

# Sensory Systems for a Control Rod Position using Reed Switches for the Integral Reactor

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## Abstract

The system-integrated reactor currently under development at the Korea Atomic Energy Research Institute is being designed with a soluble boron free operation and the use of a nuclear heating for the reactor start-up. These design features require a Control Element Drive Mechanism (CEDM) for the integral reactor to have a fine-step movement capability as well as a high reliability for a fine reactivity control. Also the reliability and accuracy of the information for the control rod position is very important to the reactor safety as well as the design of the core protection system. The position indicator is classified as a Class 1E component because the rod position signal of the position indicator is used in the safety related systems. Therefore it will be separated from the control systems to the extent that a failure of any single control system component of a channel and will have sufficient independence, redundancy, and testability to perform its safety functions assuming a single failure. The position indicator is composed of a permanent magnet, reed switches and a voltage divider. Four independent position indicators around the upper pressure housing provide an indication of the position of a control rod comprising of a permanent magnet with a magnetic field concentrator which moves with the extension shaft connected to the control rod. The zigzag arranged reed switches are positioned along a line parallel to the path of the movement of the permanent magnet and it is activated selectively when the permanent magnet passes by. A voltage divider electrically connected to the reed switches provides a signal commensurate with the position of the control rod. The signal may then be transmitted to a position indicating device. In order to monitor the operating condition of the rotary step motor of CEDM, the angular position detector was installed at the top of the rotary step motor by means of connecting it between the planetary gear and the rotating shaft of the rotary step motor. The permanent magnet positioned in the planetary gear holder which is designed to rotate at  $60^\circ$  corresponds to each step of the rotary step motor. Therefore the angular position detector can measure a one step angular increase of the rotary step motor by means of detecting the angular position of the permanent magnet using the reed switch assembly outside the pressure housing of the angular position detector. The angular position detector with planetary gear can measure precisely the control rod position by considering the gear ratio and the ball screw lead as well as check on the operating condition of the rotary step motor of CEDM on a real time basis. The two sensory systems of the position indicator and the angular position detector will cooperate with each other to measure the position of the control rod more reliably.

*Key words* : Integral Reactor, CEDM, Position Indicator, Angular Position Detector

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## 1. Introduction

The present paper is related to position sensing means and more particularly, to a magnetic position sensor using a permanent magnet and a compact arrangement of reed switches in a nuclear power plant. The reed switch position transmitter (RSPT) was used as a position indicator for the control rod in commercial nuclear power plants made by ABB-CE. But this position indicator has some problems when directly adopting it to the integral reactor. Its indicating resolution (1-1/2 inch (38.1mm)) is suitable to measure the position of a control rod which is driven by a motor

having steps of 3/4 inch (19.05mm). But the Control Element Drive

Mechanism (CEDM) for the integral reactor is designed to raise and lower the control rod in steps of 2mm in order to satisfy the design features of the integral reactor which are the soluble boron free operation and the use of a nuclear heating for the reactor start-up. These design features require a CEDM for the integral reactor to have a fine-step movement for a fine reactivity control. [1] Also the resolution of the information for the control rod position is very important to the reactor safety and the design of the core protection system. Therefore the resolution of the position indicator for the integral reactor should be

achieved to sense the position of the control rod more precisely than that of the RSPT of the ABB-CE. This paper adopts a compact arrangement design of the reed switches and a magnetic field concentrator in the RSPT type position indicator in order to reduce the resolution of the position indicator for the integral reactor. A survey of the RSPT type control rod position indication system and its actual implementation in the existing nuclear power plants in Korea was performed first. [2] The control rod position indicator having a high performance for the integral reactor was developed on the basis of the RSPT technology identified through the survey. [3] The permanent magnet is connected to the end of the Control Element Assembly (CEA) extension shaft and move together with the CEA inside the upper pressure housing. The reed switch assembly outside the upper pressure housing detects the position of the permanent magnet. Therefore the arrangements of the permanent magnet and the reed switch are the most important procedure in the design of the control rod position indication. [4] In addition to the position indicator we adopted an angular position detector to monitor the operation condition of the rotary step motor and to increase the measuring accuracy of the control rod position. [5]

