Sinusoidal Voltage Control of a Single Phase Uninterruptible Power Supply by a High Gain PI Circuit

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***Abstract* – This paper presents analysis and design of a new control method of a single-phase voltage-source uninterruptible power supply (UPS) inverter with a high Q L-C low-pass filter. When a PWM inverter is used to feed the load, a L-C low-pass filter must be employed to eliminate the switching frequency component of output voltage harmonics. But, it may be observed that the high Q L-C low-pass filter causes oscillation of the output voltage on light load because the inverter is not able to decide on the one optimum control gain on all region of the output power. Therefore, it is proposed to develop High-Gain Control which is accomplished by increasing of the controller gain without additional sensors to avoid such problems and achieve a high reliability. Developed high speed High-Gain Control must be adopted with following compensator.**

(a) Saturation compensator of the normal controller.

(b) Integrator wind-up compensator.

In this paper, developed High-Gain control is applied to an UPS having a flywheel energy storage element. As a result, it is confirmed that the developed new High-Gain Control method reduce the oscillation of the output voltage and the system is perform in stability.

I. INTRODUCTION

Nowadays, the electric power system in Japan has high reliability, and the occurrence of power failure became very sparse. But instantaneous voltage accidents owing to natural causes, such as thunder, cannot be avoid completely even if the most recent technologies are adopted to the system. Therefore, the wide use of computers and other equipments which are sensitivity to variation of the source voltage require Uninterruptible Power Supplies (UPS). However, it is very difficult to obtain good waveforms of UPS systems using conventional control methods because there are many stabilized problems which depends on the variation of circuit and load parameters.

II. MAIN CIRCUIT DIAGRAM AND INVERTER MODEL

Fig.1 shows the half bridge PWM inverter of the UPS which is applied to proposed High-Gain Control. Particularly, when a PWM inverter is used to feed the load, a high Q L-C low-pass filter becomes necessary to eliminate the switching frequency component of the output voltage. The cut off frequency of this filter is set 1.6kHz because of the switching frequency of this PWM inverter is set 16kHz. The model of this PWM inverter with L-C filter is shown in Fig.2 [1]. Where the controller of the PWM inverter suppose to the constant gain. The transfer function of L-C filter is given by following (1).

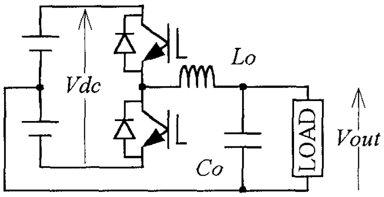

Fig.1. Configration of half bridge inverter

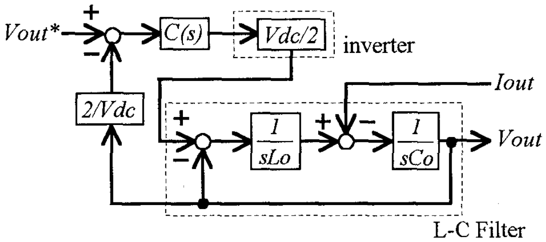

Fig.2. Output voltage feedback inverter model

$$G(s) = \frac{1}{1 + L_O C_O s^2} \qquad (1)$$

where Lo and Co are inductance and capacitance of the L-C filter, respectively. This L-C filter has very high gain characteristics at the cut off frequency f_C which is obtained by (2).

$$f_C = \frac{1}{2\pi\sqrt{L_O C_O}} \qquad (2)$$

III. THE BASIC CONTROL METHOD OF INVERTER

Fig.3 shows a conventional control circuit of the PWM inverter with L-C low-pass filter of constant DC link voltage Vdc [2]. The PWM inverter is controlled by the output voltage follow-up control PWM method to supply low total harmonic distortion (THD) output voltage to the load. The control flow is shown at follows:

1) The sinusoidal wave data SIN which is synchronized to source voltage Vin is obtained by the phase locked loop circuit (PLL) and a read only memory (ROM) using the pole signal of the source voltage waveform. The ROM is recorded a basic sinusoidal waveform data.

