AN APPLICATION OF STATIC INDUCTION TRANSISTOR FOR HIGH POWER DRIVER AMPLIFIER

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ABSTRACT

The concept of nuclear closed-cycle gas turbine system is turning to revive as a load of the High Temperature Gas Cooled Reactor (HTGR). Owing to its thermo-dynamical prominence and practicality of the magnetic bearing, this system could be new energy system for energy saving and environment protection.

The key technology of the machine is, from the valuable lessons in Germany, the bearing problem and complete gas sealing of high speed rotating shaft.

The magnetic bearing could solve the problem if the amplifier would be large powered enough and reliable as similar level as the reactor. Owing to high power and frequency capabilities, the static induction transistor (SIT) will be applicable for power switching devices in the bearing amplifier. Besides those capabilities, its electro-static durability would make the handling easier.

The fundamental tests were carried out on the experimental power amplifier employing SITs. The paper reports on the electrical requirements of bearing amplifier with data of typical power devices and the fundamental characteristics of the amplifier.

1. INTRODUCTION

The closed cycle gas turbine is under discussion in the countries for the application of High Temperature Gas Cooled Reactor (HTGR) due to its prominence of thermo-dynamical efficiency and environment protection.

In spite of the experienced difficulties in Germany[1),2)], especially on difficulty of helium gas tightness from the high speed shaft, owing to the favorable capabilities of magnetic bearing, new concepts of nuclear gas turbine are reviving from the past industrial and commercial difficulties.

The concepts commonly applies magnetic bearing so far to solve problems on helium leakage, lubrication and vibration accompanying with conventional bearings.

No effective method can be applicable to suspend and seal massive turbine rotor from the high pressure gas. It is also difficult to give sufficient damping and suspending force in such high speed condition owing to properties of helium.

In so far as conventional bearing technology, the nuclear gas turbine will meet much difficulties, however, the magnetic bearing will make the difficulties less with larger power.

Due to the properties of helium, speed of the turbo rotor becomes very high in about 8000 to 9000rpm and from the requirement of resource saving and radio active protection the machine must be sealed completely against leakage of the gas. These condition makes the rotor very difficult to suspend in well damped and stiff condition. Thus it is necessary to develop large powered, high frequency and energy efficient power amplifier.

The present authors report the capability on the switching type power amplifier employed Static Induction Transistors (SIT)[3] to give future prospect in the nuclear gas turbine.

2. POWER REQUIREMENT AND CHARACTERISTICS OF SIT

The design studies on the closed cycle gas turbine[4] shows that the turbine could not help increasing operating speed up to 9,000rpm(150 Hz) or more.

As the attractive force of magnet is proportional to the square of magnetizing force for constant gap and the imbalance force of rotor depends on the square of operating speed, thus the turns of magnet winding becomes linearly proportional to the rotor speed for constant current. Considering that the inductance of magnet winding is proportional to the square of turns and that the reactance, a product of inductance and controllable rotor speed, the reactance voltage of magnet becomes proportional to the cube of rotor speed for constant current. In other words, apparent power of the bearing magnet increases proportionally with the cube of controllable rotor speed. According to the facts mentioned above, examples of simple calculation are tabulated in Table 2.1 for the case of 90 ton rotor mass, 50 μm distance from mass center to journal axis and 0.588 m^2 cross sectional area of a pole piece.

Table 2.1 Typical Magnet Data for High Speed Large Turbine Rotor Bearing*1)

MAX. CONTROL *2) SPEED (rpm)	9,000			6,000			3,000		
MAGNETIZING *3) FORCE (AT)	637			425			212		
COIL TURNS (T)	50	30	20	50	30	20	50	30	20
CURRENT (A)	12.7	21.2	31.9	8.50	14.2	21.3	4.24	7.07	10.6
INDUCTANCE (H)	1.85	0.666	0.295	1.85	0.666	0.295	1.85	0.666	0.295
REACTANCE (Ω)	1744	628	278	1163	419	185	581	209	92.7
TERM. VOLT. (kV)	22.15	13.31	8.87	9.89	5.95	3.94	2.46	1.48	0.98
APPARENT POWER (kVA)	283	283	283	84.4	84.4	84.4	10.4	10.4	10.4

*1)Calculated for 50 μm deviation from mass center to journal axis and 0.588 m^2 pole piece cross sectional area.
*2)Not necessarily equal to operating speed.
*3)All data for one of two coils of three-divided pole pairs with 0.5mm gap.

