The AC Device for Repositioning of Garter Springs in CANDU Reactors

Matija Cenanovic and **Hugo Maureira**
Ontario Hydro

Introduction

Proper spacing between the pressure tube and the surrounding calandria tube of the fuel channels in CANDU reactors is maintained by spacers (garter springs). It was established that many garter springs are no longer in their correct positions in Ontario Hydro's operating reactors. Analysis has confirmed that the displaced springs can lead to contact between the pressure tube and the calandria tube, resulting in eventual pressure tube failure, such as the one which occurred 1 August 1983, in channel P2G16 of Pickering 'A' Nuclear Generating Station. To prevent this, a novel AC device was developed at Ontario Hydro Research Division to reposition the garter springs without any harmful effect on the fuel channel integrity.

This paper describes the development of this device. The development started with the recognition of the technical problem, invention [1] of the AC device and proof of principle of operation, theoretical analysis and engineering development, integration into the SLAR system, field trial of the preproduction tooling, and, finally, manufacture of devices for field implementation of the SLAR program.

Recognition of The Repositioning Problem

The problem can be briefly summarized as follows: 1.) access to the garter spring; 2.) moving the garter spring.

Since the only permissible access was stipulated to be from inside the pressure tube, in order to produce a physical force to move the garter springs, there is need to establish some sort of coupling between the garter spring and a device that can exert force on the garter spring. In the case of electromagnetic forces, there are two fundamental difficulties in achieving significant interaction with the garter spring:

1. electromagnetic shielding of the pressure tube (as shown in Figure 2);
2. unfavorable material properties of the garter spring in terms of very low electrical conductivity, non-magnetic characteristics, and similarity to the pressure tube material.

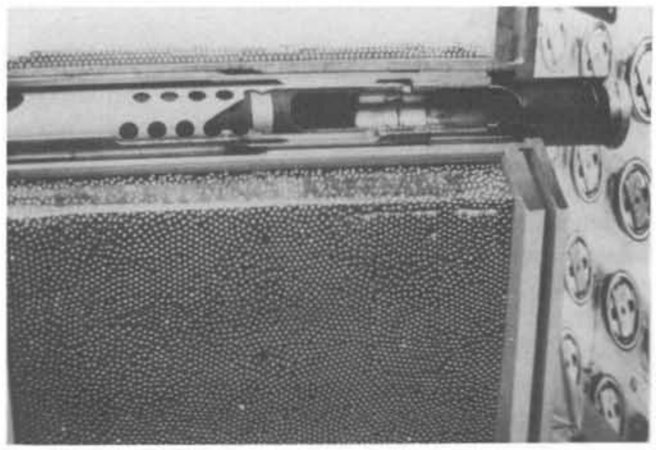

Figure 1: Sectional view of a reactor channel. A garter spring is shown on the extreme right.

An individual solution to each of the above-mentioned difficulties could be achieved by decreasing or increasing the frequency to solve 1. and 2., respectively.

By using too high a frequency, the shielding effect becomes dominant, and in extreme cases no significant field diffuses through the pressure tube wall. A crude

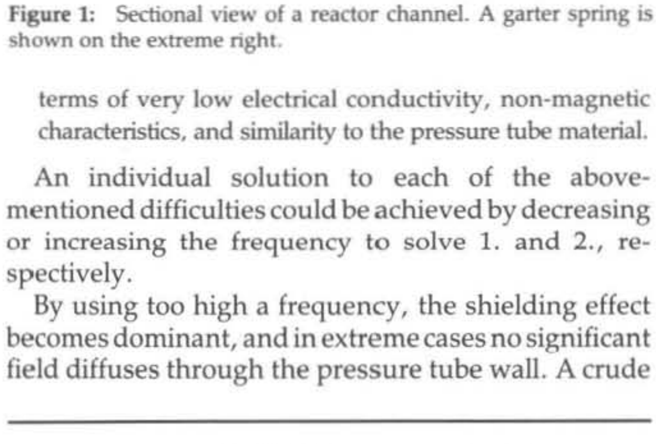

Figure 2: AC device in the fuel channel arrangement.

way of dealing with the extensive shielding effect at high frequency is simply to apply a quantitative rather than qualitative approach, by increasing the operating current. An enormous current is required to obtain some small fraction of the total field in the vicinity of the garter spring. However, there are strict limitations imposed by the fuel channel and the electromechanical system as a whole, which have to withstand the stresses associated with these enormous currents.

