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Point of Soft Switching Technology on Practical Application

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Abstract:

Remarkable progress has been performed in power electronics, using high frequency switching based on the improvement of power semi-conductor devices. In the other hands, it gives us serious problems, such as, insulation, increasing of the high frequency leakage current, and electric corrosion of bearing in the loaded motors driven by inverters using high frequency switching. To improve these problems, many researches have made especially on the application of soft switching technologies. From this point of view IEE-Japan had started the research groups on soft-switching technology 1997 and 1999. This paper is a survey based on the discussion in this research group with results of ARCP inverter applied for 210kVA power supply.

Keyword : Soft Switching, ARCP-Inverter, Auxiliary Power Supply, SI-Thyristor

1. Introduction

In the field of power electronics, it is realized to get high performance using high frequency switching, based on improvement of power semiconductor devices as IGBT. It gives us many remarkable contributions not only for power conversion also for many industrial systems like vector control which gives us new filed on motor drive system.

This high frequency switching gives us higher dv/dt on the out put pulse in the same time. As a results of this high frequency switching, we have met serious problems like failure of insulation, increasing of high frequency leakage current, and sometimes electric corrosion of bearing in loaded motors. [1]~[7]

Soft switching technology is very effective for these problems and reduction of switching loss in devices also, so there are many researches and trials.[8]-[11]

From this point of view IEE-Japan had established the research committee on soft-switching technology 1997 and extension 1999. In this paper, I will introduce major soft switching technologies applicable for high power converter, based on the survey made by this committee, with a practical result of ARCP (Auxiliary resonant commutation pole) inverter which was developed for railway motor couch as auxiliary power supply by Toyo Electric Mfg. Co., Ltd. [38]

2. Circuit topologies proposed for this use

2-1 General review

Soft switching are applied for DC/DC converters of small power range widely, however, there are many difficulties on the application for high power equipment, for instance, increasing of peak stress for main devices, increasing of the power loss in resonance circuits, difficulty to meet controllability required from high class application and so on.

There are proposals using adjustment of the gate drive current for IGBT, or make some arrangement on snubber circuit in smaller power converter. However, it is necessary to make up soft switching by main circuits configuration in high power converters.

From these points of view there are many proposals as follows:

(a) Resonant DC link methode
To get ZVS(zero volt switch) or ZCS(zero current switch) by oscillation of input DC current or voltage.

(b) Commutation using inductor
To get soft switching using loss less snubber in turn-off state, and current suppression effect by inductance which added to main circuit, in turn-on state.

(c) Partial resonance inverter
To make resonance when the device is turn on or turn off stages only.

2-2 Parallel resonant DC link method

Fig.2-1 shows proposal of parallel resonant DC link inverter which has resonant circuit by L_r and C_r in DC stage and makes ZVS or ZCS in main devices when the DC voltage is zero by the resonance circuit operation. [15]

In this proposal it is possible to use main devices in stead of device T_c.

In this topology has merits as follows;

(1) No switching loss in main devices.
(2) No higher frequency than resonant frequency.
(3) Need not use snubber circuit.

However has some disadvantages as follows,

(a) Peak voltage up to 2 times of power supply or more by resonance.
(b) Big power dissipation in resonance circuit at partial load operation.

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(c) In this topology the output power is adjusted by PDM (pulse density modulation), so it is necessary to use very high frequency than output frequency to get wide control range.

(d) Difficult to get good distortion factor in output current.

To improve these disadvantages there are some proposals for suppression of peak device stress by adding auxiliary circuit like fig.2-2. [16][17] By this improvement the peak voltage of DC stage V_{crmax} is clamped to original voltage of $E_{dc}+V_{cc}$ (voltage of capacitor C_c). However, it requires additional control for this circuit and gives us additional loss in added circuits,

2-3 Commutation using inductor

Fig.2-3 shows an example of this proposed circuit.[18][19] In this circuit the waveform of the output terminals between u, v, and w are pulses modulated by PWM, but output waveforms between terminals of capacitor C_{zc} are in sinusoidal waves.

In this propsal there is no resonance circuit, however, it is possible to get soft switching by loss less snubber of C_{R1}, C_{R1}' at turn off, by inductors L_{zc} at turn on.

