Implementation of Inverter Systems for DC Power Regeneration

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Abstract – This paper deals with implementation of inverter systems for DC power regeneration, which can regenerate the excessive DC power from DC bus line to AC supply in substations for traction systems. From the viewpoint of both power capacity and switching losses, a three-phase square-wave inverter system is adopted. To control the regenerated power, the magnitude and phase of fundamental output voltages should be appropriately controlled in spite of the variation of input DC voltage. Inverters are operated with modified α-conduction mode to fix the potential of each arm. The overall system consists of the line-to-line voltage and line current sensors, an actual power calculator using d-q transformation method, a complex power controller with PI control scheme, a gating signal generator for modified α-conduction mode with δ and α, a DPLL for frequency followup, and power circuit.

1. Introduction

Regenerative braking systems are used in most railway systems. Braking power fed back into the DC bus line is first absorbed by other powering trains. However, if there is no powering trains in the same section of DC bus line or the braking power exceeds the power needed by nearby trains, the voltage of the DC bus line becomes rising more and more. If this voltage exceeds some level, braking resistors are operated to protect overall system against high voltage and, as a result, electric energy is spent wastefully as heat energy. To cope with this problem, inverter systems can be used to feed the excessive regenerated DC power back into AC supply.

In the DC power regenerating system, the voltage of DC bus line is decreased according to the regenerating power during the regenerating operation to AC supply. However, the output voltage of the system should be matched to the voltage of AC supply with respect to magnitude, frequency, phase, and waveform.

Because inverters are inherently the one of switching converters, the output voltage waveform is a pulse type and therefore the quality of the AC supply becomes poor due to the injected harmonic currents. To reduce the harmonics injected into the AC supply, PWM method is suitable because of its flexibility. However, frequent switchings cause high switching losses, especially in high power systems such as traction systems. During the operation for DC power regeneration, the excessive electric power should be regenerated into AC supply as soon as possible within the permissible range. The efficiency of the regenerative inverter system is decreased by the reactive power included in the regenerated power.

This paper deals with implementation of inverter systems for DC power regeneration which can pump the excessive regenerated energy from DC bus line to AC supply. The system for experiments is a prototype with the power rating of 5kVA at 220V.

2. Inverter System for DC Power Regeneration

2.1 inverter system

Fig. 1 shows the configuration of traction system with inverters for regeneration. Powering trains are supplied from AC supply (in traction substations) by way of rectifiers, and the excessive energy fed back from either braking trains or trains running on railway with gradient is regenerated into AC supply through inverter systems.

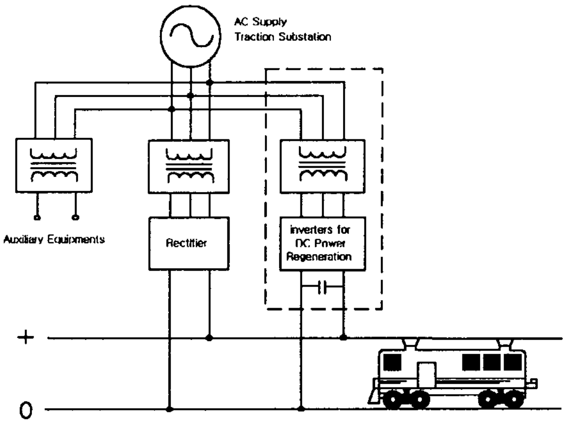


Fig. 1. Traction system with inverters for regeneration.

In the viewpoint of power capacity, thyristors are suitable as switching elements. But thyristor controlled inverters have some problems such as commutation failure. If inverter system for DC power regeneration is furnished separately from the rectifier for powering, the inverter capacity may be smaller than the rectifier capacity and thus IGBT inverters can be used. It was reported that the ratio of the capacity of inverter to that of rectifier lay between 1/13 and 1/8.3 [1].

In the case of Seoul subway systems, AC supply is the power receiving line of 22,900 volts and the no-load output voltage of rectifiers for powering is DC 1,593 volts. One section of DC bus line is about 3 ~ 4 km in length and one traction substation covers two sections of the DC bus line.

