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Soft Switching Inverter with An Auxiliary Active Quasi-Resonant DC Link Snubber for AC Servo Motor Drive

Sang-Pil Mun* · Chil-Ryong Kim · Jong-Kurl Lee · Man-Kyu Park · Soon-Kurl Kwon**

Abstract

This paper presents a simple circuit topology of the auxiliary active quasi-resonant DC link snubber-assisted three phase voltage source soft-switching inverter for small scale PM motor drive applications. The pulse processing drive circuit interface and its soft-switching operation are discussed from an experimental point of view. Moreover, its conductive noise is measured and evaluated for electrical AC servo motor drive as compared with that of the conventional hard switching inverter.

Key Words : Active Auxiliary Quasi-Resonant DC link Snubber, AC Servo Motor Drives, EMI/RFI

1. Introduction

In recent years, with the development of power conversion circuit topologies using MOS gate controlled power semi- conductor devices; MOSFETs and IGBTs, the introduction of the increase in the switching frequency of the inverter and converter becomes indispensable in order to improve its controllability, to reduce undesired sound, and to downsize.

Although, in the conventional hard-switching PWM semi- conductor power conversion circuit systems, the increase of switching losses in the power semiconductor devices and the increase in size of the heat sink are becoming the big issue due to the interference by the overlap of the voltage and the current in the switching power devices. In addition to this, the conductive and radioactive electromagnetic noise arises due to the switching surge which results from *dv/dt* and *di/dt*.

Moreover, in the inverter or converter which is applied to the variable speed AC motor or servo drives, the new problems are breaking out due to the high *dv/dt* such as the high-frequency leak current which flows into the ground line through the stray capacitance between the stator windings and the frame of the motor, the motor shaft voltage and the bearing current. On this account, the inverter AC servo drive installations with the high speed power semi- conductor devices such as

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IGBT, MOSFET etc. tend to have these problems more and more obviously. As a basic solution for these problems, the soft switching power conversion circuit techniques which turn on and off all the power semiconductor devices in the switching mode semiconductor power conversion systems under the zero voltage or zero current mode transitions using the active auxiliary quasi-resonant snubber, and its related control techniques are indispensable. For the moment, the corroborative performance evaluations and studies on the active quasi- resonant snubber circuit and its applied inverter or converter are expected. Some circuit topologies have been proposed for the three phase voltage fed soft switching inverter circuit such as quasi-resonant DC link, quasi-resonant AC link and auxiliary quasi-resonant commutation pole.

This paper deals with a circuit topology in the single auxiliary active quasi-resonant DC link snubber circuit for the soft switching three phase voltage-fed inverter for the small scale PM motor drive. It presents the evaluations for the soft switching of the quasi-resonant snubber circuit. A conductive noise of the three phase voltage-fed inverter using this quasi- resonant snubber is measured for permanent magnet (PM) motor drive, and it is compared with that of the conventional hard switching three phase inverter.

2. Auxiliary Quasi-Resonant DC Link-Assisted Soft Switching Inverter

2.1 Circuit Configuration

The configuration of the small scale PM motor drive control system using auxiliary active quasi-resonant DC link single snubber three phase voltage-fed soft switching inverter is described in Fig. 1. The stator windings of the PM motor play as the low pass filter of the three phase voltage-fed inverter. The U-phase arm equivalent circuit as shown in Fig. 2 is used in order to explain the operation mode of the auxiliary active quasi-resonant DC link single snubber circuit. This circuit is composed with the main switch of the auxiliary circuit S_{c1} in order to clamp the DC busline at the DC voltage source V_s, the auxiliary switches in the auxiliary circuit S_{a1} and S_{a2} in order to carry out the quasi-resonance, the main quasi-resonant capacitor C_r which is connected in parallel to the inverter main switch S_{INV}, the auxiliary quasi-resonant capacitor C_a which is connected in parallel to the switch S_{a2}, and the auxiliary quasi-resonant inductor L_r.

