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A Power Control System for the Rod Drive Coil of Control Element Drive Mechanism in Pressurized Water Reactor

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Abstract

In this paper, we propose a new type of power control system for the rod drive coil of the CEDM of the PWR NPP in order to supply more reliable DC power. The electrical modelling of the controlled rod drive coil was done by referring related documentations. The design of the proposed system is based on this electrical model satisfying the existing specification. A high power DC-DC converter scheme is adopted utilizing the SMPS technique in the design of the proposed system. In order to show the effectiveness of the proposed system, an experimental system with the capability of 3.2 K Watt was set up for a rod with four cores and some computer simulations and experimentations were carried out. The result shows a very similar tracking performance with that of the existing system to the driving command. As a result of this, the proposed method can be applied to the power control system for the rod drive coil of the CEDM of the PWR NPP.

1. Introduction

The main function of the control system for the control element drive mechanism(CEDM) of the pressurized water reactor(PWR) nuclear power plant(NPP) is inserting and/or withdrawing of the element according to a command in order to regulate the output power of the NPP. The control system also plays an important auxiliary role in making all the elements dropped into the reactor core to shut down when the reactor trip signal occurs during an emergency state[1].

Currently, an AC-controlled type of power control system for the CEDM of the PWR NPP is being operated. The 3-phase AC power from a motor-generator set is adjusted by using an SCR(Silicon Controlled Rectifier) circuit and other auxiliary circuits. This type of power control system is operated in a simple manner since the generated AC power is used without any modification. However, the system may be apt to work improperly due to several sensitive auxiliary circuits to external noise. This improper working of the power control system may result in an unwanted reactor trip caused by the unreliable input power supply. In order to overcome this problem, a new type of power control system with relatively less number of auxiliary circuits is required.

With the recent development of high power components, the current technical trend of power control system is changed from the AC-controlled type into the DC-controlled type. Many researches on this DC-controlled type system are being actively done[2-7]. In this paper a DC-controlled type power control system is proposed for the rod drive coil of the CEDM of the PWR NPP. Among several schemes on the DC-controlled type of the system, high power, high frequency full bridge zero-voltage switching pulse width modulation (FB ZVS PWM) DC-DC converter scheme is adopted utilizing the switching mode power supply(SMPS) technique. Then, the scheme is applied to the power control of the rod drive coil of the CEDM of the PWR NPP. The FB ZVS PWM DC-DC converter scheme is a kind of SMPSs with relatively simpler circuits and less number of those. The volume reduction of the magnetic elements in the system can be achieved by the operation of the system in a high frequency. The loss caused by the high frequency switching can be reduced with the aid of the ZVS operation.

This paper is described as follows. In section 2, the existing system and the proposed system are presented. In section 3, experimental results and some discussions are presented. In section 4, concluding remarks and further studies are presented.

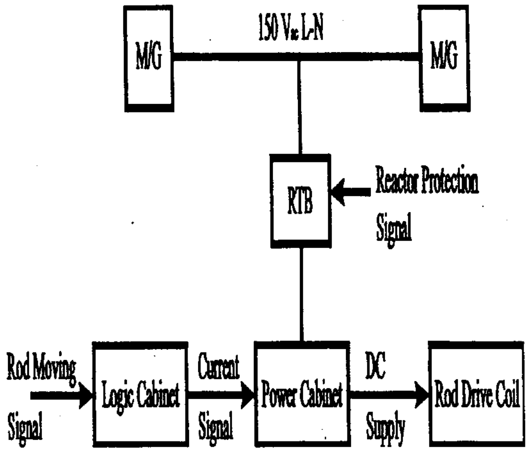

Fig. 1. Control Element Drive Mechanism System in PWR NPP[1]

2. The Power Control System for the CEDM of the PWR NPP

2.1. Overview of the CEDM of NPP

The output power of an NPP is regulated by the extent of insertion and/or withdrawal of control elements into and/or out of the reactor core. The equipment called a CEDM drives the control element. A CEDM consists of a motor/generator (M/G) set, a reactor trip breaker(RTB), a logic cabinet, a power cabinet and a rod drive coil as shown in Fig. 1. The logic cabinet sends sequential commands to the power cabinet in order to move the control element. The power cabinet converts the AC power generated by the M/G set into the DC power and supplies it to the rod drive coil according to the selection logic signal from the logic cabinet. There are four coils in a CEDM. Each coil is driven by its independent voltage command. The voltage commands are transistor-transistor logic(TTL) level signals and are of three kinds such as lift, latch and zero command. The