In this circuit the output current is limited less than circulating current. If we use conventional PWM control using constant carrier frequency, it request us big circulating current in spite of partial loaded condition or lower modulation factor.

As improvement, it is proposed to modulate the carrier frequency sinusoidal, to higher frequency in small output and to lower in high output.[20]

2-4 Partial resonance inverter

(1) Partial resonance inverter by passive element

Fig.2-4 shows resonant pole inverter.[21] Adding resonant reactor L_r, and resonant capacitor C_F, soft switching are performed in main devices, by the partial resonance with loss less snubber capacitors C_{r1}, C_{r2}'.

In this circuit to get soft switching, it is necessary to be negative current in inductor when main switches turn on. As a results large current of inductor is requested, it gives us higher loss. AS improvement, it is proposed to use variable hysteresis band in PWM control comparator.

Fig.2-5 shows resonant diode pole inverter, improved circuit of above circuit shown in fig.2-6, by adding diodes for voltage clamping and free wheeling of load current. [22]

Although it is available to get good partial resonance by this circuit, in the same time gives us some drawbacks as follows;

(a) Big resonance current is needed in smaller load operation.

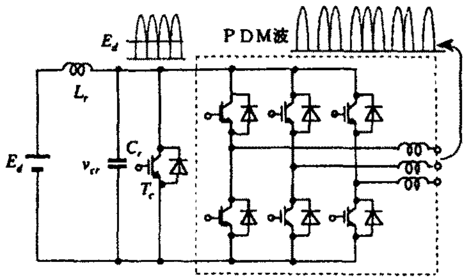


Fig.2-1 Parallel resonant DC link Inverter

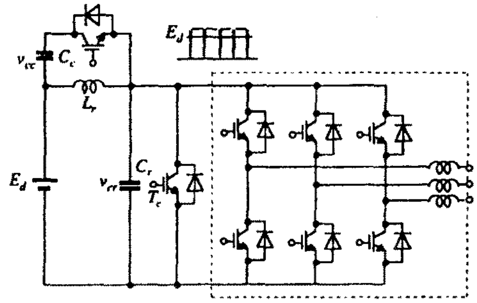


Fig.2-2 Parallel resonant DC link Inverter with voltage cramp

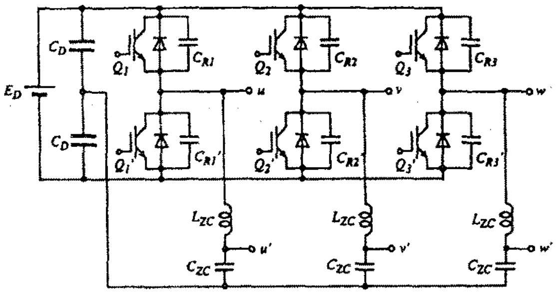


Fig.2-3 Inductor commutation inverter

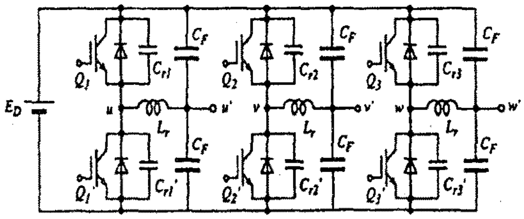


Fig.2-4 Resonant pole inverter

(b) By the overlapping of load current and resonance current, loss of reactor L_r is high.

(c) There are some difficulties in keeping of resonant condition or increasing of resonant current by power line voltage disturbances.

(d) Difficult to keep soft switching condition in heavy load

To improve these problems remarkable idea using current transformer shown in fig.2-6 was proposed. [23] This circuit gives us good result by adding passive elements only. However, there is remaining one problem that this circuit requires big size current transformer.

(2) Partial resonance DC link inverter

Fig.2-7 shows an example of partial resonant DC link inverter. We can get partial resonance by adding resonance circuit shown in figure. [24]

By turning on T_{r1}, *and* T_{r2} in the same time, initial current flows through T_s, and by turning off of T_s the voltage of C_r goes down to zero. To change off on-devices at inverter, they are switched in the interval of zero voltage. By turning off of T_{r1}, T_{r2}, current of reactor L_r flows through diodes D_{r1},D_{r2} and charge up capacitor C_r. After the voltage of C_e goes higher than supply voltage, the current flows to power supply through diode D_s, and the voltage of C_r is kept to the same voltage of power supply. Then ZVS of T_s is performed. By turning on of T_s, the current of reactor L_r degrees to zero and after it diodes D_{r1},D_{r2} are turn off. There is no switching loss at turning off of T_s, because this turn off is performed at the period of the voltage of C_r is equal to power supply.