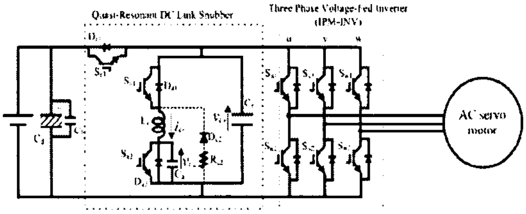


Fig. 1. Auxiliary quasi-resonant dc link snubber-assisted soft switching inverter for AC servo motor drive system

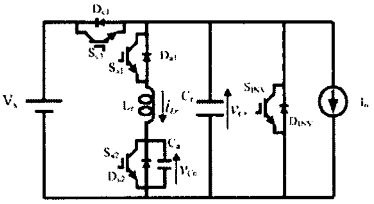


Fig. 2. Fundamental equivalent circuit of auxiliary quasi-resonant dc link single snubber circuit

This circuit topology is based on the loss-less snubber effect using LC quasi-resonant phenomenon by the switching of the DC voltage source clamp switch S_{c1} and the auxiliary switches S_{a1} and S_{a2}. Using this effect, the DC busline voltage across the main quasi-resonant capacitor C_r is brought down to the zero voltage, and then, ZVS/ZCS turn on and ZVS turn off in the main active power switches of the voltage-fed inverter bridge arm are able to be achieved.

2.2 Circuit Operation

The operation mode of the auxiliary active quasi-resonant DC link snubber to achieve the soft switching of this inverter is explained for each mode with the current source load model circuit. Each mode transits as Fig. 3. The equivalent circuits are described in Fig. 3. The switching patterns of each power semiconductor device and the voltage and current waveforms of the quasi-resonant snubber circuit are illustrated in Fig. 4.

<Mode 0> : The voltage clamp switch S_{c1} and the auxiliary switch S_{a2} are both on state and the load current is flowing.

<Mode 1> : When the switching signal of the inverter main switches comes, S_{a1} is turned on at the ZCS condition. And then, the quasi-resonant inductor current i_{Lr} is boosted enough to pull down the main quasi-resonant capacitor voltage to zero volt.

<Mode 2> : When the quasi-resonant inductor current i_{Lr} reaches to the first quasi-resonant initial current I_{boost1}, S_{c1} and S_{a2} are both turned off at ZVS condition, and the quasi-resonance with L_r, C_r and C_a starts.

<Mode 3> : When the main capacitor voltage v_{Cr} is pulled down to the zero voltage, the diode which is connected the main switch S_{INV} is conducted and then S_{INV} is turned on at ZVS/ZCS condition.

<Mode 4> : The quasi-resonant inductor current i_{Lr} begins to increase to the negative direction and it is boosted enough to boost the main capacitor voltage to the DC voltage source voltage V_s. The auxiliary switch S_{a1} is turned off at ZVS/ZCS condition during this period.

<Mode 5> : When the quasi-resonant inductor current i_{Lr} reaches to the second quasi-resonant initial current I_{boost2}, S_{INV} is turned off at ZVS condition, and the quasi-resonance with L_r, C_r and C_a starts.

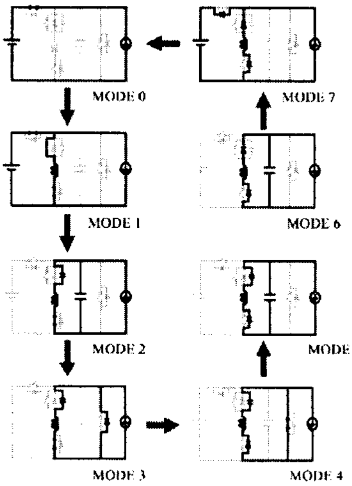


Fig. 3. Soft switching mode transitions and its equivalent circuits

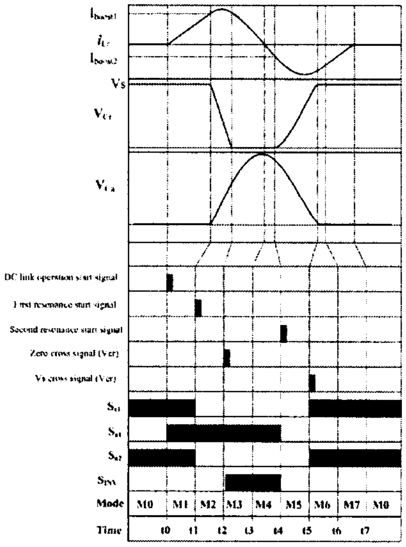


Fig. 4. Switching patterns and the operation waveforms of the quasi-resonant dc link single snubber

<Mode 6> : When the main quasi -resonant capacitor voltage v_{cr} reaches to the DC voltage source voltage V_s, the diode D_{c1} which is connected to the voltage clamp switch in back-to-back is conducted. S_{c1} and S_{a2} are both turned on at the ZVS/ZCS condition while the diode D_{c1} is conducted.