Fig. 2 shows the overall inverter system for DC power regeneration.

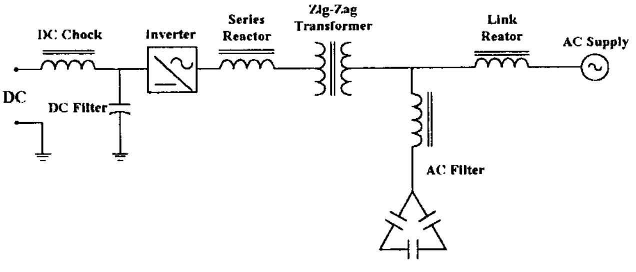


Fig. 2. Inverter system for DC power regeneration.

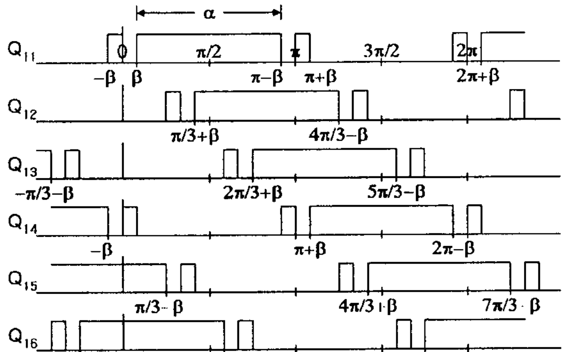
During the regenerating operation from DC bus line to AC supply, the input voltage of inverters is decreased, but the output voltage should be matched with the voltage of AC supply. This means that the magnitude and phase of the fundamental output voltage should be maintained constant with the variations of DC input voltage.

We control the square-wave inverter with modified α-conduction mode. In modified α-conduction mode, each switching element conducts one time for α degree in one half-period and twice for β degree in the other half-period to fix the potential of output terminals[2]. Control signals should be reduced by β degree round a center of 90°. Otherwise, not only the magnitude but also the phase of the fundamental output voltage is varied. The gating signals shown in Fig. 3(a) are shifted from each other by π/3 to obtain three-phase balanced voltages.

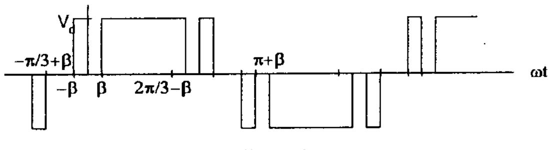
Using the relation of β=(π−α)/2, the line-to-line voltage, v_{UV}, that is shown in Fig. 3(b) can be expressed in Fourier series as

$$v_{UV} = \sum_{n}^{odd} V_{n\alpha} \sin n\left(\omega t + \frac{\pi}{6}\right) \tag{1}$$

where $V_{n\alpha} = \frac{4V_d}{n\pi} \cos\frac{n\pi}{6} \left\{2\cos n\left(\frac{\pi}{2} - \frac{\alpha}{2}\right) - 1\right\}$.



(a) gating signals



(b) Line-to-line voltage v_{UV}

Fig. 3. Output voltage in modified α-conduction mode.

Because n is an odd number, cos $n\pi/6=0$ for $n=3m$ and therefore the orders of remaining harmonics are $6m\pm1$.

If the value of pulse width, α, lies between π/2 and π, the range of the rms fundamental voltage is

$$\frac{\sqrt{6}}{\pi}(\sqrt{2}-1)V_d \le V_{1,l-l} \le \frac{\sqrt{6}}{\pi} V_d \tag{2}$$

and the margin of voltage variation is 58.6%. In the traction system that we have studied, the starting and ending voltages for the excessive DC power regeneration are DC 1,750 volts and DC 1,630 volts, respectively; the control margin of 6.9% is required. As the results, though the input voltage of the inverter system is varied in the range of 1,630 ~ 1,750 volts, the output voltage can be maintained constant.