## 2. System description

Fig. 1 shows a general view of the position indicator assembly and the angular position detector assembly on the pressure housing of CEDM. The CEDM consists of four CEA Position Indicators (PIs), a Rotary Step Motor (RSM), an Angular Position Detector (APD), an Extension Shaft Assembly (ESA) connecting CEDM and a Control Element Assembly (CEA). Each of the CEDMs is attached to a CEA by an extension shaft. The CEDM is used to vertically position the CEA and the position indicator is used to sense the position of the CEAs in the reactor core by using the reed switches outside the upper pressure housing. Each CEDM is capable of withdrawing, inserting, holding, or tripping the attached CEA from any point within its stroke in response to an operating signal. The position indicator is designed to have 4 channels in order to satisfy the design requirements of a sufficient independence and redundancy for the indication of a safety related signal. Casing of RSM is made with the use of welded joints. The separate CEDM units are joined to each other by flanges with studs and nuts. Each part and subassembly of the CEDM are located on the reactor central cover and connected to it by means of a thread and an omega seal weld. Communication line between the CEDM and control hardware is provided by cables. [1-4]

Following are each design requirement for operating the position indicator and the angular position detector for the integral reactor.

*Design requirement of the position indicator and the angular position detector*

Operating temperature : 0 – 50 °C  
 Operating pressure : atmospheric pressure  
 Humidity : 20 – 90 %  
 Resolution : 20mm (position indicator)  
 Resolution : 2mm (angular position detector)

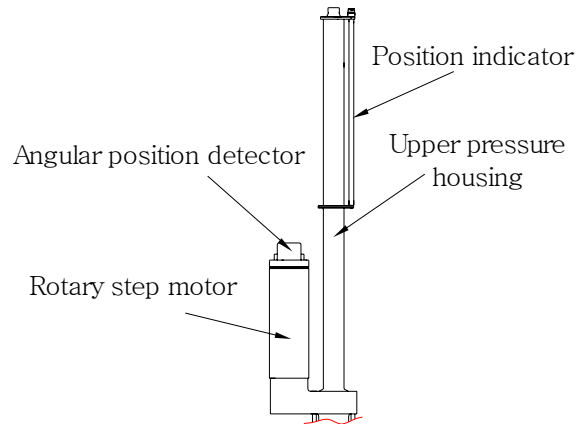


Fig. 1 General view of the CEDM assembly

The position indicator provides an analog voltage signal proportional to the CEA position by using precision resistors and it magnetically actuates the reed switches. The resolution of the position indicator depends on the interval of the reed switches and the magnetic flux density of the permanent magnet located on the extension shaft of the CEDM. The angular position detector also uses the reed switches and the permanent magnet located on the rotor shaft of the rotary step motor.

## 3. Components of the position indicator and the angular position detector

### 3.1. Permanent magnet

The monitoring of the control rod position in a nuclear reactor is complicated by the fact that the control rod is typically submerged in a fluid and during operation of the reactor the temperature of this fluid and the rod itself becomes quite high. Also another limit for the flexibility of the design is an undesirable communication between the interior and exterior of the pressure housing. The usage of the permanent magnet as the measuring medium of the control rod enables the position of the control rod to be monitored accordingly without the necessity of providing communication between the interior and exterior of the pressure housing in which the movable control rod is situated.

At a position indication the permanent magnet located at the top of the CEA extension shaft assembly travels from the zero position to the top level. The permanent magnet is fixed and travels with the reactor control rod. And a series of axially aligned flux

responsive reed switches located immediately outside the non-magnetic upper pressure housing extend in a direction parallel to the control rod drive. At the angular position detector the permanent magnet located in the holder of the gear rotates in the pressure housing of the angular position detector. An individual flux responsive reed switch is actuated by the magnet passing in proximity to it.

Neodymium Iron Boron (NdFeB), the most powerful Rare Earth magnet available today, possesses a high energy range from 8MGOe to 48MGOe and a wonderful coercive force. As the third generation of the Rare Earth permanent magnet, NdFeB products are less brittle than SmCo and used in a wide variety of applications. The maximum energy product,  $(BH)_{max}$  and the Coercive force,  $H_c$  of the NdFeB are stronger by about 3 times and 5 times respectively than those of the Alico which was used as a permanent magnet for the RSPT of the ABB-CE. Therefore we adopt the NdFeB instead of the Alico as the permanent magnet in order to design a compact size of the magnet for a high resolution of the position indicator for the integral reactor. Following are the characteristics of the NdFeB permanent magnet (N35UH) used in the position indicator and the angular position detector for the integral reactor.