Resorting to low-frequency and very high currents will not solve the problem either, for theoretical and practical reasons. At low frequency, the garter spring is essentially resistive, making the electromechanical energy conversion process highly inefficient or impossible.

Another way to view this limitation is from the field theory point of view [2, 3]. Low electrical conductivity, the nonmagnetic property, and the very small dimensions of the garter spring cross-section (girdle wire loop) will result in a very small critical diffusion time constant, and a high critical frequency would be required for any interaction with the garter spring. If one uses a low-frequency source, for which the penetration depth ('skin effect') is much greater than a critical dimension (cross-section of the girdle wire), then, quite simply, the field will not notice the presence of that wire. In the extreme case of zero frequency (DC field), there will be no interaction at all. In conclusion, if one resorts to a brute force increase of the current to enormous values, the practical limitations of the system are obvious. Geometrical confinement and other constraints, and electrodynamic and thermal problems associated with fuel channel and equipment integrity are insurmountable obstacles.

The solution, offered by the AC device, to resolve this conflict between electromagnetic requirements and use of the readily available line frequency, proved to be elusive.

An electromagnetic method and device for repositioning a poorly conductive object (garter spring) behind a conductive wall (pressure tube) was developed on a principle similar to a linear induction motor with an ill-defined and shielded 'rotor'.)

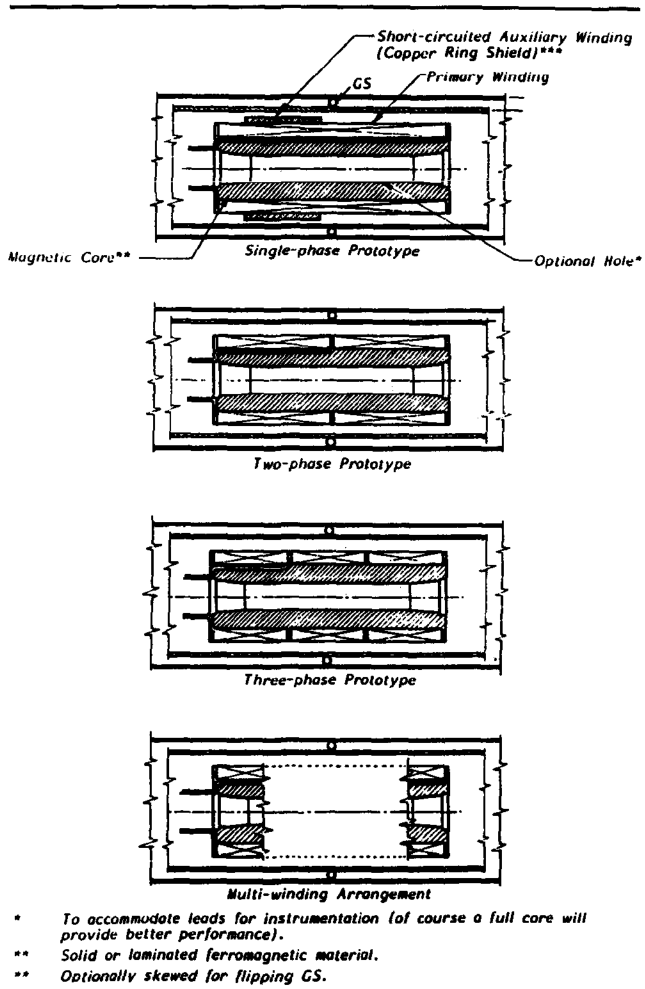

Figure 3: Typical prototypes of the AC device.

Principles of Operation of the AC Device

The principle feature of the AC device is an efficient conversion of magnetic energy into a continuous mechanical movement of the garter spring, through the conductive wall of the pressure tube, without any adverse effects on the fuel channel integrity. Two fundamental difficulties were overcome, simultaneously, to achieve significant electromagnetic interaction with the garter springs.

The governing principle of the AC device is the creation of a travelling magnetic field in a fashion similar to that in a linear induction motor. The use of low (line) frequency makes the shielding effect of the pressure tube negligible; yet the proper phase shifts are created between the steady AC currents flowing in the arrangement of windings placed over the special ferromagnetic core, to create the 'stationary' member of a linear motor, while the poorly conductive garter spring represents the 'travelling' part. The travelling magnetic field is created by a system of currents linking a high-permeability magnetic core. These currents are steady-state AC currents, with appropriate spatial and time phase shifts. For convenience, line frequency is used, although this is by no means the optimum value.