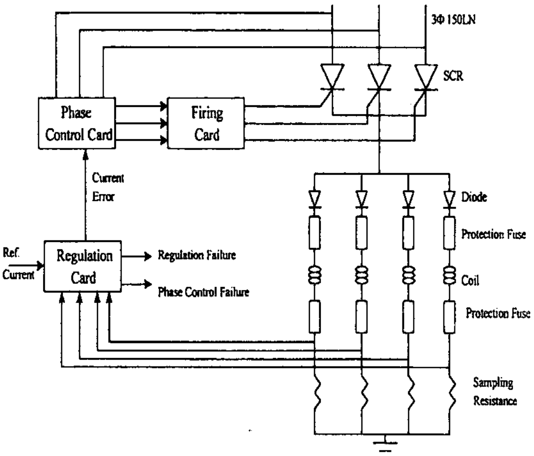

Fig. 2. The Power Control Circuit in the Power Cabinet[1]

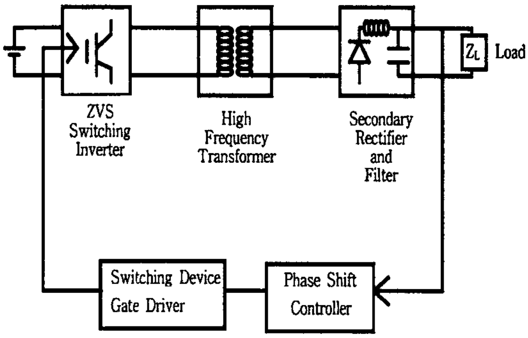

Fig. 3. The Schematic Diagram of the Proposed Power Control System

applied voltage levels to the rod drive coil for the commands are DC 120-160 Volt, DC 30-60 Volt, and DC 0 Volt, respectively.

As mentioned previously, the objective of this paper is to propose a new type of power control system in the power cabinet in Fig.1. This can substitute for the existing system as shown in Fig. 2. The proposed type of power control system for the PWR NPP is shown in Fig. 3 and will be described in detail later.

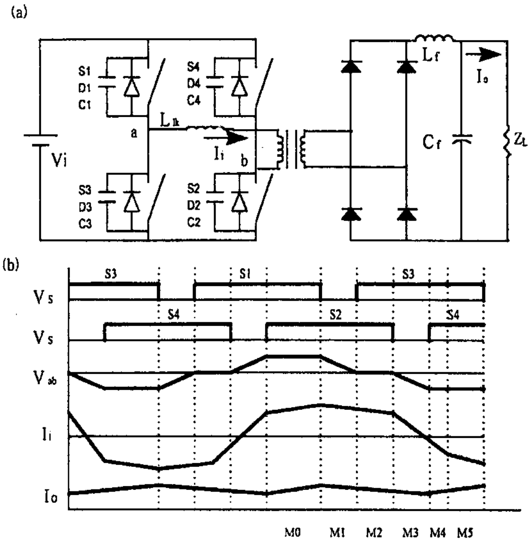

Fig. 4. (a) The Schematic Diagram of FB-ZVS PWM DC-DC Converter (b) Waveforms at Some Points

2.2. FB ZVS PWM DC-DC Converter

In the SMPS, as the switching frequency is increased, the size of magnetic circuit components such as a transformer and an inductor can be reduced drastically. The switching loss, generally, increases in proportion to the switching frequency. It is well known that the zero-voltage switching (ZVS) and/or the zero-current switching(ZCS) technique is one of the soft switching methods. The switching is carried out when the voltage and/or the current is zero. The switching loss reduces even at a high frequency. The ZVS technique is adopted in this paper to minimize the switching loss at the turn-on time. Fig. 4(a) shows the circuit diagram of the FB ZVS PWM DC-DC converter. Fig. 4(b) shows waveforms of some interesting points of the converter circuit. In Fig. 4(a), S1-S4, C1-C4, D1-D4, L_{lk} and Z_l denote isolated gate bipolar transistor(IGBT) switching devices, internal capacitances of IGBTs, free wheeling diodes of IGBTs, the leakage inductance of the high frequency transformer and the electrically modelled load of the converter, respectively. The operating principle of the converter is briefly described below.

<Mode 0 : S1, S2 Conduction Stage>

The S1 and the S2 are in the conduction stage and the amount of the current through the output filter increases linearly.