*Magnetic characteristics of the NdFeB permanent magnet (N35UH)*

- Operating temperature : below 180 °C
- Residual magnetic flux density,  $B_r$  : 11.7 – 12.1 KGs
- Coercive force,  $H_c$ : 10.8 – 11.5 KOe
- Maximum energy product,  $(BH)_{max}$  : 33 – 35 MGOe

3.2. Reed Switches

The reed switch consists of a pair of flexible reeds made of a magnetic material, and sealed in a glass tube filled with an inert gas. The reeds are overlapped but separated by a small gap. The contact area of each reed is plated with a noble metal, such as Rhodium or Ruthenium, to provide the switch with stable characteristics and a long life. Application of a magnetic field, generated by a permanent magnet or a coil, to the reed switch causes both reeds to be magnetized. This produces an N-pole at the contact area of one reed, and an S-pole at that of the other reed, in a manner shown on Fig. 2. If the magnetic attracting force overcomes the resistive force caused by an elasticity of the reed, the reeds come in contact (Pull-In) i.e., the circuit is closed. Once the magnetic field is removed, the reeds are separated again by the effect of the elasticity of the reed (Drop-Out) i.e., the circuit is opened.

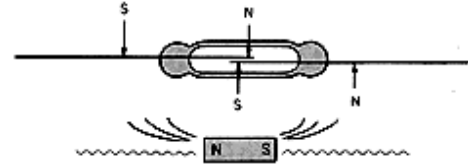


Fig. 2 Magnetization of the reed switch

The reed switch HYR-2001(Type3) is selected to embed the position indicator assembly of the integral reactor because it has been proven in the RSPT of the ABB-CE. The Pull in Value (AT) of a reed switch is related to the decision on the magnetic size and operating range of the reed switch. In order to control the Pull in Value of a reed switch, we specified an additional grade (Type3) for HYR-2001.

Dimensions Unit: mm (inch)

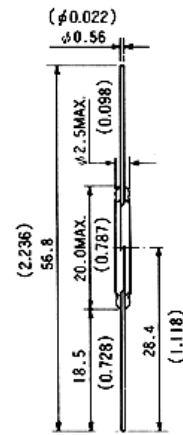


Fig.3 Dimensions of the reed switch HYR-2001

TABLE 1: Characteristics of the reed switch HYR-2001

Contact Material	Rhodium
Max. Contact Rating	10W
Max. Switching Voltage	200VDC
Max. Switching current	0.5A
Max. Initial Contact Resistance	100 mohms
Pull in Value (AT)	40-45
Min. Drop out Value (AT)	6
Min. Breakdown Voltage	300 VDC
Max. Contact Capacitance	0.4pF
Min. Insulation Resistance	$10^{10}$ ohms
Typ. Resonant Frequency	3kHz
Electrical Life (Resistive loads)	$10^7$ (5VDC, 10mA) $10^6$ (100VDC, 100mA)

Test Coil	TC-0502
Features	General application

The magnetic flux density for operating the reed switch can be calculated by using the Pull in Value (AT) and the dimension of the test coil. Fig. 4 is a sectional view of the used test coil TC-0502 which has a cylindrical shape with a hole at the centerline. The reed switch is placed in the hole of the test coil during the test.

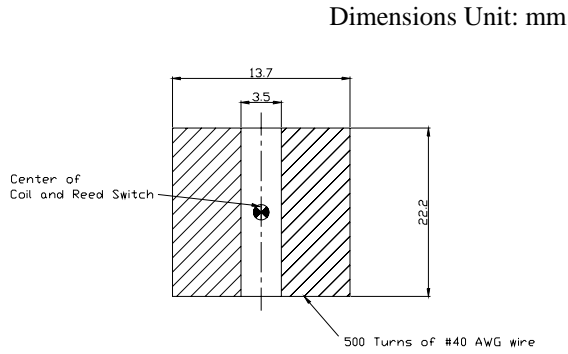


Fig 4 Dimensions of the test coil TC-0502

At the center of the test coil TC-0502 the magnetic flux density can be obtained by the following equation (1).

$$B^* = \mu_0 H 10^4 = (4\pi \times 10^{-7})(10^4)H = 0.0126H \quad (1)$$

where

$B^*$  : Equivalent magnetic flux density

$\mu_0$  : Permeability at vacuum

$H$  : Magnetic flux intensity [AT/m]

Equation (1) can be expressed as equation (2).

$$B^* = 0.0126 (NI / L) = 0.0126 (NI / 0.0222) \quad (2)$$

where

$N$  : Number of coil turns

$I$  : Current

$L$  : Height of test coil

The required range of the magnetic flux density needs to cause the reed switches HYR-2001(Type3) to contact close and can be calculated by using the Pull-in-Value (40-45 AT) of the HYR-2001(Type3) in Table 1.

$$B^*_{low} = 0.0126 (40/0.0222) = 22.7 \text{ Gauss} \quad (3)$$

$$B^*_{high} = 0.0126 (45/0.0222) = 25.5 \text{ Gauss} \quad (4)$$

#### 4. Position indicator

Two reed switches are provided at each elevation along the voltage divider network. These two switches are connected in series. It is important that the redundant switches (i.e. two switches in series) are

included in the design to protect against the possibility of a single switch being stuck in the closed position. At the 20mm level there are two switches which are wired in parallel to the moving direction of the magnet. In order to enhance the resolution of the position indicator the arrangement of the reed switches is designed to be more compact than that of the ABB-CE. Fig. 5 is the arrangement of the reed switches on the terminal strip in the position indicator assembly.

