A Comprehensive Review on Solenoid-type In-vessel Control Rod Position Indicators (IV-CRPI) for i-SMR

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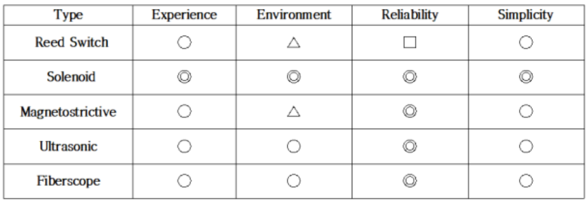
1. Introduction

Small Modular Reactors (SMRs) have emerged as a pivotal solution for the global energy transition, offering enhanced safety and siting flexibility through their integrated and compact designs. Accordingly, the Republic of Korea is currently developing the innovative-SMR (i-SMR) as a strategic response to these global trends. The unique feature of the i-SMR is the adoption of the In-vessel Control Rod Drive Mechanism (IV-CRDM) including In-vessel Control Rod Position Indicator (IV-CRPI). This integration is primarily intended to achieve a compact reactor design and fundamentally eliminate risk of the Reactivity Initiated Accidents (RIA), such as control rod ejection.

In conventional large-scale nuclear power plants like the APR1400, reed switch-type sensors have been successfully utilized as position indicators. However, this method is difficult to apply to in-vessel environments with high temperatures exceeding 300 °C. In this condition, the magnetic permeability of the reed switch materials undergoes significant changes, which leads to degradation in sensing reliability.

To determine the most suitable technology for these harsh conditions, a technical survey and feasibility review were conducted on various linear displacement sensors. As summarized in Table. 1, magnetostrictive, ultrasonic, and fiberscope sensors offer high accuracy in standard industrial applications. However, they are unsuitable for in-vessel use because their detectors and sensing elements cannot withstand the high temperature within the reactor vessel. In contrast, the solenoid-type sensor is identified as the best candidate, offering high environmental suitability and structural simplicity, which are essential for reliable operation inside the RPV [1].

Table. 1. Comparative feasibility review of various linear displacement sensors [1].



Type	Experience	Environment	Reliability	Simplicity
Reed Switch	○	△	□	○
Solenoid	◎	◎	◎	◎
Magnetostrictive	○	△	◎	○
Ultrasonic	○	○	◎	○
Fiberscope	○	○	◎	○

***legend: ◎(Excellent), ○(Good) □(Acceptable), △(Poor)**

2. Design of Solenoid Type Position Indicator

The solenoid-type IV-CRPI developed by Woojin operates using a triple-coil configuration consisting of S0, S1, and S2. The primary sensing coil, S0, measures the vertical displacement of the ferromagnetic drive rod; as the rod is inserted, the inductance of S0 increases linearly. To ensure accuracy, S1 and S2 serve as fixed reference points that define the boundaries of this linear range. Specifically, S1 is designed to indicate the inductance level of S0 when the drive rod is fully withdrawn, while S2 corresponds to the state where the rod is completely inserted [2].

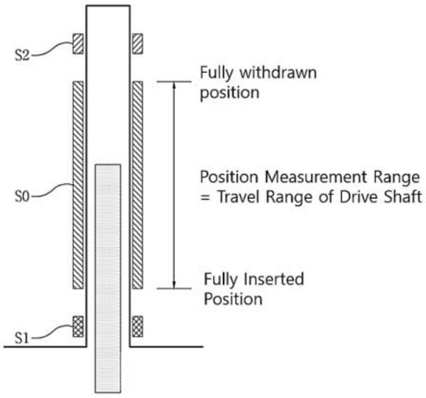


Fig. 1. Schematic diagram of solenoid-type position indicator [2]

By performing linear interpolation of the real-time S0 inductance measurement using the reference values provided by S1 and S2, the system can precisely determine the exact physical position of the drive rod. The most significant advantage of this architecture is its inherent capacity for temperature compensation. Since S0, S1, and S2 are co-located within the same high-temperature environment, their respective inductance values shift simultaneously in response to temperature fluctuations. Because the position is calculated based on the relative ratio between these three inductance values, the temperature-induced signal drift is effectively compensated, allowing for stable and reliable position monitoring even during any temperature swings of reactor operation [2].