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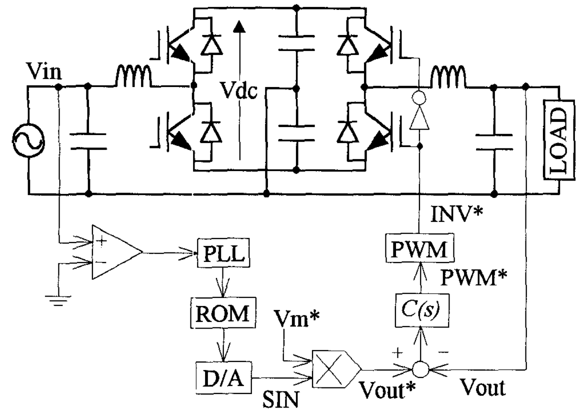


Fig.3. Control circuit diagram of PWM inverter

2) The output voltage reference Vout* which is obtained by multiply SIN by the output voltage amplitude reference.
3) The error of Vout* and output voltage Vout is input to the compensator *C(s)* and the inverter reference PWM* is obtained by output of the compensator.

Then, the closed loop transfer function of this control circuit is given by (3). It is clear that the stable condition of this control circuit is shown at (4) by Routh method.

$$G(s)=\frac{Ds^2+Ps+I}{L_O C_O s^3+Ds^2+(P+1)s+I} \quad (3)$$

$$\left.\begin{array}{l} L_O, C_O \ge 0 \\ P, I, D \ge 0 \\ D(P+1) \ge L_O C_O I \end{array}\right\} \quad (4)$$

where *P*, *I* and *D* are proportional gain, integral gain and differential gain of the PID compensator, respectively. In half bridge inverter, if PWM* contain offset, the voltage of two DC link capacitor will not be equal. And the output voltage of UPS does not permit offset voltage. Therefore, it is necessary that the PI compensator is rejected offset voltage to the full. But the frequency response of the controller using the PI compensator has a phase delay characteristics as shown in Fig.4 and the output voltage waveform is contained the harmonic components. Consequently, the differential compensator is needed for improvement of the above problem.

IV. PROPOSAL OF NEW CONTROL METHOD OF PWM INVERTER

The open loop transfer function of Fig.3 is obtained by (5).

$$G(s)=\frac{C(s)}{s^2 L_O C_O+sL_O/Z(s)+1} \quad (5)$$

where *Z(s)*, *C(s)* is Laplace transformed load impedance and transfer function of the compensator, respectively. From the above equation, it is clear that this control loop is factor of the oscillation of resonance frequency of the L-C filter in light load. Therefore, it is necessary that the inverter is considered to the following methods for avoid the above oscillation:

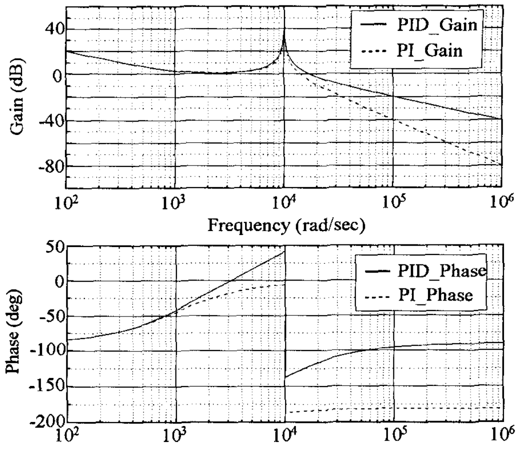


Fig.4. Frequency responses of PI and PID compensator

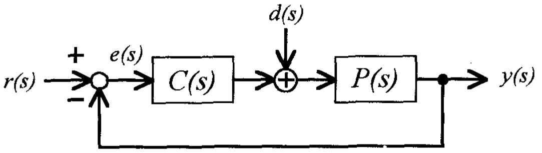


Fig.5. Ordinary feedback control circuit

- Modification of the main circuit
- Be dispersed by use of high order filter

- Feedback control of the capacitor current of L-C filter

- Adopting of the band eliminate filter which resonance frequency to the control loop

However these methods have the following demerits:

- These methods are sensitive to parameter changes of main and control circuit
- These methods need many sensors and controllers.