<Mode 7> : The quasi-resonant inductor current flows through D_{c1} and regenerated to the DC voltage source V_s.

The necessary conditions for the parameter design of the parallel quasi-resonant DC link circuit are as follows:

<Condition 1>

The voltage of the main quasi-resonant capacitor must be pulled down to zero voltage and boosted to the DC voltage source voltage again in order to complete the zero voltage switching.

<Condition 2>

The initial quasi-resonant current must be set as small as possible and *di/dt* at the boost must be as gradual as possible.

<Condition 3>

The peak value of the quasi-resonant current must be as small as possible in order to reduce the circuit loss and to reduce the load for the semiconductor devices at the quasi-resonant mode.

<Condition 4>

The operation period of the DC link circuit must be as short as possible.

<Condition 5>

The *dv/dt* of the main quasi-resonant capacitor at the boost and at the buck must be as gradual as possible not to effect to the operation period of the DC link circuit.

<Condition 6>

The voltage of the auxiliary quasi-resonant capacitor must be as low as possible. In these conditions, <Condition 1> is the essential condition for the DC link circuit to achieve the soft switching, and if the <Condition 1> is not satisfied, the main switches in the inverter become hard switching. According to these conditions, the circuit parameters of the DC link circuit are designed.

2.3 Simulation Results

In order to confirm the circuit parameter design, the simulation of the auxiliary quasi-resonant DC link is carried with the fundamental equivalent circuit. The operation wave forms of the auxiliary quasi-resonant circuit are shown in Fig. 5. According to Fig. 5, the main capacitor voltage v_{cr} is pulled down to the zero voltage and pulled up to the DC busline voltage V_s again. As a result, the soft switching operation has been completed.

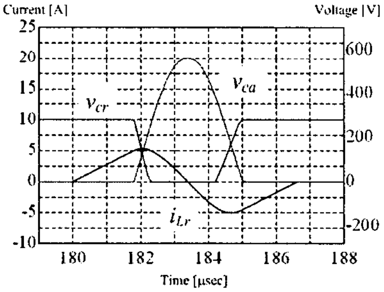


Fig. 5. Simulation results of the quasi-resonant DC link circuit

3. Instantaneous Space Vector Modulation Vector Pattern

Fig. 6 indicates the instantaneous space voltage vector area and the reference voltage vector $\tilde{v}_A^*$ of the three phase voltage-fed inverter. When the auxiliary active quasi- resonant DC link circuit is applied, if the shorter reference voltage vector than the quasi-resonant period is inputted, the next quasi-resonant operation starts during the quasi-resonant period.

As a result, not only failing the soft switching but also it breaks the power semiconductor devices due to the voltage surge by *di/dt* and current surge by *dv/dt*. In the conventional vector pattern, the short vector is out putted when the modulation ratio M is low and the area switch. Therefore, when it is applied to the AC servo drive systems, it can be considered that the zero speed operation might not to be achieved. For this reason, in this paper, in the case of low modulation ratio and the area switch, the new vector pattern to realize the short voltage vector as represented in Fig. 7 is applied.

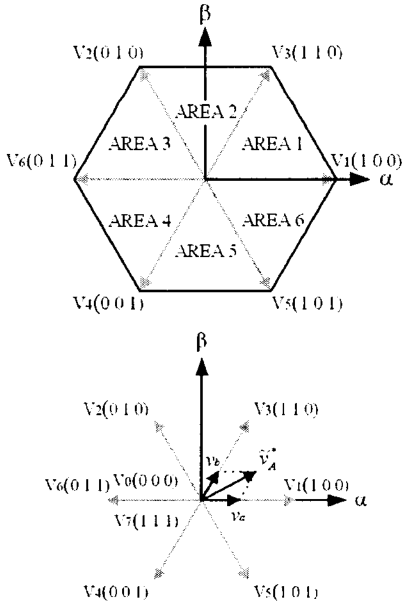


Fig. 6. Vector area and reference voltage vector of instantaneous space voltage vector.