2.2 System Configuration for Harmonic Reduction

To reduce the harmonic contents, two inverters are connected in series like as Fig. 4. The second inverter is phase shifted by π/6 and the line-to-line voltage is

$$v_{uv} = \sum_{n}^{odd} V_{n\alpha} \sin n\omega t. \tag{3}$$

If the output voltages of two inverters are combined, the THD of voltage is decreased due to the phase shift of π/6, but the orders of remaining harmonics are the same as before. By duplication of two inverters, the power capacity of each inverter may also be decreased, that becomes of advantage in manufacturing the high power system.

In the output voltage of the inverter system, the lowest order of harmonics is 5th order. To remove the lowest order harmonic voltage, it is used the zig-zag connected output transformer as shown in Fig. 4. N_{221} must be the same as N_{222} for keeping the direction of phasor voltages, v_{UV}, v_{VW}, and v_{WU}. Denoting turn ratios, $N_{12}/N_{11}=N_1$ and $N_{221}/N_{21}= N_{222}/N_{22} =N_2$, v_{RO} can be expressed as

$$\begin{aligned} v_{RO} &= N_1 v_{UV} + N_2 v_{uv} - N_2 v_{vw} \\ &= \sum_{n}^{odd} V_{n\alpha}\left(N_1 + 2N_2 \cos\frac{n\pi}{6}\right) \sin n\left(\omega t + \frac{\pi}{6}\right) \end{aligned} \tag{4}$$

where $n=6m\pm1$ and is in phase with v_{UV}. The peak value of n-th harmonic voltage, V_{np}, is

$$V_{np} = V_{n\alpha}\left(N_1 + 2N_2 \cos\frac{n\pi}{6}\right). \tag{5}$$

If the relation of

$$N_1 + 2N_2 \cos\frac{5\pi}{6} = 0 \tag{6}$$

is satisfied in eq. (5), V_{5p} becomes zero. This implies that if the relation between turn ratios N_1 and N_2 is $N_1 = \sqrt{3}N_2$, 5th harmonics is removed. By substituting the relation of $N_1 = \sqrt{3}N_2$ into eq. (5), V_{np} becomes as the following.

$$V_{np} = V_{n\alpha} N_2\left(\sqrt{3} + 2\cos\frac{n\pi}{6}\right) \tag{7}$$

Reconsidering the above equation, the other harmonics that satisfy the relation of $\sqrt{3}+2\cos(n\pi/6)=0$ can also be removed. As a result, all the harmonics of $n=6(2m-1)\pm1$

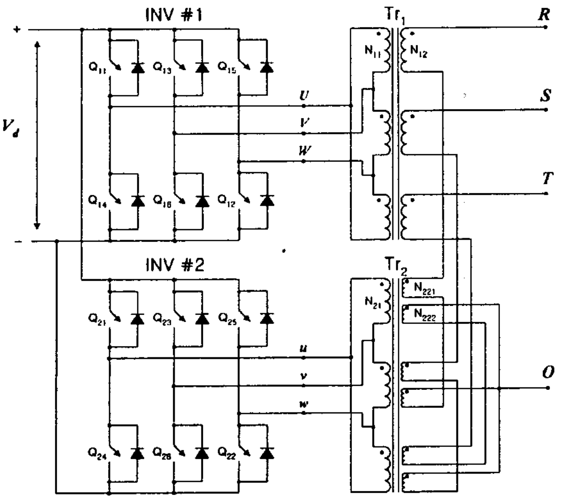


Fig. 4. Configuration of inverter system for regeneration.

orders are additionally eliminated and only the harmonics of $n=12m\pm1$ orders are remained.

The line-to-line output voltage of the inverter system, v_{RS}, is as follows.

$$v_{RS} = \sum_{n}^{odd} V_{na}\, N_1 \left(\sqrt{3}+2\cos\frac{n\pi}{6}\right)\sin n\left(wt+\frac{\pi}{3}\right). \tag{8}$$

In the viewpoint of THD reduction, we install a 12th AC filter instead of the 11th AC filter [3].