In addition, the efficacy of the usual control method of the PWM inverter could be obstructed by the following two points:

- Non-linearity owing to the PWM
- Non-linearity owing to the saturation of the controller

Developed High-Gain Control method can clear up the all above points. By increasing of the controller gain, it can avoid the use of additional sensors to achieve high reliability for settle the above points.

V. BASIC PRINCIPLE OF HIGH-GAIN CONTROL METHOD

Fig.5 shows the block diagram of the ordinary feedback control circuit.

In this figure, the closed loop transfer function *Gr(s)* from *r(s)* to *y(s)* is given by following (6).

$$Gr(s)=\frac{y(s)}{r(s)}=\frac{C(s)P(s)}{1+C(s)P(s)} \quad (6)$$

where *r(s)*, *y(s)*, *C(s)* and *P(s)* are reference, output, transfer functions of compensator and plant, respectively. And (7) is obtained in the case of $|C(s)|>>1$.

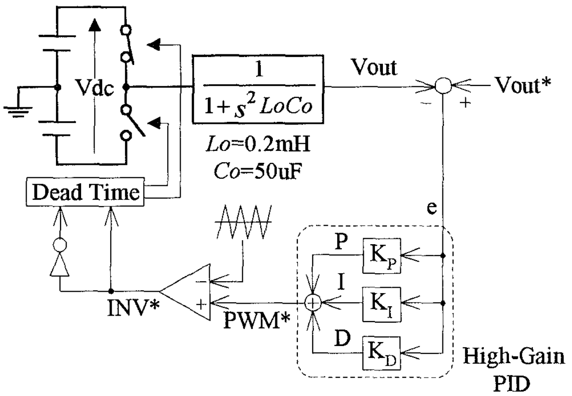
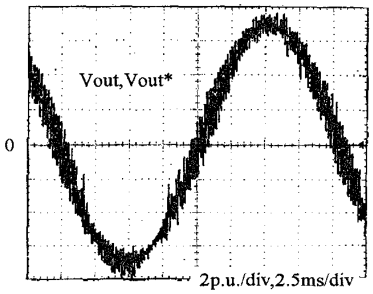
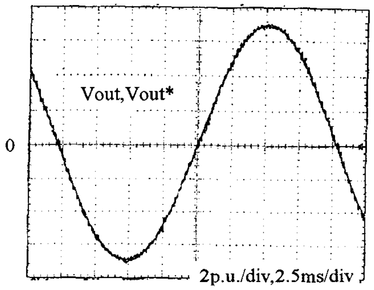


Fig.6. Analog circuit simulator of half bridge inverter



(a) With low gain compensator



(b) With high gain compensator

Fig.7. Results of the analog simulation
using High-Gain controller

$$Gr(s)\approx 1 \qquad y(s)\approx r(s) \tag{7}$$

Therefore, the system can be consider a completely follow system. The transfer function $\sigma(s)$ from reference $r(s)$ to error $e(s)$ is given by following (8).

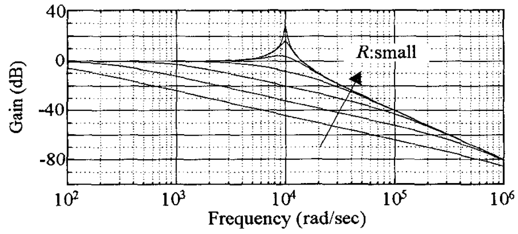
$$\sigma(s)=\frac{1}{1+C(s)P(s)} \tag{8}$$

where $\sigma(s)$ is sensitive function. And (9) is obtained in the case of $|C(s)|>>1$.