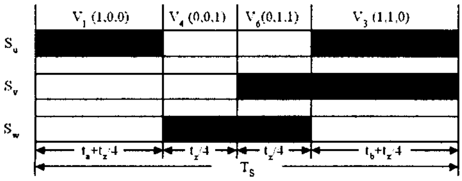


Fig. 7. Time-sharing switching pulse sequence

When the reference voltage vector is allocated in area 1, if the neighbor vectors, the sampling time and the DC voltage source voltage are defined as v_a, v_b, T_s and V_s, the v_a vector output time t_a, v_b vector output time t_b and the zero vector output time t_z are defined as follows

$$t_a = \frac{|v_a|}{V_1} T_s = \sqrt{\frac{3}{2}} \frac{|v_a|}{V_s} T_s \tag{1}$$

$$t_b = \frac{|v_b|}{V_3} T_s = \sqrt{\frac{3}{2}} \frac{|v_b|}{V_s} T_s \tag{2}$$

$$t_z = T_s - t_a - t_b \,. \tag{3}$$

In the new vector pattern, V_1 is outputted ta and quarter of $t_z(t_a+t_z/4)$ period, V_6 is outputted quarter of $t_z(t_z/4)$ period, V_3 is outputted tb and quarter of $t_z(t_b+t_z/4)$ period, and V_4 is outputted quarter of $t_z(t_z/4)$ period. On the average of the one sampling period, the short reference voltage vector and area switch vector are realized without outputting the short vector.

In Table 1, the switching space voltage vector and its magnitude for V_a and V_b direction and V_c vector which counteracts the V_a and Vb vector and substitute as zero vector for each area are indicated.

Table. 1. Divided vector for each area

Area	AREA 1	AREA 2	AREA 3
v_a vector	V1	V3	V2
Magnitude of v_a	$\dot{v}_{A\alpha}^* - \dot{v}_{A\beta}^* / \sqrt{3}$	$\dot{v}_{A\alpha}^* + \dot{v}_{A\beta}^* / \sqrt{3}$	$2\dot{v}_{A\beta}^* / \sqrt{3}$
v_b vector	V3	V2	V6
Magnitude of v_b	$2\dot{v}_{A\beta}^* / \sqrt{3}$	$-\dot{v}_{A\alpha}^* + \dot{v}_{A\beta}^* / \sqrt{3}$	$-\dot{v}_{A\alpha}^* - \dot{v}_{A\beta}^* / \sqrt{3}$
v_c vector	V6,V4	V4,V5	V5,V1

Area	AREA 4	AREA 5	AREA 6
v_a vector	V6	V4	V5
Magnitude of v_a	$-\dot{v}_{A\alpha}^* + \dot{v}_{A\beta}^* / \sqrt{3}$	$-\dot{v}_{A\alpha}^* - \dot{v}_{A\beta}^* / \sqrt{3}$	$-2\dot{v}_{A\beta}^* / \sqrt{3}$
v_b vector	V4	V5	V1
Magnitude of v_b	$-2\dot{v}_{A\beta}^* / \sqrt{3}$	$\dot{v}_{A\alpha}^* - \dot{v}_{A\beta}^* / \sqrt{3}$	$\dot{v}_{A\alpha}^* + \dot{v}_{A\beta}^* / \sqrt{3}$
v_c vector	V1,V3	V3,V2	V2,V6

4. Experimental Results and Their Evaluations

4.1 Configuration of Experimental Setup

The configuration of the experimental system and the specification of the experimental system are shown in Fig. 8 and Table 2, respectively. In this system, the operation of the auxiliary active quasi-resonant DC link snubber three phase voltage-fed inverter is confirmed, and the conductive noise of the system is measured. In this experiment, since IPM (PM50RSA060) is used for the inverter main switches, the on time and off time both have about 2[μsec] delay.

