o is 1326 uF for the 200V line. And the 31.6kVA linear inductive load with power factor of 80% and 39.2kW non linear load by the rectifier circuit are connected to the AC line. The almost same inductance value 0.03mH for Lb as Ls is used and divided 2:1. Then L_{b2}=0.02mH,L_{b1}=0.01mH.The PWM converter is constructed by the IGBT module. The carrier frequency is 10kHz. The operating DC voltage E_{dr} is 350V. The AC voltage e_a with 250 V peak limiter for 240V rms AC voltage is used to investigate the system operation.

6.1 Basic Operation of the Compensator

In this section, we explain some simulation results only for the case of the line voltage distortion. The rectifier circuit is not connected to the line.

Fig.7 shows the simulation results for k=0 as the operating condition. The sinusoidal PWM waveform is applied to the utility line to be compensated through the coupling inductance L_b. The top waveform is the line voltage e_a,the second one is the AC utility line voltage e_o and the third one is the filtered waveform e_{bf} of the AC side voltage e_b of the PWM converter, the forth one is the compensation current i_b and the bottom one is the utility line current i_a waveform. As can be seen, the output terminal voltage e_o is somewhat improved by connecting the sinusoidal voltage e_b.

Fig.8 shows frequency spectrums for e_a, e_o and e_b respectively. It can be observed that the harmonics component C_n is reduced by the inductance ratio L_a and L_b as expressed in (4) although the fundamental component are the same.

Fig.9 shows the operating waveforms for the feedback

Table 1 Rating and circuit parameters

System Rating	P[kVA]	V1[V]	V2=Ea[V]	F [Hz]	Fs [kHz]	Edr [V]
	100	6600	200	60	10	350
Line Side Parameters	Ls [%]	Ls = La [mH]	ra [Ù]	kc [%]	Co [uF]	ro [Ù]
	3	0.03185	0.1	20	1326	0.1
Coupling Inductances	Lb [mH]	rb[Ù]	Lb1 [mH]	rb1 [Ù]	Lb2 [mH]	rb2 [Ù]
	0.03	0.1	0.02	0.066	0.01	0.033
AC Load Parameters	Lan [mH]	ran [Ù]	LdL [mH]	RdL [Ù]	RaL [Ù]	LaL [mH]
	0.03185	0.1	10	2	1	0.002

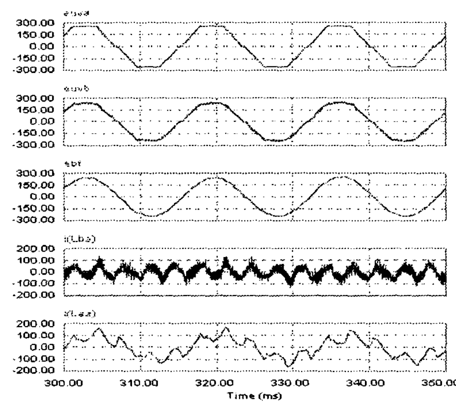

Fig. 7 Basic operating waveforms for (k=0)

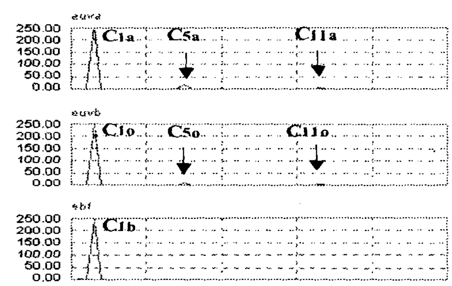

Fig. 8 Frequency spectrums. for Fig.7

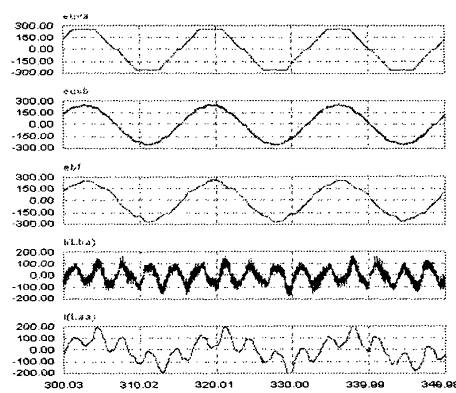

Fig. 9 Terminal voltage control waveforms (k=3)