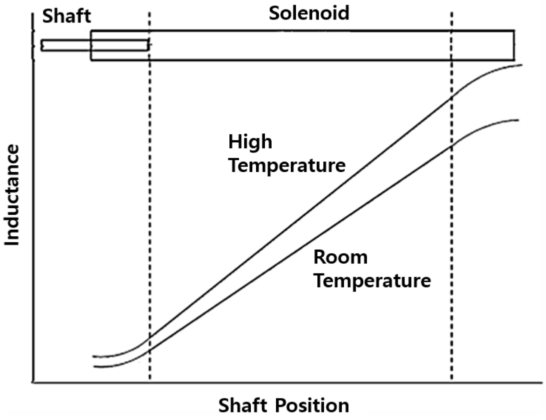


Fig. 2. Impact of temperature on the inductance -position relationship [2]

3. Operational Principle of Solenoid Type Position Indicator

The solenoid-type IV-CRPI operates based on the variation of inductance induced by the axial movement of a ferromagnetic rod within the S0 coil assembly. As stated in Eq. (1) (please see Section 6 in the later part of the paper), the inductance is defined as the ratio of the total magnetic flux linked with the coil turns to the input current. According to Hopkinson’s Law, this magnetic flux is further determined by the relationship between the magnetomotive force (NI) and the magnetic reluctance, as expressed in Eq. (2) and Eq. (3). The reluctance, which characterizes the opposition to magnetic flux, is a function of the solenoid's geometry specifically its length and cross-sectional area and the magnetic permeability of the core material, as formulated in Eq. (4)[3].

When a ferromagnetic rod, such as SS410, is partially inserted into the solenoid, the core becomes a composite medium consisting of both the rod and the empty space filled with air. In this configuration, the total magnetic reluctance is the sum of the resistances offered by the rod-filled ($\boldsymbol{l_A}$) and air-filled ($\boldsymbol{l_B}$) sections, as represented in Eq. (5). By substituting Eq. (5) into the magnetic flux definition in Eq. (3), the expression is expanded in Eq. (6) to explicitly show the interaction of the rod material's permeability and its geometric distribution within the assembly. Finally, by substituting the flux expression from Eq. (6) back into the initial inductance definition in Eq. (1) and replacing the air-filled length variable ($\boldsymbol{l_B}$) with $\boldsymbol{l - l_A}$, the inductance is established as a specific functional model of the rod position in Eq. (7) [3].

The derivation in Eq. (7) demonstrates that the inductance increases monotonically as the ferromagnetic rod moves deeper into the solenoid assembly. As Finite Element Analysis (FEA) and experimental validations shown in Fig. 3. However, non-linearities inevitably occur at both ends of the displacement range due to the fringe field effect, where the magnetic flux spreads and changes unevenly near the physical boundaries of the solenoid [3]. So, the effective position-sensing range is limited to the region where the inductance exhibits a linear increase.

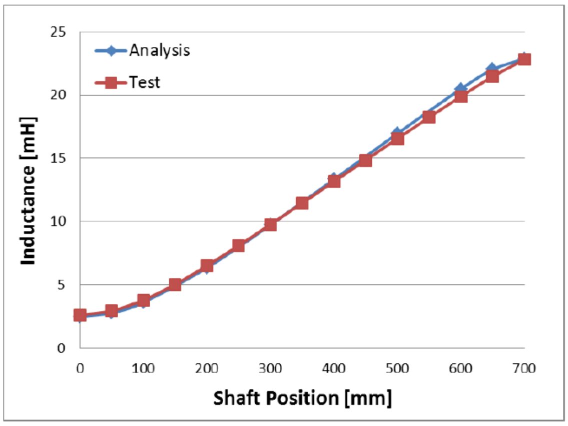


Fig. 3. Validation of the solenoid type position indicator model: Comparison between numerical FEA simulations and experimental test data [4].

According to the relationship established in Eq. (7), the measured inductance is proportional to the magnetic permeability of the drive rod. Since the permeability of ferromagnetic materials like SS410 increases with increasing ambient temperature, any thermal fluctuation in the reactor leads to a corresponding shift in the inductance signal, even at a constant rod position. This inherent temperature dependence of magnetic permeability, as illustrated in Fig. 4, underscores the necessity of implementing a robust thermal compensation mechanism to maintain measurement integrity.