Table. 2. Design specifications and circuit parameters

DC power source voltage		V_s	280[V]
Auxiliary resonant snubber circuit	Main resonant capacitor	C_r	10[nF]
	Auxiliary resonant capacitor	C_a	10[nF]
	Resonant inductor	L_r	101[μH]
	Power switching devices (IGBT CM75DY-12H)	S_c, S_{a1}, S_{a2}	Maximum rate I_c=75[A], V_{CES}=600[V]
Voltage serge suppression snubber	Voltage clamp capacitor	C_s	0.22[mF]
	Snubber diode	D_s	USR30P12
	Snubber registance	R_s	20[Ω]
PM motor (BM0230 by Shinko Electric Co., Ltd. Japan)	Leakage inductance	L_{load}	10[mH]
	Stator registance	R_{load}	7.5[Ω]
	Number of magnetic pole	P	8
	Rated current	I_{max}	1.4[Arms]
Main circuit	Power switching devices (IPM: PM50RSA060)	S_{u1}~S_{w2}	Maximum rate I_c=50[A], V_{CES}=600[V]
Sampling frequency		T_s	10[kHz]

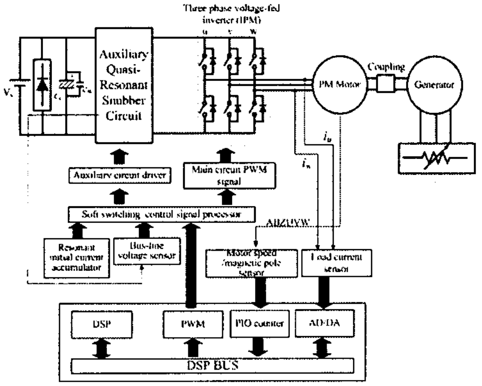


Fig. 8. Experimental setup system

As a result, the switching timing of the main circuit delays if the switching pattern indicated in Fig. 4 is applied. Therefore, the first quasi-resonant start signal is used as a trigger signal and the switching timing of the main switches are decided by 74LS123. In terms of the motor control, the current loop and the speed loop are not configured yet, and the vector control is carried out setting the d-axis voltage reference at zero and the q-axis voltage reference as a constant value. For the conductive noise measurement, the soft switching and the hard switching are compared under the condition of the same peak load current value. Additionally, for the conductive noise measurement, the line impedance stabilization network (LISN) and the EMC analyzer are used as illustrated in Fig. 9.

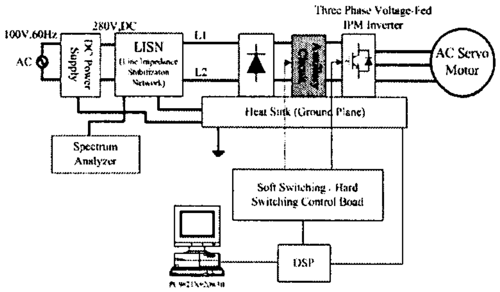


Fig. 9. Conductive noise measurement configuration

4.2 Experimental Results

In the experimental system, the operation of the auxiliary active resonant DC link snubber three phase voltage-fed inverter is confirmed, and the conductive noise of the system is measured.

(i) Quasi-Resonant DC Link Snubber

Fig. 10 indicates the operation wave forms of the active auxiliary quasi- resonant snubber circuit. According to this figure, the voltage of the main quasi-resonant capacitor which is connected in parallel to the inverter main switches is pulled down to the zero voltage and pulled up to the DC bus-line voltage V_s, and all the main switches in the inverter achieved the zero voltage soft switching (ZVS) during this DC bus-line notch mode period. Fig. 11 Three-phase load current waveforms.

(ii) Three Phase Voltage-fed Inverter with Quasi-Resonant DC Link

Fig. 12 indicates the U-phase load current wave form in case that the q-axis voltage reference is set at 0.2 and d-axis voltage reference at 0. In this experiment, d-q axis values are normalized by the DC power supply voltage V_s. Although the q-axis voltage reference is small as 0.2, since the counteractive vector is outputted not using the zero vector, the quasi-resonant operation of the quasi- resonant snubber circuit doesn't fail at all and the sinusoidal load current is acquired. In this case, the motor is driven at 1500[rpm]

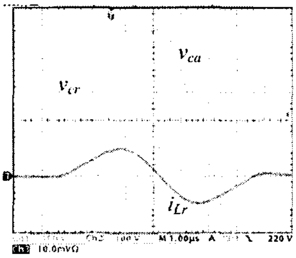
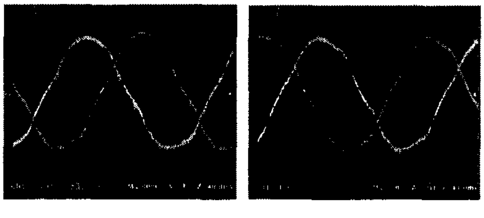