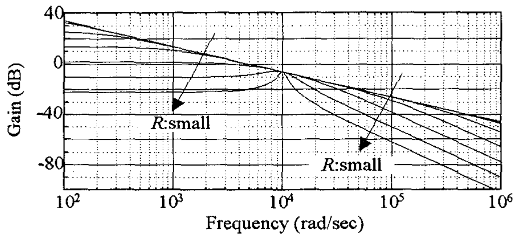
$$\sigma(s)\approx 0 \tag{9}$$

Therefore, it is noted that the system is robust control system to the variation of the plant. The transfer function from disturbance $d(s)$ to $y(s)$ is obtained by (10).

$$\sigma(s)P(s) \tag{10}$$



(a) Voltage feedback



(b) Current feedback

Fig.8. Frequency responses on voltage and current feedback control

Therefore, the system can be considered that the system rejects completely the effect of disturbance.

Fig.6 shows an analog circuit simulator of the half bridge inverter system which is experienced on this High-Gain control principle. In Fig.6, the inverter is constructed by analog switch IC and the compensator and the L-C filter are constructed OP-Amp. Fig.7 shows the results of the analog simulation using Fig.6. Simulation parameters are:

DC link voltage :20p.u.
Vout* :50Hz,Sinusoidal Wave,14Vp.u.pp
PWM carrier :16kHz,Triangle Wave,24Vp.u.pp
Dead time :4.5us
Load :No load

It is clear that High-Gain controller can be easily damped L-C oscillation of the output voltage.

VI. PREVENTIVE CONTROL OF THE CONTROLLER SATURATION AND INTEGRATER WIND-UP

A. Saturation

Usually, it cannot be realized that the gain set up to infinity because the gain of the compensator has its limit. In the matter of the compensator at all, its compensator of itself may saturate even if each component does not saturate. Therefore, when output of the compensator saturate, this system must be selected the feedback control loop and the feed forward control loop. In Fig.2, the open loop transfer function used the output voltage feedback and the output current feedback controls are represented as (11) and (12) at resistive load R.

$$Gv(s)=\frac{R}{s^2L_OC_OR+sL_O+R} \tag{11}$$

$$Gi(s)=\frac{1}{s^2L_OC_OR+sL_O+R} \tag{12}$$

Fig.8 shows frequency response at load change. These results express this system become steady used the output current feedback in light load, and the output voltage feedback in the other load. Therefore, developed controller

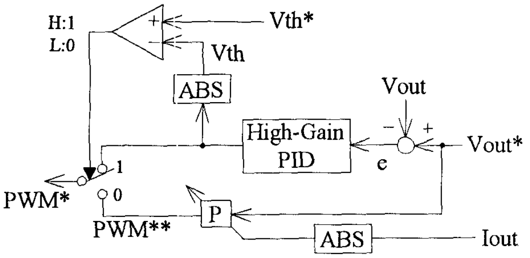
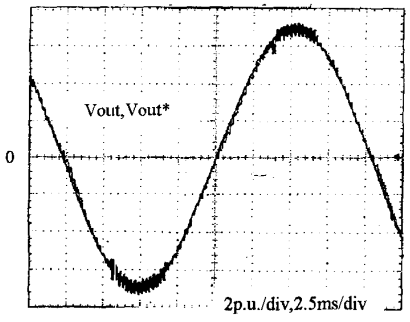
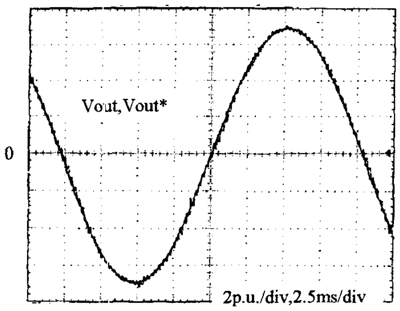


Fig.9 Saturation controller



(a) Without saturation controller



(b) With saturation controller

Fig.10. Output voltage waveforms with the saturation controller

proposes to select the feedback control in above two controls according state of load as shown in Fig.9.