3. Power Control

The output voltage waveforms of the above inverter system are not sinusoidal but three-phase balanced. Therefore, per-phase circuit like as Fig. 5 can be used for analysis. Because there exist only link reactors, power circle diagram is the same as Fig. 6 and the regenerated complex power, $S_{AC} = P_{AC} + jQ_{AC}$, is as follows [4].

$$P_{AC} = \frac{|V_{R1}||V_A|}{X_l}\sin\delta \tag{9}$$

$$Q_{AC} = \frac{|V_A|}{X_l}(|V_{R1}|\cos\delta - |V_A|). \tag{10}$$

where V_{R1} : Fundamental component of V_{R0}
V_A : A-phase voltage of AC supply
δ : Phase difference between V_{R1} and V_A

To improve power factor at the input terminal of AC supply, the reactive power should be close to zero. In eq. (10), if the relation of

$$|V_{R1}| = \frac{|V_A|}{\cos\delta} \tag{11}$$

is satisfied, the regenerative reactive power becomes zero. From eqs. (9) and (11), it can be seen that the active power,

$$P_{AC} = \frac{|V_A|^2\tan\delta}{X_l}, \tag{12}$$

may be regenerated with the condition of δ > 0. In Fig. 6, since both circles have the same radius, receiving-end circle may intersect the active power axis under the condition of $|V_{R1}| > |V_A|$. If this condition is satisfied, there exist two points for $Q_{AC} = 0$. The condition for $Q_{AC} = 0$ and $P_{AC} > 0$ may be met at the point H in the right half-plane.

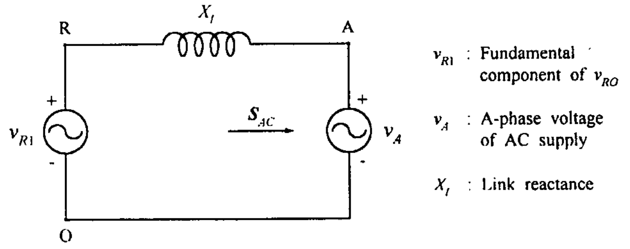


Fig. 5. Per-phase circuit.

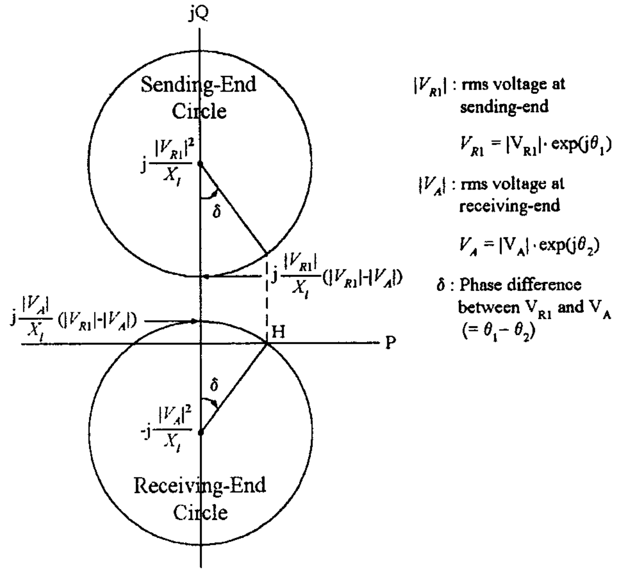


Fig. 6. Power circle diagram.

Assuming that $|V_A|$ is constant, $|V_{A1}|$ and δ should be controlled to control the active and reactive power. Since active power and reactive power are coupled with $|V_{R1}|$ and δ, decoupling is needed for smooth control.

There are two decoupling methods. One is to divide the current flowing in link reactor into active and reactive components, and control each component independently. The other is to ignore the variables with relatively low sensitivity according to controlled variables. This method is simple to implement and effective even for low switching frequency. Because regenerating systems have the restriction of switching frequency due to their power capacity, the latter method is convenient for implementation.

The above control method is based on the fundamental components and thus the reactive power produced by harmonics is not considered. Therefore, it is needed a controller capable of controlling the reactive power nearly to zero even for nonsinusoidal cases.

Because the phase difference is below 10 degrees and the output voltage of inverter systems is varied within the range of 15 percents [3], active power is more sensitive to phase difference and reactive power more sensitive to the magnitude of output voltages which is the function of conduction angle. Consequently, active power and reactive power are the functions of phase difference and conduction angle, respectively. PI controllers are used to control the active and reactive power.