Table 2.1 indicates that required apparent power amounts more than 20 kVA for a magnet pole consisted of four teeth and two coils even controllable speed remains up to 3,000rpm for 9,000 rpm operating speed. And for 9,000rpm controllable speed, required apparent power to a pole exceeds over several hundreds kVA for the same condition.

For simplicity and reliability of the amplifier, it is desirable to use larger power devices with high frequency capability. The MOS-FET module, as a typical example of nearly 1000 volt and 100 ampere capability, involves 28 MOS-FET in a module as shown in Table 2.2. This makes rather difficult to distribute uniform current to individual devices and can not help decreasing the utility factor of them.

The static induction transistor(SIT)[3], on the other hand, is not so common but has several beneficial capabilities on device power and fast switching owing to its less channel resistance and the gate capacitance comparing to similar MOS-FET module. Besides the capabilities on power and frequency, The benefits of relatively low forward resistance, higher voltage and stronger electrostatic durability make SIT favorable for the large power amplifier requirement.

3. DESCRIPTION OF CIRCUIT

The H-bridge switching circuit is commonly used for final stage of large powered magnetic bearing amplifier due to its higher efficiency. The circuit applies this bridge circuit in principle to the power stage with auxiliary diodes DA1 and DA2 in inverse parallel with the switching devices T1 and T2. The medium power SITs, assigned as TM-201H in Table 2.2, are used with conventional PWM modulator amplifier as shown in Fig. 3.1. The devices T1 and T2 switch the circuit synchronously of the load from DC source in PWM manner and the diodes D1 and D2 resurrect induced current to the capacitor C1 during T1 and T2 are opened.

Thus the average DC current through the inductive load depends on the relative on-time or duty time in a switching cycle. As the resurrecting charge to the capacitor C1 is proportional to the charge supplied in on-time, capacitance of C1 could be reduced with the switching frequency. And the discharge from C1 saves the current supply from the source thus the source current reduces than the load current.

Table 2.2 Typical Characteristics of Large Power Switching Devices

Symb	Characteristic	Multiple 28 MOSFET Module KW 94-Series (Gentron)				Single SIT	
		Sing.	Half-H	Full-H	Temp. *1)	TS-300H	TM-201H
Vdss	Drain-Source Volt. (V)	1000 (Vgs=0V, Id=6mA				1200	1200
Id	Module Drain Curr. (A)	192	96	32	100° C	-	-
	Average Curr./Tip (A)	6.86	3.43	1.14		100	100×2
Vgst	Gate Threshold Volt. (V)	4.5 (Vds=5V, Ids=6mA)					
Vgs	Gate-Source Volt. (V)	±20				15	70
Pd	Max. Power Dissip. (W)	5000 (25° C)				3000	800×2
Igss	Forward Gate-Source Leakage (μA)	4.8 (Vgs=20V)				200	100
Idss	Zero Gate Volt. Drain Current (mA)	9.6 (Vds=400V, Vgs=0V)				0.2	0.1
		.06 (Vds=400V, Vgs=0V)			125° C		
Rds-on	Drain-Source On-Resistance (mΩ)	.02	.04	.06		400	650
		(parallel resistance)				(single chip)	
Ciss	Input Capacitance (μF)	.02	.1	.03		.025	.016
Cdss	Output Capacitance(μF)	.03	.01	.004			
td-on	Turn-On Delay T. (ns)	126, (Vdd=24V, Ic =600A, Z_O=4.7 Ω)				350	250
tr	Rise Time (ns)	280					f_{cotoff} =10MHz
td-off	Turn-Off Delay T. (ns)	630				350	300
tf	Fall Time (ns)	210					
Rejec	Thermal Resist. (° C/W)	.02	.04	.09		.04	-
	Operating Temp. Range	-25 to 150° C				-25 to 150° C	

*1) 25° C, except specified temperature

The series connected 100μH reactor L1 also acts upon improvement of efficiency suppressing the feed current from supply to inductive load during T1 and T2 were closed and choking reverse current to supply.