The AC device is a compact magnetic device, consisting of an arrangement of windings placed on a ferromagnetic core of high magnetic permeability, and with a high magnetic flux density saturation point. The magnetic core plays a fundamental role in making the CANDU device compact. It can be shown theoretically that the flux density on the same bounding surface in the magnetic field, using magnetic core materials with magnetic flux density $B = 1.6$ Tesla (which is a typical saturation point for ferromagnetic materials), is about 25,000 times as great as that in the electric field (using the nominal breakdown strength of air of 3×10^{6} V/m), or about 50,000 times as great for a special ferromagnetic material, vanadium permendur (B = 2.4 Teslas), employed in the AC device. Hence, a constant high-energy density is achieved through the use of the magnetic core with the steady-state AC current. In the AC device, the windings can be configured as single-phase or polyphase, and are energized from a continuous AC source. The core can be designed as a straight cylinder in its simplest form, or it can be designed to take more complex forms.

The AC device can take various design forms based on the same principle of operation but different engineering requirements, as shown in Figure 3. For instance, the fundamental single-phase prototype has a metal shield, which provides a low magnetic field region, where the garter spring tends to hide and rest, occupying a minimum energy position. The shield is essentially a copper ring which acts as an auxiliary winding from the circuit theory point of view, or as an electromagnetic shield from the field theory point of view. Induced currents in the copper ring cause the magnetic flux in the shielded portion to be shifted in phase (lag) with respect to the flux in the non-shielded portion (flux window). This results in a magnetic field gradient in space and in time, creating a travelling magnetic field. In case the garter spring needs to be flipped in the inclined position, the coper ring is designed to effect the flipping action (skewed copper ring under the desired angle of inclination). The single-phase AC device prototype is shown in Figure 4.

In the case of a two-phase AC device, the current phase shift in the second phase is predetermined by the source supply, and it is selected by choice to be 120° – but it can be different. In a special case, when the phase shift is 90°, this two-phase prototype becomes identical to a fundamental single-phase prototype.

In the case of the three-phase AC device shown in Figure 5, or, in general, a multi-phase AC device, the principal remains the same, as shown in Figure 3.

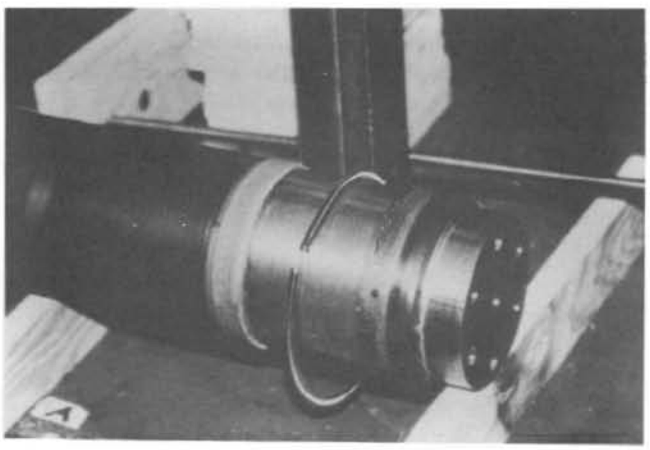

Figure 4: A single-phase AC device.

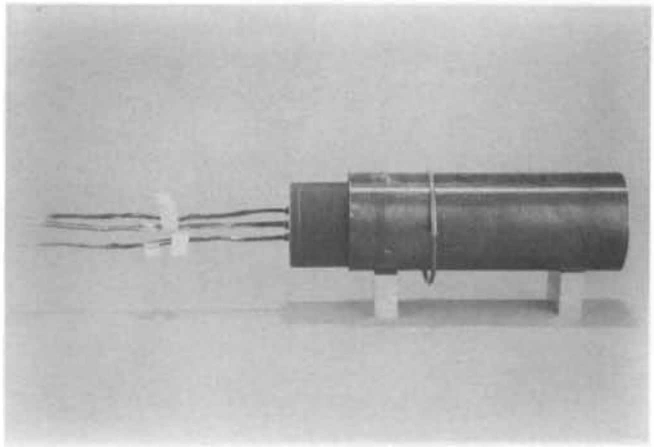

Figure 5: A three-phase AC device (LIM)

Prototypes may incorporate other features, such as more complex winding arrangements, to produce a rotating field superimposed on a linear travelling field, to create a 'screwing' type of motion of the garter spring, and eliminate or reduce the need for unpinching when and if it occurs. Further engineering optimization is possible.