The position indicator is designed to provide a stepped analog out signal proportional to the CEA position within the reactor core. The circuit of the position indicator consists of a voltage divider network suitable for use with an external power supply of 15 VDC. The analog circuit is composed of the precision resistor and the magnetically actuated reed switches. The analog output signal range of the position indicator is from 3 to 9.8 VDC, which corresponds to the full mechanical traveling distance of the CEA. The analog output signal is step-wise linear and continuous over this range. The accuracy of the analog output signal is such that the indicated CEA position is within plus or minus 10mm of the actual CEA position at all the positions along the entire length of the CEA travel.



Fig 5 Photograph of arrangement of the reed switches

Fig. 6 shows the voltage divider network. The position indicator provides a step-wise output signal at positions corresponding to every step. Equation (5) is used to calculate the output voltage signal of the position indicator. As the magnet moves upward along the position indicator assembly from the bottom to the top in the upper pressure housing, the output voltage linearly increases step-wise at 0.2VDC increments.

$$V_o = \frac{R_a + R_c \times SN}{R_a + R_b + 35 \times R_c} \cdot V_{in} \quad (5)$$

where

$V_{in}$  : Applied Voltage (15VDC)

$V_o$  : Output Voltage

$R_a$  : Resistor (600  $\Omega$ )

$R_b$  : Resistor (1000  $\Omega$ )  
 $R_c$  : Resistor (40  $\Omega$ )  
 $SN$  : Steps Number of Reed Switches

The serially wired two reed switches are located every 20mm from the 0 step to the 34th step. One set is composed of serially wired two reed switches.

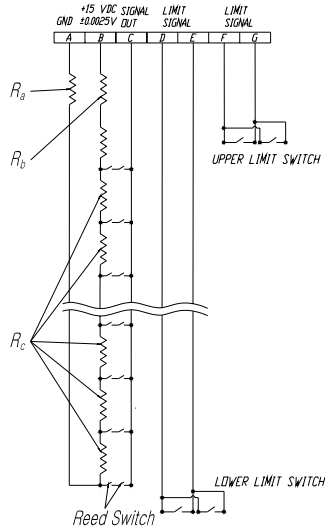


Fig 6 Voltage divider network

The position indicator is designed such that while the reed switches are being actuated by the NdFeB magnet, at least two sets of the reed switches in the analog circuitry are always closed. Between every step there are transient areas which occur by a contact closing of three reed switches which is the 2-3-2 contact closing sequence.

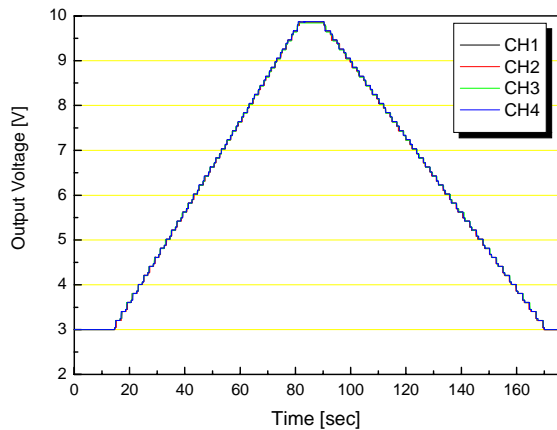


Fig 7 Experimental results

Fig. 7 shows the experimental result of the position indicator manufactured for the performance test. Experimental results of the 4 channels of the position indicator were achieved simultaneously when the NdFeB magnet was moving up and down in the upper pressure housing. The velocity of the NdFeB magnet was 10mm/sec and the sampling time was 0.02 second

during the test. The output signal voltage was in good agreement with the calculation data. No spurious signals resulted from the CEA motion or the magnetic fields created by the CEDM step motor.

## 5. Angular Position Detector

Fig. 7 shows a sectional view of the angular position detector and its major components are 2 pairs of planet and sun gears, a holder of the planet gear, a magnet and reed switches around the housing of an angular position detector. As the angular position change of the rotor shaft of the RSM comes to the spline of the angular position detector, the planetary gear system magnifies the angular position of the rotor shaft of the RSM to help the reed switches to measure the angular position according to a one step angular increase of the rotary step motor. The detecting the target of magnet for the reed switches is in the holder of the planet gear.