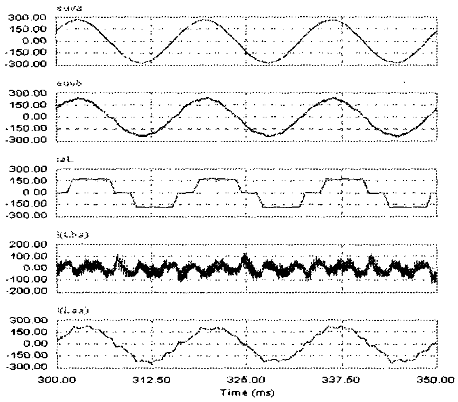

Fig. 10 Operating waveforms as active filter (k=3)

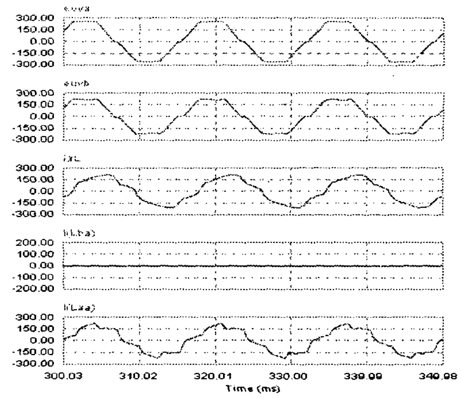

Fig. 11 Operating waveforms before compensation.

coefficient gain k=1. It can be seen that the output voltage e_0 becomes sinusoidal waveform because the harmonics component can be full compensated by the PWM converter. In this case, the compensating current i_b increases than that of k=0. And the voltage waveform of the PWM converter varies to improve effectively the line voltage. On the contrast with the direct instantaneous voltage control method [3], the system construction becomes easy.

6.2 Operating Waveform as Active filter

Fig.10 shows the similar operating waveform for the two times rectifier load shown in the Table 1 to see clearly the active filter operation. The common output terminal point voltage can be improved so that the feedback coefficient factor k = 3 is selected. It can be seen that the consternating current i_b flows to suppress the harmonics of the requtangular wave load current as a result of the terminal voltage control. Then, the AC line current waveform is considerably improved.

6.3 Operating Waveform as Full Compensator

In this section, we show some simulation results of the proposed compensator for the line voltage and the load current distortion.

Fig.11 shows the voltage and current waveforms before compensation. The voltage e_0 is somewhat distorted than the AC line voltage e_a because the load current with harmonics component of the rectifier circuit flows through line inductance L_s. Although the lagging current of the inductive load flows ,the phase displacement angle becomes small by the capacitor current i_c to improve the power factor of the factory AC line.

Fig.12 shows the operating waveforms for k=0 connecting the sinusoidal voltage to the output terminal through the coupling inductor L_b. As can be seen, the output voltage waveform e_0 is improved by the compensating current i_b. The AC line current waveform i_a is composed of the load current and the compensation current i_b.

As increasing the feedback gain k for the inductance voltage, the output voltage e_0 becomes well. Fig.13 shows the operating waveforms for k=3 ,while the compensating current becomes large. As expressed in equation (10), Approximately two times of compensating current flows for the k=3 compared with that for k=0 because the coupling inductance L_b is almost same as the line inductance $L_s=L_a=L_b$. The AC line current distortion is owing to a compensating current for the voltage distortion of the AC utility line.

The capacity of the PWM converter is decided not only by the inductance ratio L_b/L_s but also the feedback gain k.