There are many proposals about this partial resonance DC link inverter, and many additional improvement also.[25][26]

(3) ARCP(Auxiliary resonant commutation pole) inverter

In this strategy partial resonance is performed by using auxiliary resonant circuits added to each phase circuits. Detail explanation is in next chapter.

2-5 Soft switching inverter using resonant circuits added to AC output

Fig.2-8 shows an example of this proposal. [27] In this topology the adjustment of output is performed by PDM(Pulse density modulation).

2-6 Conclusion of this chapter

As mentioned above, there are many proposals in soft switching inverter especially for higher output power. They have features in its way and disadvantages in the same time. It is difficult to find out one circuit suitable for all applications. It is very important to select the most suitable topology for each application based on design assessment.

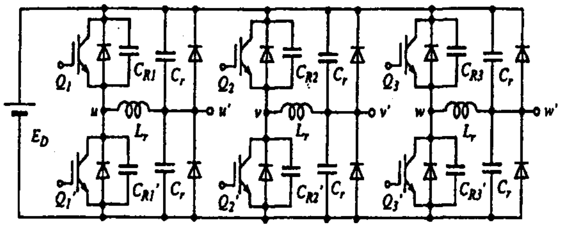


Fig.2-5 Resonant diode pole inverter

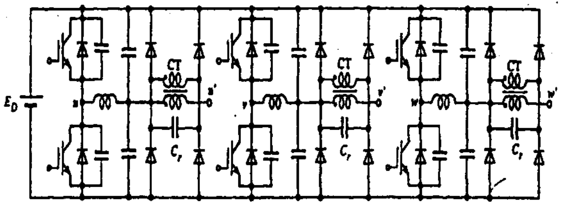


Fig.2-6 Resonant diode pole inverter with current transformer

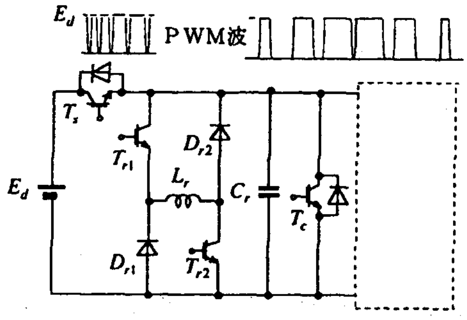


Fig.2-7 Partial resonance DC link inverter

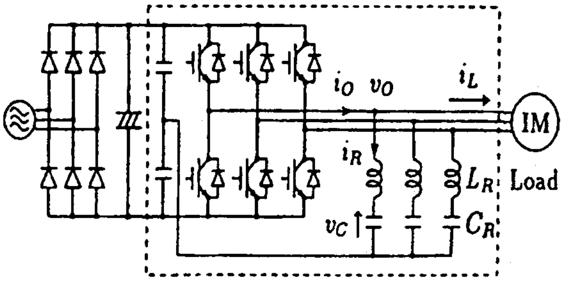


Fig.2-8 Soft switching inverter with AC side resonant circuits

3. ARCP inverter

3-1 Fore word

This concept is based on the proposal made by Dr. W. Mc Murray. [28] In this topology, partial resonance are performed by the operation of resonance circuits added to each phase. Although the circuit configuration is complex, it is possible to get good resonance condition in wide operation range, and to reduce peak stress of main devices.

there are many papers and proposals of improvement [29], applications [30][32], reduction of loss [31] ,and so on.

3-2 Basic circuit configuration

In this topology we add resonance circuits which are constructed by auxiliary devices S_{A1}, S_{A2} to each phase as shown in fig. 3-1. In this figure, C_{r1}, C_{r2} and L_r are resonance capacitors and reactor.

C_1, C_2 are used for keeping of neutral potential and for filter capacitor in DC stage.

Fig.3-2 shows operating waveforms of important position in this circuit. And fig.3-3 shows operation modes about this circuit.