Engineering Development and Integration of the AC Device into the SLAR System

The AC device was conceived prior to the initiation of the SLAR program. Because of its technical merit, cost, and compliance with the SLAR requirements, the AC device was selected for the 'repositioning portion' of the SLAR system.

In addition to the fundamental principles of the operation of the AC device, established initially, detailed circuit modelling was performed to simulate the electromagnetic coupling of the device to a garter spring through the pressure tube. These calculated values were in good agreement with the experimental results.

A number of progressively better prototypes were designed, built, and tested. Simple, two-phase and three-phase prototypes were developed. The geometry of the prototypes was imposed by the pressure tube inner diameter and SLAR tooling configuration, and interfacing requirements.

Initial prototypes were built with a solid magnetic core. Subsequent prototypes were built with a laminated vanadium permendur core to reduce thermal losses, as shown in Figure 6.

The AC device could, in principle, be as long as the fuel channel. However, because of the pressure tube sag, the overall length of the two devices mounted on the SLAR tool was selected to be approximately 0.25 m.

In addition, the entire AC device had to be capable of operating in the heavy water environment of the fuel channel. For this reason it was developed and built

Figure 6: Three-phase AC device with a laminated core.

with a special polyurethane encapsulation, as shown in Figure 6.

Since, the AC device operates at low voltage (typically 400 V, 3 phase), and at low current (typically 100 A per phase), the insulation requirements would not normally be too difficult to meet. However, because of the importance of the SLAR project, and the high reliability requirements, the AC device was designed, built, and tested to be inherently safe. The electromagnetic force acting on the garter spring was developed to be in excess of 30 g, with attained values of up to 50 g, which is about three times the minimum force necessary to move the unpinched garter spring. During the engineering development phase, a number of electromagnetic, thermal, and mechanical parameters had to be established, in order to be able to interface the AC device with the SLAR tool. It was necessary to demonstrate the performance capability of the device under the constraints imposed by the SLAR system, including the environmental requirements (wet channel, radioactive, etc.). The power supply and control system to supply power and control to the AC device (LIM) was also designed, built, and tested, allowing selection of one of the two AC devices on the SLAR tool, and selection of the direction and control of garter spring movement. In addition to force-profile measurements, thermal duty cycle tests were performed to establish the size of the power conductor of the umbilical cable, used by the SLAR tool to feed the hydraulic line, the power line, and the sensor's signals through the reactor channel. Ten different prototypes were produced during this phase, in order to add successive improvements and incorporate design features required by SLAR (i.e., arrangement of leads, size of centre core, etc.). This imposed additional and premature difficulties on design. Near completion of the development phase, the AC device was incorporated into SLAR preproduction tooling, to be used during field trials.

Field Demonstration at Pickering 'A' NGS

The first field trial of the SLAR preproduction tooling took place on 12 April 1986 at Pickering 'A' NGS, Unit 4, Channel K10. The repositioning of the garter spring by using the AC device was successful, and the main objective of the field trial to move a garter spring by more than 50 cm was met. The allocated reactor down-time did not allow for the entire trial program.

Following the field trial, 46 AC Devices for the field implementation of the SLAR program were manufactured.

Conclusion

A key component of the SLAR (Space Location and Reposition) system for commissioned CANDU reactors was developed at Ontario Hydro Research Division. This component is a novel low-power AC device. The AC device was designed to reposition the spacers or garter springs within the gas annulus space of the fuel channels in CANDU reactors. The device operates safely and without any harmful effects on fuel channel integrity. The engineering development and integration into the SLAR system was done according to the SLAR program performance, environmental, and interfacing requirements and constraints.

Two AC devices were incorporated in the preproduction SLAR tooling system and successfully proven in a field trial performed in April 1986 in the wet channel K10 at Pickering 'A' Nuclear Generating Station, Unit 4. The AC device, or LIM, was demonstrated to be safe and easy to operate in the reactor's hostile environment. This will result in very large savings to Ontario Hydro and other CANDU reactor owners in terms of extended reliable reactor life.

References

1. *Cenanovic MB.* Electromagnetic method and apparatus for repositioning objects behind a conductive wall. Canadian Patent Application Serial No. 514, 463.
2. *Cenanovic MB.* Electromagnetic forming of zirconium and other strong alloys. 20th Annual Conference of Metallurgists, Hamilton, Ontario, August 23–27, 1981.
3. *Cenanovic MB.* Magnetic metal forming by reversed electromagnetic forces. 4th IEEE International Pulsed Power Conference, Albuquerque, New Mexico, Paper 6.4, June 1983.