If the absolute value Vth of PWM* in Fig.9 exceeds the threshold level Vth*, PWM* is changed the feed forward signal PWM**. PWM** is modulated Vout* by the amplitude of the output current. Of course, if Vth does not exceed Vth*, the control loop changes the usual control loop. Fig.10 shows the output voltage waveforms on analog simulation with the preventive control of the controller saturation. Simulation parameters are:

DC link voltage :20p.u.
Vout* :50Hz,Sinusoidal Wave,14Vp.u.pp
PWM carrier :16kHz,Triangle Wave,24Vp.u.pp
Dead time :4.5us
Load :No load
Vth* :10p.u.

It is note that the oscillation is reduced at near the peak where the output of the compensator is large.

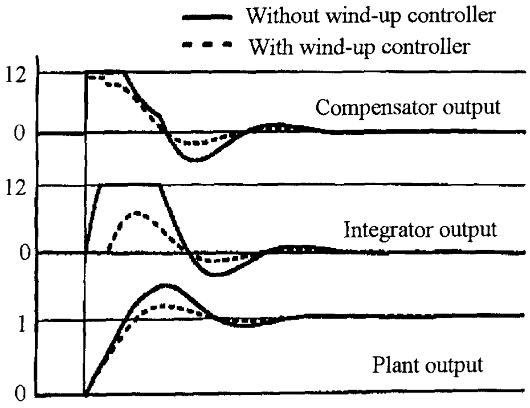


Fig.11. Integrator wind-up performance

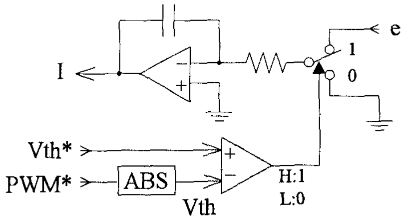


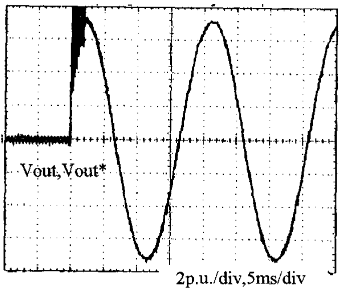
Fig.12. Integrator wind-up controller

B. Integrator Wind-up

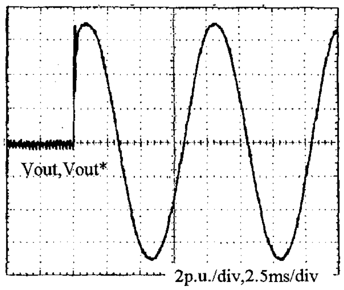
It may be observed the integrator wing-up phenomenon in this system. If the integrator wind-up has occurred, the integrator still continue integrate operation but the compensator output is saturate. This perform is shown in Fig.11 [3]. Therefore the response of all system becomes high oscillatory. It is easy to occur integrator wind-up at large gain. Therefore developed controller proposes to modify the control circuit as shown in Fig.12. In Fig.12, if the absolute value Vth of PWM* exceeds the threshold level Vth*, the input error signal of integrator is selected 0 for prevent the integrator to hold the input of integrator. And if Vth does not exceed Vth*, the control loop changes the usual control loop. When this controller is used, the step response is shown Fig.11. This result shows the response of system become quickly used the integrator wind-up controller. Fig.13 shows the output voltage waveforms on analog simulation using the integrator wind-up control when Vout* is changed. Simulation parameters are:

DC link voltage :20p.u.
Vout* :50Hz,Sinusoidal Wave,14Vp.u.pp
PWM carrier :16kHz,Triangle Wave,24Vp.u.pp
Dead time :4.5us
Load :No load
Vth* :10p.u.

It is clear that the oscillation is reduced at changing point of the output voltage reference Vout* where the output of the integrator is large. The step change of Vout* is equivalent to the step change of load. Therefore, this result shows that this controller can reduce the output voltage variation.