From these figures:

Mode I : $(\sim t_0)$

This is a steady state mode before output voltage changes from negative to positive. By the lagging load current, the load current flows through diode D_2 not main device S_2. Resonant capacitor C_{r1} is charged up to E, C_{r2} is discharged to zero.

Mode II : $(t_0 \sim t_1)$

In the condition diode D_2 conducting, drive S_{A1} to turn on and gate off for S_2.

S_2 is turned off in ZCS, and S_A turns on in ZCS by suppression effect of reactor L. Increasing of reactor current i_r and after current of D_2 is zero, load current I_0 is held by i_r.

Mode III : $(t_1 \sim t_2)$

This region is in recovery condition of D_2.

Mode IV : $(t_2 \sim t_3)$

The resonance starts in fig.3-2

the voltage of C_{r1} is clamped to zero by D_1.

Mode V : $(t_3 \sim t_4)$

In the interval of i_r decreasing, S_1 is turns on in the condition of ZCS and ZVS.

Mode VI : $(t_4 \sim t_5)$

Difference current of i_r from I_0 is supplied from S_1, at a results i_r goes to zero.

Mode VII : $(t_5 \sim t_6)$

When current of i_r is zero, load current I_0 is supplied by S_1 and change to steady state.

Mode VIII : $(t_6 \sim t_7)$

In this mode, S_1 goes to off, and S_2 to on. By turn off of S_1 the current of I_0 is divided to two current for C_{r1} and C_{r2}, as a results AC output voltage is automatically changes its polarity. Although it needs not to operate resonance circuit, it is better to use auxiliary resonance commutation to accelerate the commutation in partial load condition.

At moment of t_6, make turn off of S_1 and turn on of S_{A2} in the same time. By the turn off of S_1, current of I_0 is commutated to C_{r1}, and C_{r2}, then ZVS is performed.

(In practice there is some loss by the tailing current)

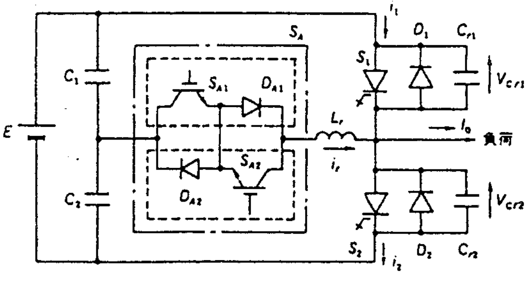


Fig.3-1 ARCP Inverter(1 phase)

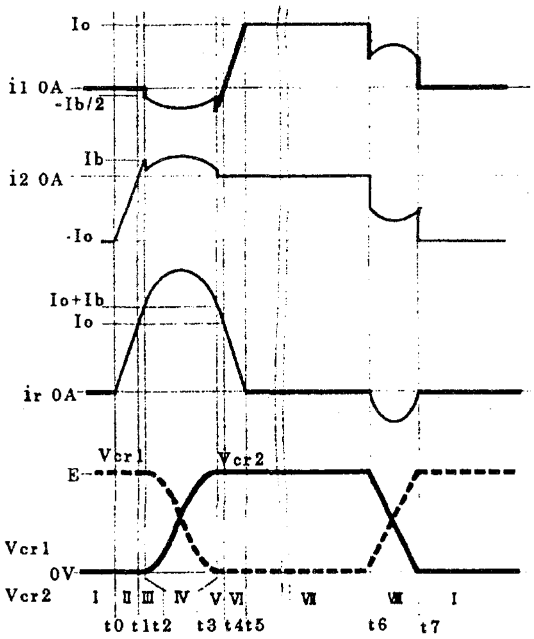


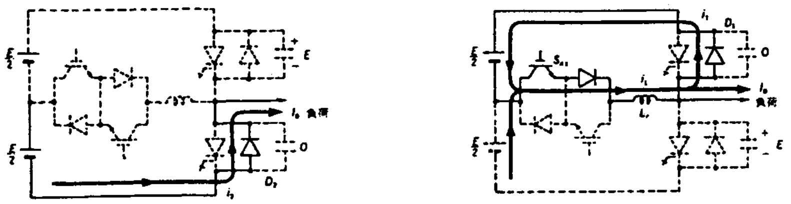
Fig.3-2 Commutation wave forms in ARCP Inverter

Mentioned above, in this topology it is possible to make ZCS and ZVS in main devices by partial resonance, as a result, it is possible to reduce switching loss of main devices, and to keep good resonant condition in spite of lode variation.