<Mode 1 : Left Leg Transition State>

The S1 is turned off and the current of the primary side of the transformer charges the C1 and discharges the C2. The L_{lk}, the C1 and the C3 forms a resonant circuit. The V_{c1} increases linearly since the resonant period is much longer than the duration of this mode. When the V_{c1} reaches the input voltage V_i, D3 begins to conduct. When the S1 is turned off, the primary side current is only the reflected current from the current of the secondary side of the transformer. The inductance size should be large enough to perform the ZVS operation of the S3.

<Mode 2 : Primary Free-Wheeling Stage>

The input voltage V_i is isolated from the output port. The primary side current circulates through the D3 and the D2. If the S3 is turned on while the D3 is conducting, the ZVS turn-on operation of the S3 can be done. The primary side voltage is clamped at zero and the primary current decreases due to the resistance effect of components. This mode finishes when the S2 is turned off.

<Mode 3 : Right Leg Transition Stage>

This mode begins with the turn-off of the S2. The energy stored in the L_{lk} charges the C1 and discharges the C4. The L_{lk}, the C2 and the C4 forms a resonant circuit. The energy stored in the L_{lk} should be large enough to make the voltage V_{c4} decrease. This is a different characteristics from that of the Mode 1. After the voltage V_{c4} becomes zero, the current of the L_{lk} should maintain a suitable value. The ZVS operation of the S4 can be obtained from the conduction of the D4.

<Mode 4 : Linear Current Ramping Stage>

In this mode, the D3 and the D4 conduct. The S4 can be turned on without loss since the V_{c4} equals to zero.

<Mode 5 : Power Transfer Stage>

The value of the leakage inductor current goes to zero. Then, the value goes to a negative value through the S3 and the S4.

After the Mode 5, voltages and currents of the circuit are reversed. This pattern repeats. The output voltage is regulated by adjusting the duty cycle of the left leg and the right leg.

2.3. Design of Power Control System and Experimental Setup

The designed power control system consists of a rectifier and filter circuit, an IGBT gate driver circuit, an auxiliary power supply and a command generation circuit as shown in Fig. 3. The CEDM of the PWR NPP requires that the maximum supplied power be 3.2 K Watt (160 Volt, 20 Amp) [1]. The proposed power control system is designed to satisfy this requirement.

The rectifier and filter circuit in the primary side converts the AC 220 Volt into the DC 300 Volt using a full bridge diode circuit and a smoothing capacitor. The converted DC voltage is applied to switching devices. The rectifier and filter circuit in the secondary side rectifies the rectangular waveform output voltage from the high frequency transformer and smooths it. This circuit supplies a DC power to the rod drive coil. The diode in the secondary rectifier circuit is of the fast recovery type widely used for high-frequency circuits.

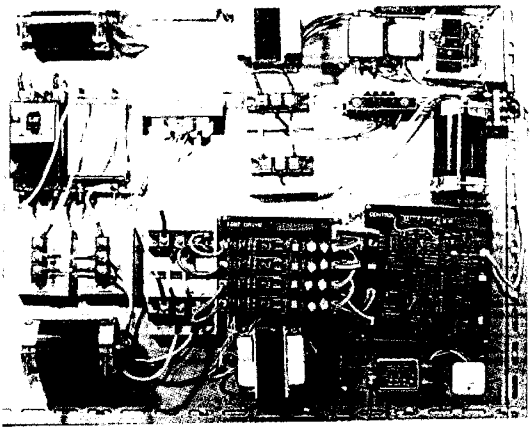

Fig. 5. Experimental Setup for the Proposed Type of Power Control System

The IGBT switching device circuit generates a rectangular waveform voltage by turning-on and/or turning-off IGBTs according to the IGBT gate driver signal. This circuit is composed of 4 identical IGBT devices and is of H-bridge type. The switching frequency is set at 20 K Hertz.

The high frequency transformer changes the rectangular waveform voltage level and transfers the power to the secondary side. This transformer is designed using a commercial core. The handling power capacity is 8 K Watt.