The reference value of conduction angle that satisfies the condition of $Q_{AC}=0$ at δ_k may be determined as the followings.

$$|V_{R1}| = \frac{1}{\sqrt{2}}\frac{4V_d}{\pi}\cos\frac{\pi}{6}\left\{2\cos\left(\frac{\pi}{2}-\frac{\alpha_{k,ref}}{2}\right)-1\right\} \cdot N_2\left(\sqrt{3}+2\cos\frac{\pi}{6}\right)$$

$$= \frac{6\sqrt{2}\,V_d}{\pi}\left\{2\sin\frac{\alpha_{k,ref}}{2}-1\right\}N_2 = \frac{|V_A|}{\cos\delta_k}$$

$$\therefore \ \alpha_{k,ref} = 2\sin^{-1}\left(\frac{\pi|V_A|}{12\sqrt{2}\,N_2\,V_d\cos\delta_k}+\frac{1}{2}\right) \qquad (13)$$

4. Implementation

The overall block diagram for the complex power control scheme is shown in Fig. 7. The overall system consists of the line-to-line voltage and line current sensors, an actual power calculator using d-q transformation method, a complex power controller with PI control scheme, a gating signal generator for modified α-conduction mode with δ and α, a DPLL for frequency followup, and power circuit.

4.1 Software

Fig. 8 shows the flow chart of control program for the controller. The program is consist of main routine, EINT1(External 1) interrupt service routine, SPRT (Serial Port Receive Timer) interrupt service routine, TINT0 (Timer 0) interrupt service routine.

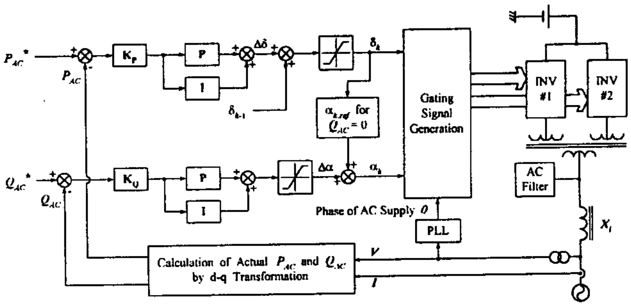
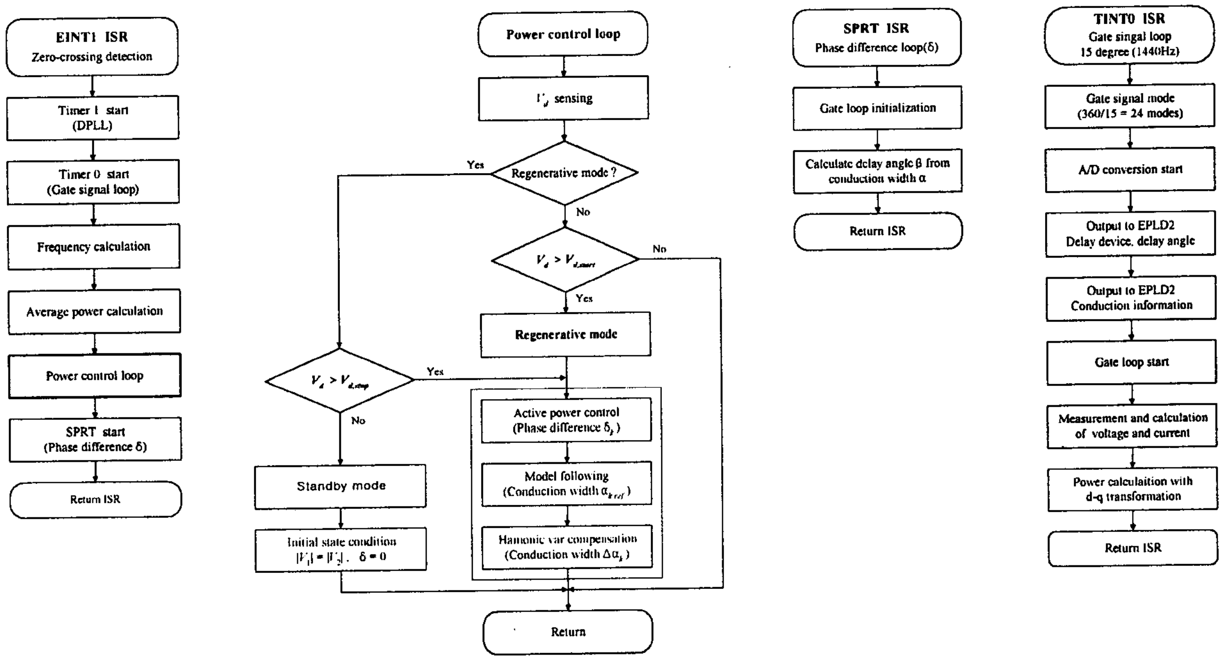