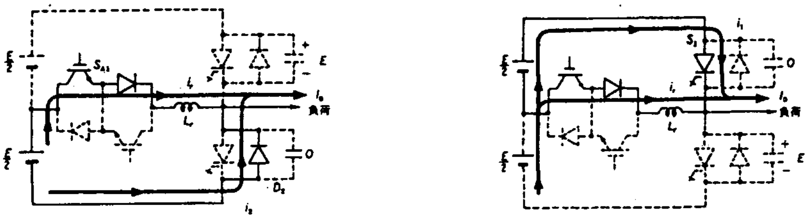
4. Practical application of ARCP inverter

4-1 Back ground

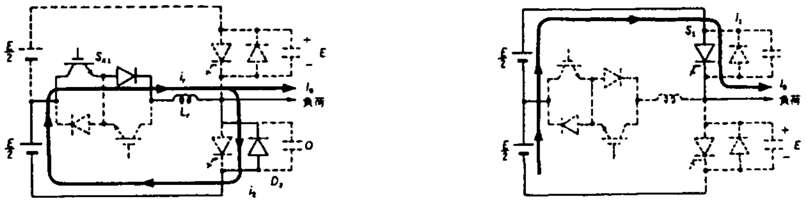
In conventional railway DC1500V is used widely for power supply. It is requested to have good inverter for many equipment of air conditioners, lights, power supply for controllers and so on.



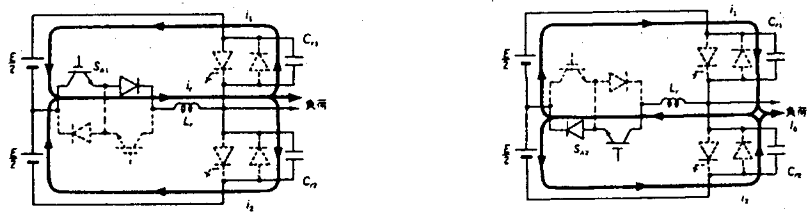
(a) Mode I (e) Mode V



(b) Mode II (f) Mode VI



(c) Mode III (g) Mode VII



(d) Mode IV (h) Mode VIII

Fig. 3-3 Commutation in ARCP Inverter

The voltage of the feeder line has wide deviation caused by load condition, distance from substation, and re-generation seriously. The voltage is change from 900V to 2000V sometimes. For this situation, the auxiliary power supply is requested to have good waveform, excellent stability against the change of the load and feeder voltage including transient also. As the auxiliary power supply is usually used 1-set for 3 or 4 coaches, the power capacity is needed over 200kVA. For these requirements high frequency switching is very effective, but there are some difficulties for the application of high voltage devices.

Additionally in railway system many high frequency currents are used in signal system. From this situation it is requested with high importance to reduce the noise revel in rail circuit.

From these points of view we tried to make excellent inverter using soft switching, by simple 2-revel inverter.

4-2 Specification of the developed inverter

(1) Specification

Table 4-1 shows the specifications. For the practical long period working test, out side style was arranged to the same size with practical equipment. [33][34]

Table 4-1 Specification of development

Items	Specification
Main circuit	ARCP 3Phase PWM Inverter
Control	Instantaneous Space Vector
input Voltage	DC 1500V
Workable	DC 900 – 1800V
Rated output	3ϕ 60Hz 440v 210kVA
Regulation	less than +/- 2%
Distortion	less than 2%

(2) Constructions

Main circuits are shown in fig.4-1. The resonance circuits are the same with S_A in fig.3-1. We chose for main devices SI-Thyristor having 4kV 2kA turn off 2 s, for auxiliary switch IGBT of 400A by natural convection cooling with heat pipe radiator.

We chose 100kHz for the resonant frequency, 5.4kHz for carrier frequency. As a results, remarkable reduction of size and weight is performed.

4-3 Experimental results

Regulation, efficiency, and some waveforms are shown in fig. 4-2 to 4-5. By these development we could get good waveform distortion less than 1.1%, good dynamic performances, and excellent noise reduction highly appreciated by signal system.