The electrolytic capacitors were commonly used in the circuits due to its larger capacity capability, however, its reliability and efficiency is not always so high because of the relatively short life and larger leakage current. Therefore if capacitance in the circuit could be reduced into the value obtainable by non-electrolytic one such as polystyrene insulated capacitor, it would give beneficial effects on reliability, life and efficiency of the

amplifier. Thus faster switching, at least, may give favorable effect on the magnetic bearing system.
The switching frequency is adjustable from about 10 to 100 kHz to know effectiveness of the capacitor C1 while 1.36μF capacitance at present.

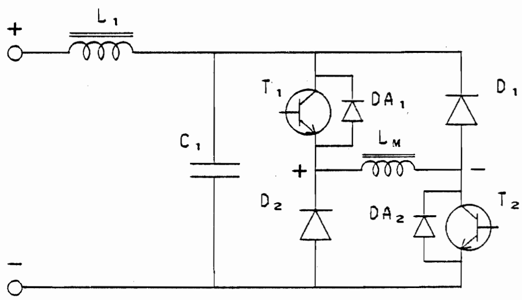

Fig. 3.1 H-bridge Power Circuit

As the capacitance of C1 depends not only on the switching frequency but on inductance of the loaded magnet, therefore the value mentioned above is only a value for the temporary inductive load for testing.
On to the effect of the capacitor, we also should take into consideration of tuning the electrical resonant frequency with the rotor frequency for improvement of the circuit efficiency. In case of the constant rotor speed, this will act to reduce amplitude of source current for the current amplitude of magnet load.

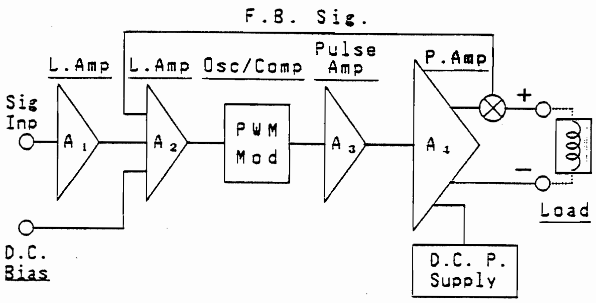

Fig. 3.2 Configuration of Driving Circuit

The adjustable voltage DC source supplies power up to 350 volt and 40 ampere to the power amplifier. A coiled wire of 28 mH inductance was loaded as a dummy load with cooling air fan. Fig. 3.2 shows conceptual entire configuration of the amplifier circuits for a magnetic pole which consists of linear amplifiers and a triangular wave oscillator and a comparator to modulate the analogous input signal into PWM signal. Negative feedback signal from the load-current signal was slightly applied only for stabilizing the thermal characteristics change of the younger stages.

4. TEST RESULT AND DISCUSSION

The DC characteristics to the inductive load are shown in Fig. 4.1 with output current(□), supplied current(+) from the DC power supply and the ratio of them(◇). The output current shows nonlinearity near the both end of input DC signal. This caused from distortion of triangular wave and insufficient negative feed back will be improved by sufficient negative feed back.
The supplied current(+) lays below the output current(□) and thus the ratio(◇) of them remains between zero to 1.0 which is shown in the value of ten times in Fig. 4.1. The reason the ratio remaining under 1.0 is that the induced current through the inductive load returns to the capacitor C1 through diodes D1 and D2 in the time T1 and T2 are opened thus the current from the power supply becomes less than the load current as mentioned in preceding section.