The sensing circuit detects a voltage level of the load using a resistor divider circuit and operational amplifiers(OP AMPs). A current sensor and OP AMPs detects a load current. The phase shift controller compares the command signal and the sensed signal. The controller generates a PWM control signal to the switching device gate driver circuit to compensate the error between the command signal and the sensed signal. In this paper, the phase shift controller part is implemented utilizing an integrated circuit(IC). The ML4828, a product of MicroLinear, Inc., is used in the experiment. The switching device driver circuit applies DC ± 15 Volt to the IGBT gate

Table 1. Main Component Specification

Function	Name	Specification
IGBT	MG100J2YS50	100Amp
1st side Diode	DD104N16K28FN	1000Volt 100Amp
2nd side Diode	DD50 GB60L	600Volt 100Amp
Phase Shift Controller	ML4828	BiCMOS phase modulation control IC

according to the PWM control signal from the phase shift controller. The auxiliary power supply circuit provides DC ± 15 Volt and ± 5 Volt to electronic circuits.

As mentioned in section 2.1, the voltage level across the rod drive coil should be changed according to the signal from the logic cabinet. The command circuit emulates this action just for the operational verification of the experimental setup. The circuit converts the logic signal into the analog command signal. The command circuit includes an Intel 80196KC microprocessor and a D/A converter. The experimental setup for the proposed power control system is shown in Fig. 5. Table 1 shows main circuit components and their specifications used in the setup.

3. Experimental Results and Discussion

3.1. Computer Simulations for the Experimental System

Before doing some experimentations, the operational characteristics of the system and the suitability of component values should be investigated. Some computer simulations were carried out utilizing the IsSpice package[8]. IsSpice is a commercial package used for general electrical circuit simulations. This package provides libraries of electric components in a blocked graphic form. Users can compose a circuit and observe its operation. Computer simulation was done for the

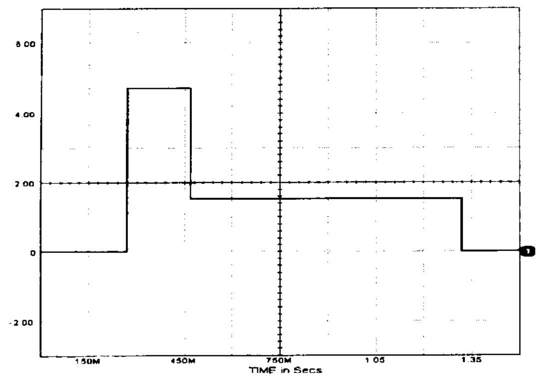

Fig. 6. The Command Sequence for the Lower Gripper Coil for Withdrawl Action

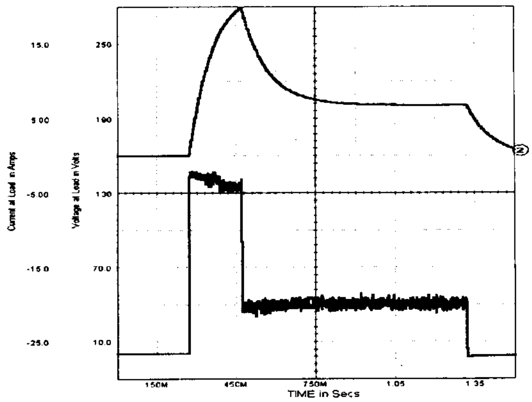

Fig. 7. The Simulation Results for the Implimented Power Control System (Load : Resistance 6[Ω], Inductance 0.6[H])

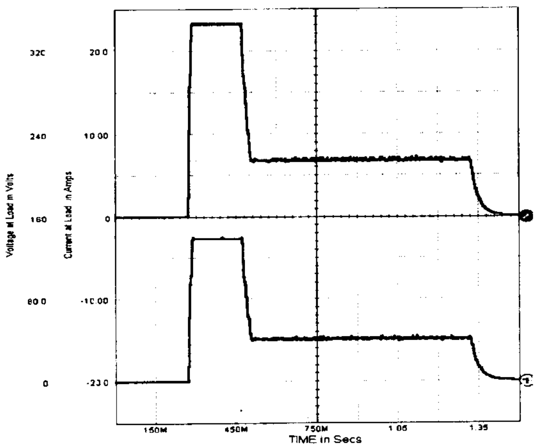

Fig. 8. The Simulation Results for the Implimented Power Control System (Load : Resistance 6[Ω])

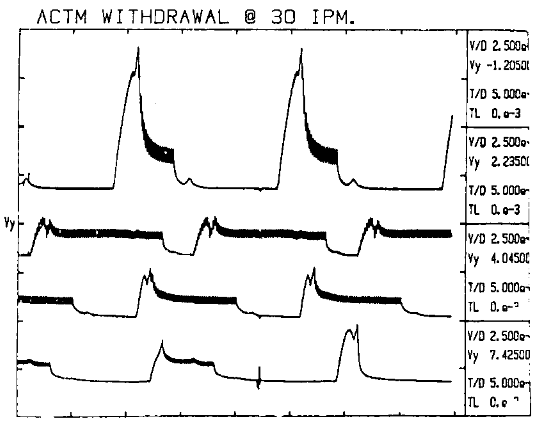

Fig. 9. The Current Waveform of Control Rod Coil in PWR NPP[1]

designed system described in section 2.3 and the rod drive coil. Some details were approximated in the simulation due to the computation time as long as the operational characteristics maintains.