Fig. 7. Overall block diagram for the complex power control scheme.

Fig. 8(a) shows the flow chart of EINT1 interrupt service routine, which is called at zero-crossing detection of AC bus voltage. EINT1 interrupt service routine is consist of internal timer 0, serial port receive timer initialization, frequency and average power calculation, and power control loop.

Power control loop shown in Fig. 8(b) is operated in either standby mode or regenerative mode according to the level of DC voltage. When DC voltage is larger than regenerating start voltage, power controller begins to operate in regenerative mode. As the excessive energy is regenerated from DC bus line to AC supply, DC voltage is decreased. When the DC voltage becomes lower than regenerating stop voltage, controller returns to standby mode.

To regenerate the energy from DC bus line to AC bus line, the output voltage of inverter system has to be lead in phase to AC supply voltage. SPRT interrupt is used to



(a) EINT1 ISR (b) Power control loop (c) SPRT ISR (d) TINT0 ISR

Fig. 8. Flow chart of control program.

control phase difference between the output voltages of regenerative inverter system and AC supply voltage. Fig. 8(c) shows the flow chart of SPRT interrupt service routine.

Fig. 8(d) shows the flow chart of TINT0 interrupt service routine that includes gate signal generation algorithm, measurement of voltage and current, and power calculation. One cycle of AC bus voltage is consist of 24 gate signal cycles. In each gate signal cycle, two devices in one arm among six arms are switched after delay angle and other devices in five arms are on-state or off-state according to conduction information.

Fig. 9 shows the block diagram for the gate signal generator. Fig. 10 shows the block diagram of an actual power calculator using d-q transformation method.

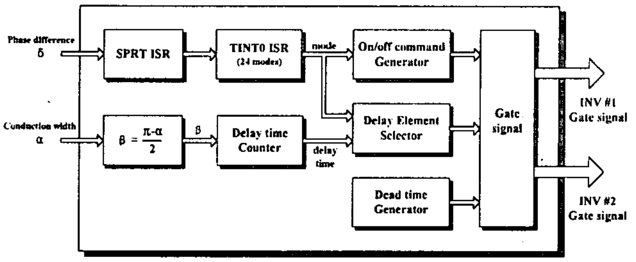


Fig. 9. Block diagram for gate signal generator.

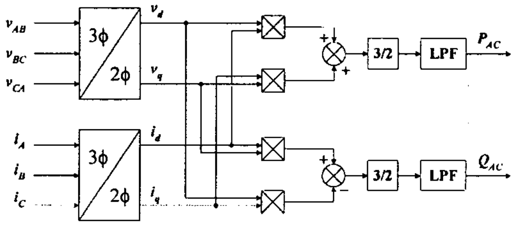


Fig. 10. Block diagram of power calculator.

4.2 Hardware

Control board for the regenerative inverter system as shown in Fig. 11 is consist of 32-bit DSP TMS320C32, two EPLDs, six analog-to-digital converters, a digital-to-analog converter and gate drive circuits. EPM7128SLC84 (EPLD1 in Fig. 11) is used for address decoding, clock generation, and status checking. EPM7160SLC84(EPLD2 in Fig. 11) is used for interrupt handling and gate signal generation.