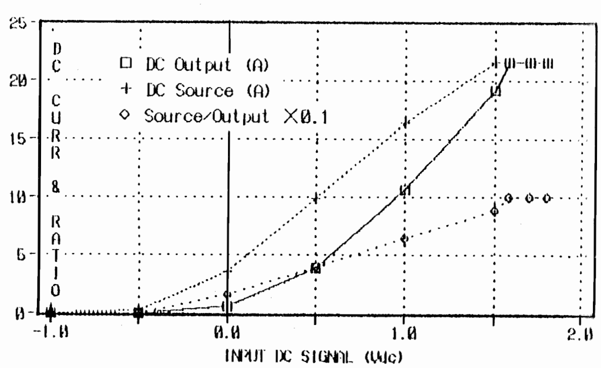

Fig. 4.1 DC characteristics

As the longer opening time of T1 and T2 comparing to closing time allows the stored electro-magnetic energy to return, however inversely, the less opening time or the greater closing time than 50% can not allows such energy recovering. Thus the supply current keeps very small value up to 0 volt of input DC signal which corresponds to 50% duty time of the switching cycle. There were no significant effects on changing the switching frequency between 20kHz to 100kHz thus 50 kHz was used through the experiments. This owes to the sufficient capacitance of C1 for the switching cycle, in other words, the capacitor C1 is very important not only for resurrecting the energy but making resonant circuit with inductive load and the capacitor. In such resonant manner, the magnetizing current circulates between magnet and capacitor and the energy supply from the source can be reduced only for the losses in the circuit.
As the capacitance for given resonant frequency is inversely proportional to the inductance, one can reduce the capacitance and AC current component with larger inductance but causes higher voltage of load terminal and DC supply. Thus the higher voltage caused by higher rotor frequency makes capacitance and voltage durability of switching devices higher.

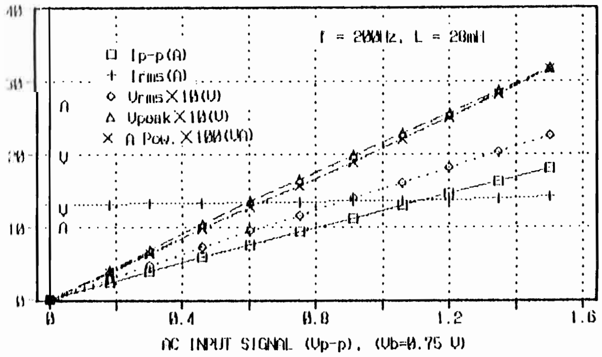

Fig. 4.2 AC characteristics

From the reason above, it should be taken into account to match impedance of the magnet with equivalent impedance of the switching device calculated as the quotient of rated voltage and current of the device.
The power consumption across the inductive load was not measurable value due to the very small load resistance less than 1mΩ but the high frequency voltage components were large enough by the reactance of load. Thus high frequency components were filtered in AC measurement and 0.75 V-DC was biased to sinusoidal AC signal to keep output current and signal positive as understood from the DC characteristics in Fig. 4.1. Typical AC characteristics were shown in Fig. 4.2 for 200Hz signal up to 1.5 volt peak to peak.
The observed voltage across load terminal(◇, △) fairly corresponds to pure inductive voltage by the AC component of current change(□). The half peak voltage(△) and apparent power(×) amounted in 317 volt and 3.17 kVA for the current amplitude of 18 ampere peak to peak for the allowable condition of the power supply.
When AC signal applied with constant DC bias voltage, the average and root mean square (RMS) of load current(+) keeps almost constant. However of course, the reactance voltage of the load increases with signal amplitude and thus the apparent power(×) also increases linearly with it.
For the practical application, as DC voltage of the load terminal can not be negative, the DC voltage of power supply should be increased so greater as keeping positive.
From this reason, the RMS or mean current have to be also increased with amplitude of signal or dynamic force to the bearing. Thus the apparent power increases roughly with the square of the force amplitude in practical.
As frequency does not affect average and RMS value of the current, voltage, and apparent power changes proportionally with frequency. Through the present experiments, the power switching device have not experienced any difficulty, however, further studies will be necessary in the more practical condition. The experiment will give a fair prospect on the application of SIT for the bearing amplifier.

5. CONCLUSION

The experimental study have properly demonstrated the possibility of the device for the nuclear gas turbine application in prospect with the power and frequency capability of it. Further studies will solve the problems on the nuclear turbo machine.

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