(a) Without integrator wind-up controller



(b) With integrator wind-up controller

Fig.13. Output voltage waveforms with the integrator wind-up controller

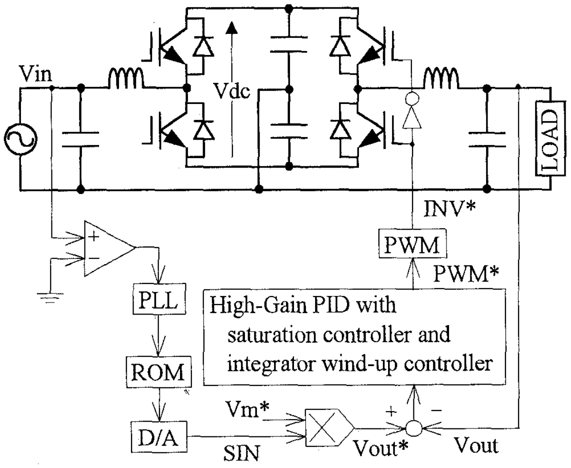


Fig.14. Proposed control circuit diagram of PWM inverter

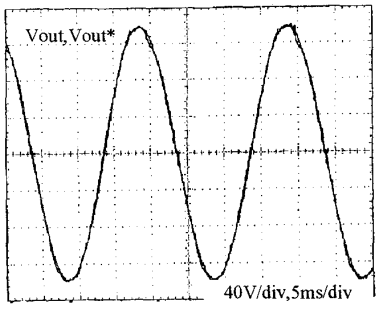


Fig.15. Output voltage waveforms using analog controls

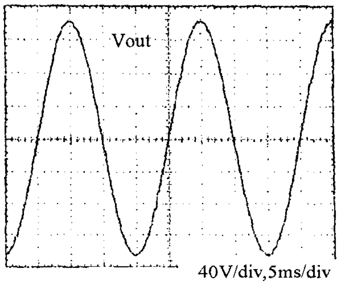


Fig.16. Output voltage waveform using digital controls

VII. EXPERIMENTAL RESULTS

Fig.14 shows the configration of the main circuit of the half bridge inverter and rectifier. The controller including the saturation and integrator wind-up controls of compensator is designed by analog circuit in accordance with above control simulation circuit as shown Fig.9 and 12. Fig.15 shows the output voltage waveforms used the circuit shown in Fig.14. The parameters in the experiment are:

DC link voltage :300V
Vout* :50Hz,Sinusoidal Wave,14Vpp
PWM carrier :16kHz,Triangle Wave,24Vpp
Dead time :4.5us
Load :No load
Vth* :9.5V.

This result is coincidence with the above simulation results. It is clear that these controllers can reduce the oscillation of the output voltage on no-load when it is most difficult case to control.

Next, Fig.16 shows experimental results when a single-chip floating point Digital Signal Processor (DSP:NEC uPD77240) instead of the adopted all analog control circuit. This digital controller and above analog controller are same performance. However, PWM circuit is used analog circuit because of PWM must perform on very fast. The parameters in the experiment are:

Sampling frequency :96kHz
DC link voltage :300V
Vout* :50Hz,Sinusoidal Wave,280Vpp
PWM carrier :16kHz,Triangle Wave
Dead time :4.5us
Load :No load
Vth* :9.5V.

This result is coincidence with the above analog control results.

Finally, all the control of the UPS is realized on the simple programs in the DSP. Fig.17 shows the configuration of the main circuit of the UPS having flywheel energy storage unit (FW) which is shown in Fig.18 [4]. The converter maintains an even DC link voltage and improves the input power factor. FW stores the energy as the rotating energy. Then, FW energy control is achieved by the control of the three-phase inverter/converter. And, FW has great two points that the energy stored efficiency is higher because of mechanical loss is very low and the life time is a few times longer than battery. The flow of this system is shown in Fig.19. In usual operation, while the energy is converted from AC to DC by the converter,