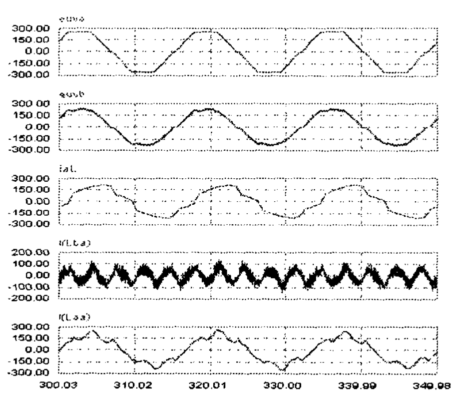

Fig. 12 Operating waveforms of the system (k=0)

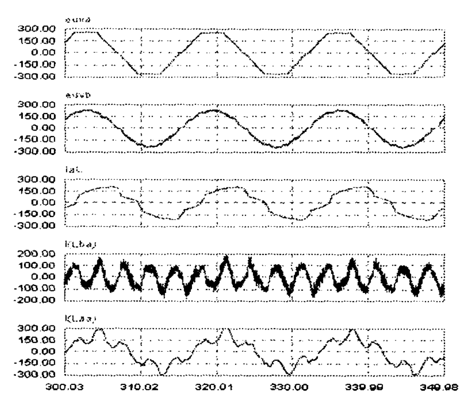

Fig. 13 Operating waveforms of the system (k=3)

On the other hand, the suppression index of the harmonics of the terminal voltage may reduce depending on the capacity reduction. If the middle value of feed back gain k between 0 and 3 is selected, the middle compensation characteristics may be obtained.

6.4 Transient Characteristics

Fig.14 shows the transient characteristics from no load to full load at the time P_x for k=3. As the considerably large capacitor C_o is connected to the output terminal, any voltage sags at the transient point P_x can not be seen. The system becomes steady state condition within several cycles after the transient as can be seen from the compensating current, the AC line current and the DC voltage of the PWM converter. The magnitude of the terminal voltage is a little bit small even for the steady state condition after 10 cycle, because of the capacitor C_o which tends to increase the terminal voltage at no load condition.

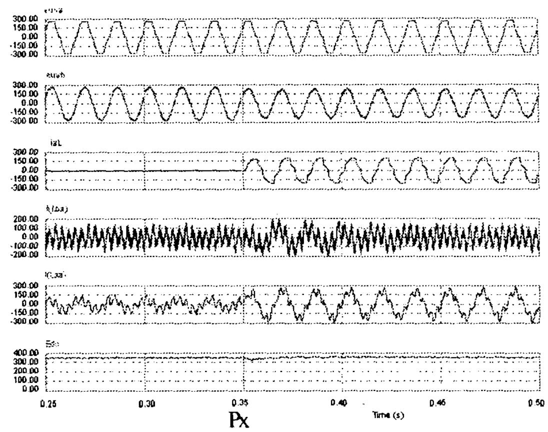

Fig. 14 Transient waveforms for step load variation (k=3).

7. Conclusion

This paper proposes a three phase harmonics compensator of the output voltage at the connected point of the utility system from the distribution line. The configuration of the compensation circuit is very simple which is constructed by the series inductance L_b, PWM converter especially when the step down transformer impedance L_s is used instead of the series line inductance L_a.

The feature is to be able to apply the sinusoidal voltage source to the compensation point between the line connected point and the AC side of the PWM converter. This compensation point can be easily moved by changing the feed back gain k of the voltage across the detecting inductance. This coefficient gain k can be varied according to the capacity of the PWM converter. The proposed new control method may operate the compensator as possible to compensate without inviting the over load or limiting the over current

Simulation results for some cases such as the line voltage distortion and the load current distortion verify the validity of the control strategy.

We will investigate and report the system operation by experimental results applying to the suitable AC compensation system such as the factory AC line.

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