The rod drive coil is the load for the power control system. This can be electrically modelled as a series resistor-inductor(RL) circuit by referring related documentations[1]. The rod drive coil resistance varies in the range of 4.5 ~ 9 Ohm as ambient temperature changes. The coil inductance also varies in the range of 0.4 ~ 0.7 Henry. Simulations were performed for several values of the inductance. The command signal used in the simulation is shown in Fig. 6. This is the driving command for the lower gripper coil at the time of withdrawal. Fig. 7 is the simulation result for the case of R=6 Ohm, L=0.6 Henry electrical load

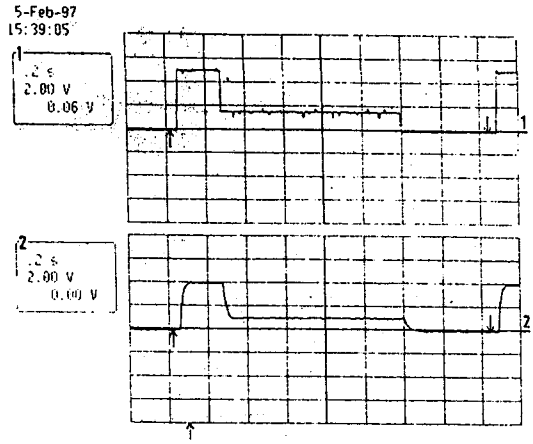

Fig. 10. Experimental Results

model of the rod drive coil. The upper graph represents the current waveform and the lower graph the voltage waveform. Fig. 8 is the case of only R=6 Ohm electrical load model of the rod drive coil. Fig. 9 represents the measured current waveform from the existing rod drive coil of the CEDM of the PWR NPP.

It is observed that the response of the current in Fig. 7 is slower than that in Fig. 8 as expected due to the effect of the inductance. It can also be observed that the result in Fig. 7 is very similar to that of Fig. 9. Now, consider that the same result as in Fig. 8 is obtained when an experimentation is carried out only for the resistor load of R=6 Ohm. Then, it can be expected that the same result as that in Fig. 7 can also be obtained when an experimentation is done for the R=6 Ohm, L=0.6 Henry load. As a result of this, a similar result with Fig. 9 can be obtained.

3.2. Experimental Results and Discussion

Some experimentations have been done for the setup shown in Fig. 5. The command shown in Fig. 6 was applied to the experimental setup. This is the same command as that in the simulation described in section 3.1. Experimentations were carried out only for resistor loads using a bank resistor set. Fig. 10 shows an experimental result to a command. The upper graph shows the command voltage. The lower graph is the response voltage across the resistor load.

Since the rod drive coil is modelled as a series RL load, the experimentation should be done for this kind of RL load. But when the experimentation was doing in the laboratory, the RL load was not available due to the large value of the inductance. On the other hand, if the experimental result for the resistor is the same as that in the simulation, it can be expected that the same result as that in the simulation is obtained for the RL load. It has already observed that the result in Fig. 10 is almost the same as that in Fig. 8. Therefore, it can be expected that almost the same result as that in Fig. 9 can be obtained when an experimentation is done for the RL load.

4. Concluding Remarks and Further Studies

In this paper, a new type of power control system was proposed for the CEDM of the PWR NPP. Some computer simulations and experimental tests were carried out to evaluate the performance of the proposed system. The system was designed by referring related documentations of the existing CEDM and the rod drive coil. In the design, the high-power DC-DC converter concept with SMPS technique has been utilized. Simulation and experimental results showed that the proposed system tracked a command well. Even though experimentations were performed only for resistor loads, the system can be used as a power control system for the CEDM of the PWR NPP.

More experimental tests should be performed for RL loads and for the real rod drive coil. After some more work, the proposed power control system can be applied to a real nuclear power plant. Therefore, the result of this paper will be utilized in the study of the reliable operation of the nuclear power plant.

5. References

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