This equipment were installed to the normal operating coach in Nanbu line of JR-East Japan at 1998, and confirmed its excellent utility by practical operation.

5. Important points for soft switching application

5-1 Choice of circuit configuration

Obviously this is the most important subject. As there is no one circuit best for all application, it is necessary to select the most suitable circuit for the application with careful assessment not only typical performance but also in the detail of practical operation.

5-2 Loss of the resonant circuit

In resonant circuit the peak current is extremely high, sometimes in partial load also. The important subject is reduction of loss in resonant circuit.

5-2 Characteristics of main device

One of important points is tailing current of the devices in the application of soft switching, especially in high power application. It is said that thyristors are more suitable for resonant soft switching, like GCT or SI-Thyristor. The characteristics of the devices should be check carefully more than conventional eqipment using hard switching. [35]

6. Conclusion

Based on the research of the committee and practical results of ARCP inverter, I had reported review of soft switching strategies and important points for high power application.

Today we have met serial problems based on high frequency switching in the practical field. The soft switching is very important for these problems, but it is not so easy to apply for practical equipment effectively.

I hope to get good solution in near future by co-operation of device engineers and circuit engineers.

Acknowledgement

This paper based on the results of the research committee of IEE Japan, and also Dr. K.Ihda and Mr.K.Harada in charge of development for AECP-Inverter in Toyo Electric Mfg. Co. Ltd. I express many thanks for those people.

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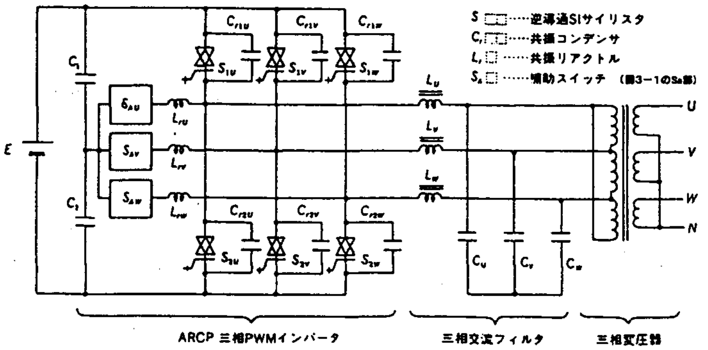


Fig.4-1 ARCP Inverter for auxiliary power supply
(Input DC1500V Output 3φ440V 210kVA)

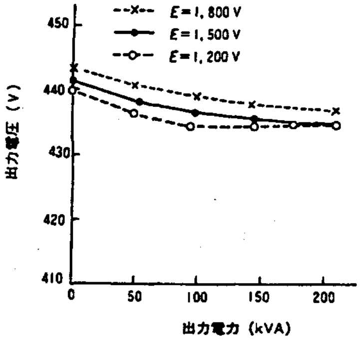


Fig.4-2 Regulation of
output voltage

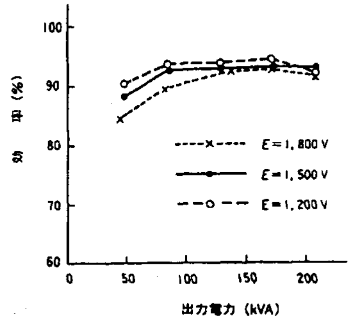
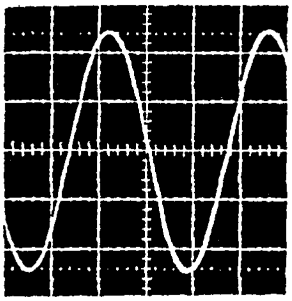
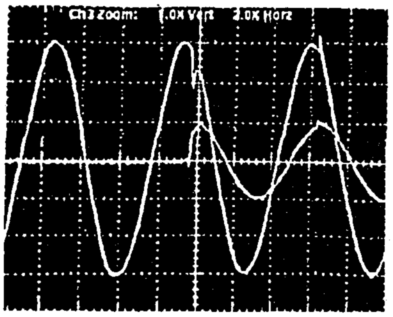


Fig.4-3 Efficiency against
to output power



全負荷時 250 V/div 5ms/div

Fig.4-4 Wave form of output
voltage in full load



全負荷投入時波形 200V/div.

fig.4-5 Wave forms on transient
at full load on

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