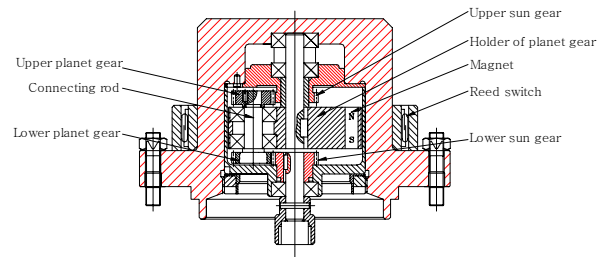


Fig. 7 Configuration of the angular position detector

Fig. 8 shows the schematic diagram of planetary gear system having the role to magnify the angular position increase of the RSM.

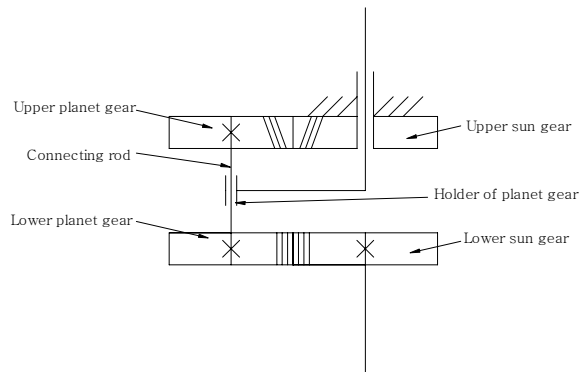


Fig. 8 Schematic diagram of planetary gear system

The principle of the planetary gear system operation is as follows. The angular increment of the magnet can be obtained by multiplying the original angular increment of the RSM by the magnification ratio  $i$ . For example if we want to set the magnification ratio  $i$  to 8 we only provide a planetary gear system with  $Z_1$  of 30,  $Z_2$  of 25,  $Z_3$  of 30 and  $Z_4$  of 32.

$$i = \frac{Z_2 \cdot Z_4}{Z_2 \cdot Z_4 - Z_1 \cdot Z_3} \quad (6)$$

where

- $i$  : Magnification ratio
- $Z_1$  : Number of teeth in the upper sun gear
- $Z_2$  : Number of teeth in the upper planet gear
- $Z_3$  : Number of teeth in the lower planet gear
- $Z_4$  : Number of teeth in the lower sun gear

Fig. 9 shows the simplified shape of the reed switch holder around the pressure housing of the angular position detector. The design feature of the reed switch holder is to provide an easy installation, maintenance and calibration for the angular position detector. Also the reed switches can be vertically mounted into the reed switch holder. The permanent magnet positioned in the planetary gear holder which is designed to rotate at  $60^\circ$  corresponds to each step of the rotary step motor. The rotation angle of the magnet can be detected by the reed switches around the pressure housing of the angular position detector.

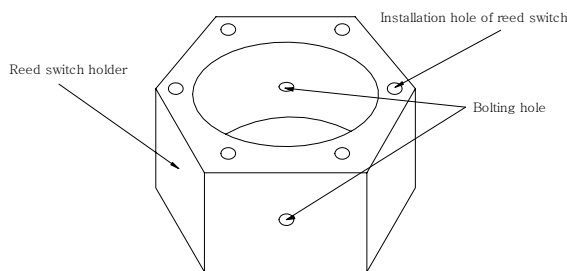


Fig. 9 Configuration of reed switch holder of angular position detector

## 6. Conclusion

In the design of a small and medium reactor, it is necessary to develop a CEDM with a fine-step movement capability as well as a high reliability for a fine reactivity control. Thus, it is also necessary to develop a position indicator with a high resolution as well as a high reliability for a fine reactivity control. In order to monitor the operating condition of the rotary step motor of the CEDM, an angular position detector is adopted to check on the operating condition and the rotational direction of the rotary step motor and to assist the position indicator which measures the control rod position.

The performance test of a position indicator with a compact arrangement of the reed switches for a high resolution was successfully carried out. The results of this study have shown that a position indicator including an NdFeB magnet and a compact arrangement of the reed switches can be effectively applied to the integral reactor CEDM after the environmental tests.

A conceptual design of the angular position detector is proposed to enhance the accuracy of the control rod position and to check on the operating condition of the rotary step motor. The confirmation of the performance of the angular position detector is fulfilled through the ACAD model, analytic equations and reed switch tests. The results of this study have shown that the angular position detector will cooperate with the position indicator to measure the position of the control rod more reliably

## Acknowledgements

This work has been performed under the nuclear research and development program sponsored by the Ministry of Science and Technology, Korea.

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