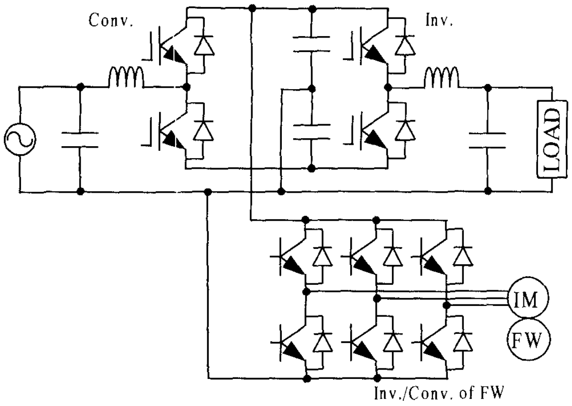


Fig.17. Configration of main circuit of UPS

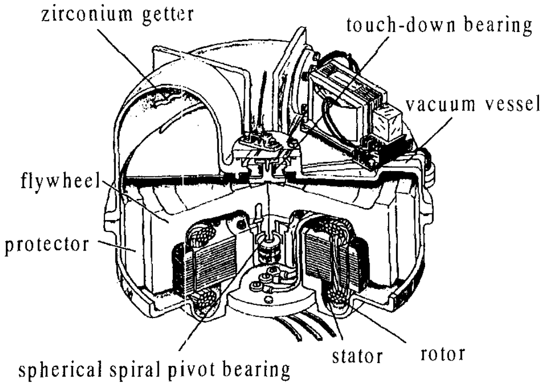


Fig.18. Flywheel energy storage unit

the energy is stored to a rotating energy of FW and output the energy converted from DC to AC by the inverter using High-Gain controller having the saturate and the integrator wind-up controllers. In a power failure, while the converter is separated from the power system, the energy is converted from a rotating energy of FW to an electric energy and output to the load. Fig.20 shows experimental results at instantaneous power failure. The parameters in the experiment are:

Sampling frequency	:96kHz (inverter)
Sampling frequency	:32kHz (converter , FW)
DC link voltage	:300V
Vout*	:50Hz,Sinusoidal Wave,280Vpp
PWM carrier	:16kHz,Triangle Wave
Dead time	:4.5us
Load	:Resistive load (1kW)
Vth*	:9.5V.

It shows that this UPS can maintain a stable output voltage during power failure.

VIII. CONCLUSION

In this paper, new High-Gain Control with following controllers of PWM inverter on the single phase UPS is described.

(A) Saturation controller for compensator saturation in High-Gain Control

(B) Integrator wind-up controller for quick response in integrator

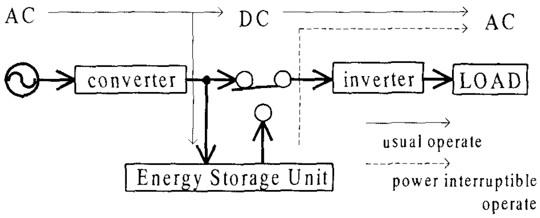


Fig.19. Power flow in UPS

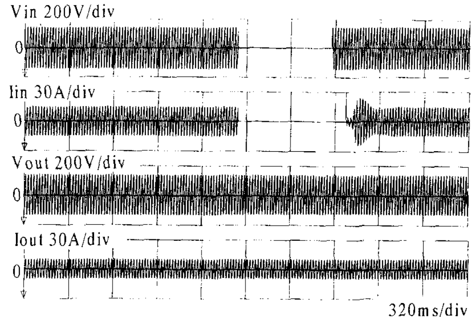


Fig.20. Experimental results at instantaneous failure

As results, the permissible variation range of the circuit parameters could be increased, and the response and the design of the controller are achieved high speed and simple construction.

The controllability of the proposed method was first verified by analog circuit simulator, and then by real circuit using both analog and digital controller. The controls of the inverter, converter and energy storage unit were performed simultaneously to verify its affordability as an UPS system.

IX. ACKNOWLEDGMENT

The authors would like to express their appreciation to Power Electronics Laboratory members of Nagaoka University of Technology and members of Components Business Division of Yokogawa Electric Corporation.

X. REFERENCES

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