Fig. 10. Operation waveforms of quasi-resonant dc link snubber circuit(100[V/div], 2.0[A/div])



(a) Hard Switching (b) Soft Switching

Fig. 11. Three-phase load current waveforms (1.0[A/div])

The conductive noise measurement result is shown in Fig. 13. In order to compare the soft switching with hard switching, the noise measurement is carried out under the peak load current at 0.8[A]. The frequency band of the measurement ranges from 150[kHz] to 30[MHz]. This soft switching inverter reduced the conductive noise level compared with the hard switching inverter under the frequency band between 1.6[MHz]and 4[MHz], and 5[MHz] and 9[MHz]. In this case, 20[dB] of the noise level can be reduced at most. On the other hand, under the band width of 8[MHz], this soft switching inverter increased the noise level compared to the hard switching inverter. Therefore, the additional improvement is required for this inverter.

(iii) Snubber-less Quasi-Resonant DC Link Circuit

In this experiment, the voltage clamp snubber is used in order to suppress the voltage surge of the auxiliary switch S_{a1}.

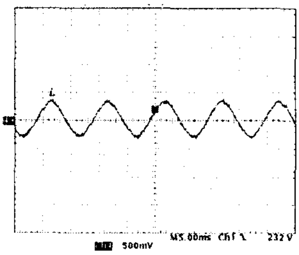


Fig. 12. U-phase load current(1.0[A/div])

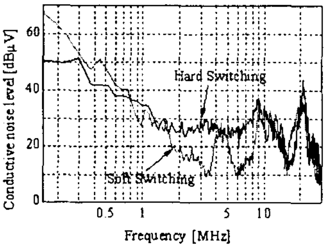


Fig. 13. Conductive noise measurements (Normal Mode)

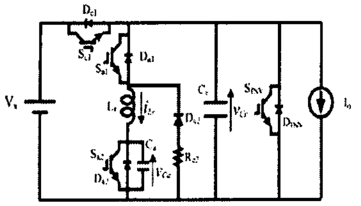
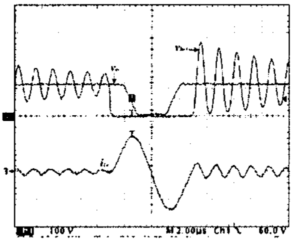
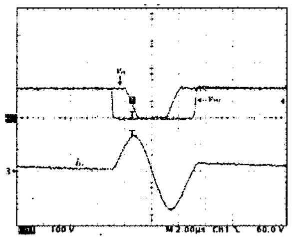


Fig. 14. Improved auxiliary quasi-resonant dc link single snubber circuit with an additional voltage clamp diode D_{c2}.



(a) without voltage clamp diode D_{c2}



(b) with voltage clamp diode D_{c2}

Fig. 15. Operating waveforms in case of using additional voltage clamp diode D_{c2}(100[V/div],1.0[A/div])

To suppress the voltage surge of the auxiliary switch S_{a1} without the voltage clamp snubber, the authors proposed the voltage clamp diode D_{c2} as shown in Fig. 14 and succeeded in suppressing the voltage surge as shown in Fig. 15. The conductive noise measurement of this circuit is not carried out yet, but it will be carried out soon.

5. Conclusion

A circuit topology of the auxiliary active quasi-resonant DC link snubber was introduced as a snubber of the soft switching three phase inverter for small scale PM motor drive systems, and its operation modes and the experimental results were described from a practical point of view. The operation of the auxiliary active quasi-resonant snubber assisted three phase voltage-fed soft switching inverter was confirmed and the conductive noise measurement was carried out under the PM motor drive.

As a result, the possibility of the electro-magnetic noise reduction by the soft switching has verified. In the future, conductive noise and radioactive noise reduction, verification of the instantaneous space vector pattern, quasi-resonant initial current control, introduction of current loop and speed loop, inter-comparison of the active quasi-resonant DC link snubberand the power loss analysis of the voltage -fed soft switching inverter with the active quasi-resonant snubber must be performed. In addition to this, feasible evaluations of the soft switching inverter for the DC brushless motor which will be begun to be used for the AC servo motor, EV drive motor, the compressor-motor drive of the air conditioner and consumer AC motor drive appliances will be pushed as soon as possible.

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Biography

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