The 12-bit ADC MAX122 is used to measure two AC line-to-line voltages, two AC line currents, and DC bus voltage and current. The 4-channel, 12-bit DAC AD664 is used to display control variables, sensed values, and system parameters.

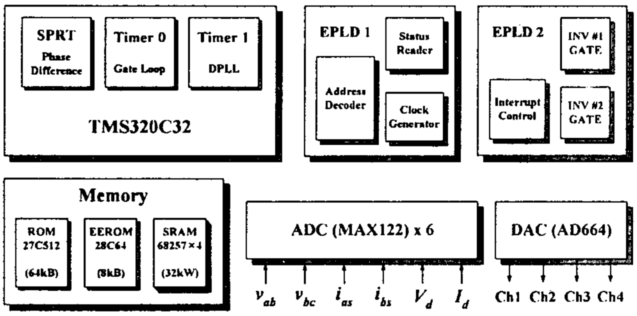


Fig. 11. Construction of control board.

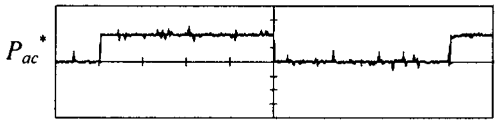
In order to implement the decrease of DC bus voltage according to active power regeneration, a semi-controlled rectifier and a DC filter are furnished in front of the inverter system. Power circuit of the regenerative system is consist of two inverters, series reactors, zig-zag output transformers, an AC filter, and link reactors.

5. Experimental results

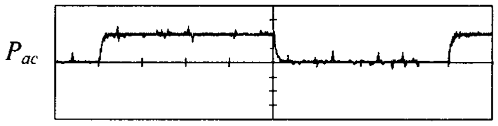
Experiments are carried out on the prototype with the rating of 5 kVA at AC 220 volts, which is installed in Power Electronics Laboratory at Dankook University. The Specifications of the prototype are listed in Table 1.

Fig. 12 shows dynamic responses to the variations of reference power. Reference values are initially P^*_{AC}=0 and Q^*_{AC}=0. Only the reference active power, P^*_{AC}, is changed from 0 kW to 4 kW at t = 5 sec, and reference values return again to P^*_{AC}=0 and Q^*_{AC}=0 at t = 25 sec. And the regenerating operation is restarted at t = 45 sec.

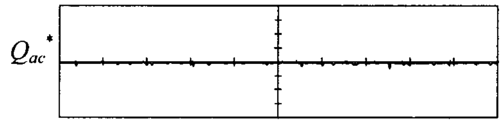
Fig. 12(a) ~ Fig. 12(d) show that the regenerative active



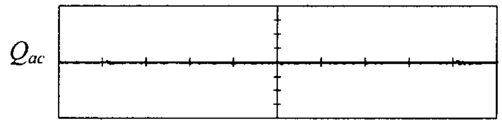
(a) Active power reference [2kW/div.]



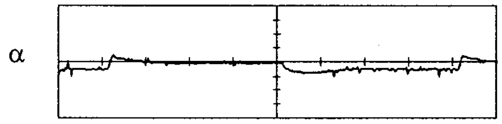
(b) Regenerating active power [2kW/div.]



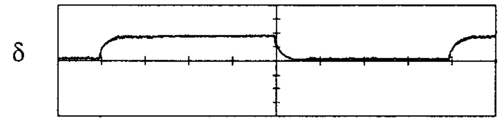
(c) Reactive power reference [2kvar/div.]



(d) Regenerating reactive power [2kvar/div.]



(e) Conduction width α [15deg./div.]
(center line of y-axis is 120deg.)



(f) Phase difference δ [5deg./div.]

Fig. 12. Dynamic Responses of regenerative inverter system.
(x-axis : [5sec/div.])