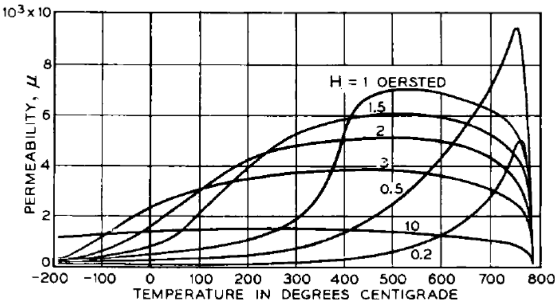


Fig. 4. Dependence of the permeability of iron on the temperature and the magnetic field strength [5]

Additionally, based on the geometric factors shown in Eq. (7), while thermal expansion could alter the physical dimensions of the coil (such as length (l) and cross-sectional area (S), its impact on the overall inductance is predicted to be negligible compared to the dominant influence of permeability variations.

4. Redundant Design of IV-CRPI for Enhanced Operational Reliability

According to the APR1400 DCD Tier 2 Section 3.9.4, each control rod assembly must be monitored by two independent position indicators to ensure continuous feedback in the event of a single-channel failure [6]. Furthermore, to maintain long-term stability and satisfy safety standards, measurement channels must be multiplexed and physically separated as specified in KEPIC ENB 2000 and US NRC Regulatory Guide 1.75[3].

Implementing such redundancy in solenoid-type indicators has been challenging because the drive rod must axially penetrate the coil assembly. However, recent research has proposed innovative redundant solenoid designs that successfully incorporate multiple measurement channels within a single housing while maintaining the required physical separation. These advancements allow solenoid-type indicators to meet the redundancy requirement.

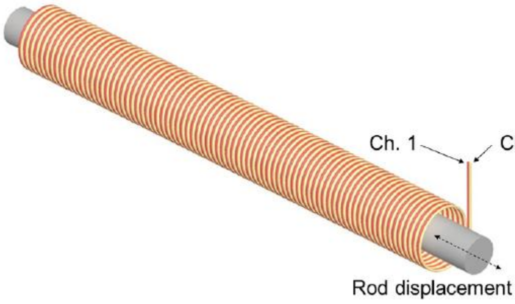


Fig.5. An example of dual-channel redundancy designs of the IV-CRPI [3]

5. Conclusion

This study investigated the design and operational principles of the solenoid-type In-vessel Control Rod Position Indicator (IV-CRPI) for i-SMR applications. The sensing mechanism is primarily driven by the axial displacement of the ferromagnetic drive rod within the coil assembly, which induces changes in inductance value. The magnetic permeability of the rod material influences the inductance values. Since this permeability varies in response to the operating temperature, it can be a critical factor that determines indication accuracy, necessitating appropriate thermal compensation.

To address the thermal effect, advanced sensing architectures such as the triple-coil configuration utilizing reference coils for linear interpolation have been proposed to effectively compensate for signal drift and maintain precise position indication. Furthermore, while the structural nature of solenoid-type indicators (where the drive rod axially penetrates the coil) has traditionally posed challenges for the redundancy requirement, recent design improvements are successfully overcoming these constraints to satisfy the requirement of nuclear safety standards.

In conclusion, unlike conventional reed switch-type indicators located outside the reactor pressure vessel, the in-vessel solenoid-type indicator presents additional technical challenges regarding thermal compensation and redundancy. Future research must focus on the rigorous design and experimental verification of these systems to ensure high operational reliability even during transient conditions, such as load-following operations where temperatures fluctuate frequently. Continued optimization of these technologies will be essential for the safe and stable deployment of next-generation integrated small modular reactors.

6. Equations

$$L = \frac{N\phi}{I} \quad (1)$$

$$\phi = \frac{F_m}{R_m} \quad (2)$$

$$\phi = \frac{NI}{R_m} \quad (3)$$

$$R_m = \frac{l}{\mu S} \quad (4)$$

$$R_m = \frac{l_A}{\mu S} + \frac{l_B}{\mu_0 S} = \frac{1}{S}\left(\frac{l_A}{\mu} + \frac{l_B}{\mu_0}\right) \quad (5)$$

$$\phi = \frac{NI}{\frac{1}{S}\left(\frac{l_A}{\mu}+\frac{l_B}{\mu_0}\right)} = \frac{\mu SNI}{l_A+\mu_r l_B} \quad (6)$$

$$L = \frac{\mu SN^2}{l_A+\mu_r(l-l_A)} = \frac{\mu SN^2}{\mu_r l-(\mu_r-1)l_A} \quad (7)$$

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