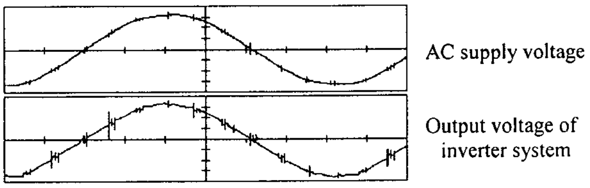
power is well controlled to its reference value and the regenerative reactive power is still remained at nearly zero. Fig. 12(e) and Fig. 12(f) are conduction width and phase difference, respectively. As expected previously, active power is the function of phase difference.

Fig. 13 shows the voltage at the output stage of the regenerative inverter system and the AC supply voltage. When the regenerative inverter system is operated in standby mode, as shown in Fig. 13(a), the output voltage of the regenerative inverter system is in phase with AC supply voltage. When the regenerative inverter system is operated in regenerative mode, as shown in Fig. 13(b), the output voltage of regenerative inverter system compared with the corresponding AC supply voltage is larger slightly in magnitude and lead in phase.

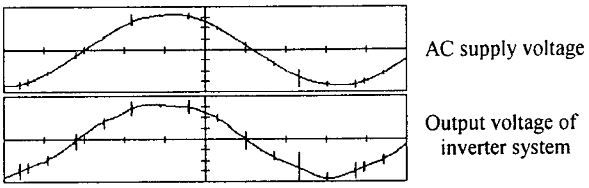
Fig. 14 shows the phase voltage and line current at the output stage of inverter system in regenerative mode. The phase difference between the phase voltage and the line current is almost 180 degrees. It means that the active power is being transferred from DC bus line to AC supply. Fig. 15 is the power factor at the input terminals of AC supply and shows that the power factor in regenerative mode is higher than 0.99. Fig. 16 shows the current flowing into AC filter.

Table 1. Specifications of prototype system.

	Quantity	Value
DC filter	Inductance	5.5 mH
	Capacitance	2200μ F
Series reactor	Inductance	0.64 mH
Output transformer	T1 turns ratio	0.51
	T2 turns ratio	0.294
Link reactor	Inductance	3.88 mH
AC filter	Inductance	0.135 mH
	Capacitance	360μ F

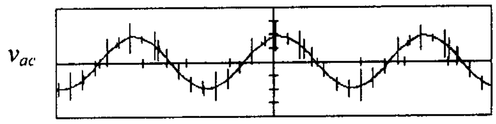


(a) Standby mode

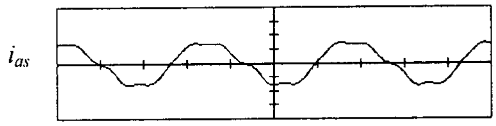


(b) Regenerative mode

Fig. 13. Output voltage of the regenerative inverter system and AC supply voltage. ([90V/div.] / [2ms/div.])



(a) Phase voltage [90V/div.]



(b) Line current [10A/div.]

Fig. 14. Output of inverter system. (x-axis : [5ms/div.])

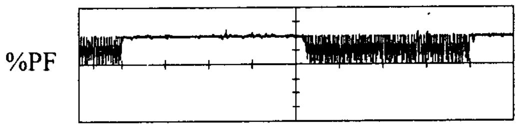


Fig. 15. Power Factor. ([50%/div.] / [5sec/div.])

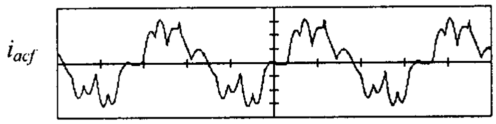


Fig. 16. Current flowing into AC filter ([10A/div.] / [5ms/div.])

6. Conclusion

This paper deals with implementation of inverter systems for DC power regeneration, which can regenerate the excessive DC power from DC bus line to AC supply in substations for traction systems.

The overall system is consist of an actual power calculator, a complex power controller, a gating signal generator, a DPLL, and a power circuit. The control board for the regenerative inverter system was constructed by using a 32-bit DSP, two EPLDs, six ADCs, and a DAC.

Experiments are carried out for the prototype with the power rating of 5kVA at 220V. Experimental results show that the regenerative active power is well controlled to its reference and the regenerative reactive power is still remained at nearly zero. The results also show that the power factor of regenerating system is higher than 0.99 during regenerative mode.

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