Advanced design of reactor coolant pump motors

Reactor coolant pump (RCP) motors for nuclear generating stations have to satisfy special demands in view of the crucial role they play in plant safety and because of their location inside the containment enclosure. ABB delivered two spare RCP motors for Southern California Edison's San Onofre nuclear power station. Although the selection criteria and the motor design are specific to this project, numerous general as well as advanced electrical and mechanical design features are typical of RCP motors being used in the nuclear industry.

A considerable number of the world's nuclear power plants have now reached an age which is close to or even equal to their original design life. Most of the equipment in these plants was designed to such conservative specifications that it is possible, by upgrading certain components, to extend the service life of the stations without impairing their reliability. What is more, refurbishing of this kind can increase the output and efficiency of the plants.

Among the critical components involved are the reactor coolant pump (RCP) motors. These motors are located in the containment enclosure of the nuclear reactor and are therefore inaccessible except when refuelling is carried out, ie at intervals of about 2 years. Safe, continuous operation is thus mandatory for these motors. Besides increasing plant reliability, a replacement motor also contributes to an improvement in operating performance.

In 1993, *Southern California Edison* (SCE) undertook an evaluation to determine whether a spare reactor coolant pump motor would be required to support continued operation of units 2 and 3 of the San Onofre Nuclear Generating Station (SONGS) until expiration of the current operating license. The two units – 1150-MWe pressurized water reactors – have been in service since 1983 and 1984, respectively 1. Each unit has four 7,230-kW (9,700-HP) RCP motors, which run constantly and are required to be operable 100 % of the time to maintain power production of the units.

The evaluation covered, among other things, motor refurbishment and repairs at various companies as well as the procurement of partial assemblies and new spare motors.

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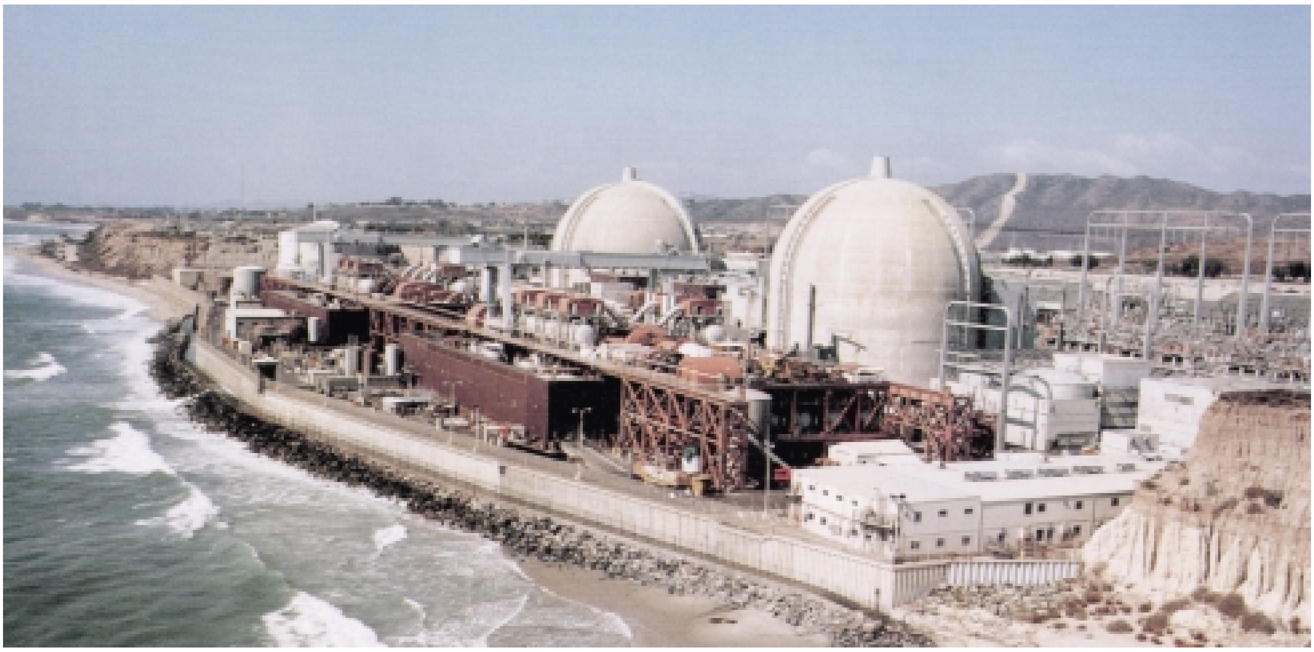
In late 1993 the decision was made to procure a new, complete 7,230-kW motor as spare. It was considered that this would be the most efficient way to support continued operation of the plant without affecting operation of the unit. The new spare motor would allow replacement and inspection of the installed RCP motors.

Background

Nuclear power plants in the USA are regulated by the Code of Federal Regulations [1]. This document applies to all items that affect the safety-related functions required to prevent the consequences of postulated accidents from causing undue risk to public health and safety of the unit. It covers design, purchasing, fabrication, handling, shipping, storage, cleaning, erection, installation, inspection and testing. Although the RCP motor is a commercially available motor, the flywheel and painting are safety-related and have to conform to the said Code of Regulations.

Once the evaluation had established the need for a spare RCP motor, SCE began drawing up specifications for such a maschine. These included technical requirements that would allow the motor to be installed at San Onofre without having to make major modifications to the facility. Design considerations included service conditions and seismic withstand capability, while the safety-related features included flywheel coast-down inertia and painting criteria.

The specifications were submitted to a very rigorous review as well as an extensive station and operation impact assessment. After approval, requests for quotations were sent to a number of qualified vendors. The bid proposals were evaluated from a commercial and a technical standpoint. Technical considerations included compliance with specifications, installation and mainten-



San Onofre Nuclear Generating Station, California. The station has two pressurized water reactors, each rated at 1150 MWe. **1**

ance of the motor, operation of the motor, and vendor experience. ABB was awarded the contract for the RCP motor. This contract was later modified to include a second spare unit.

General design features

Reactor coolant pumps in PWR nuclear power stations are typically driven by a squirrel cage induction motor (SCIM) with vertical shaft **2**. A special feature of this type of motor is that the flywheel is mounted directly on the shaft, thereby increasing the mass moment of inertia of the rotor. This extends the deceleration time of the pump and reduces the flow decay through the reactor upon loss of electrical power. Another special component is the anti-reverse rotational device (ARRD), which prevents back-rotation of the pump in the event of the motor becoming de-energized. The thrust bearing of the motor-pump set is integrated in the motor. This bearing is of the tilting-pad type, and is self-equalizing and self-lubricated. It absorbs downthrust during start-up and upthrust during normal operation. A high-pressure lift system allows easy line-up with the pump. The thrust bearing, which is located on top of the motor, is combined with a guide bearing, a second guide bearing being located at the bottom. The guide bearings are also of the tilting-pad type.

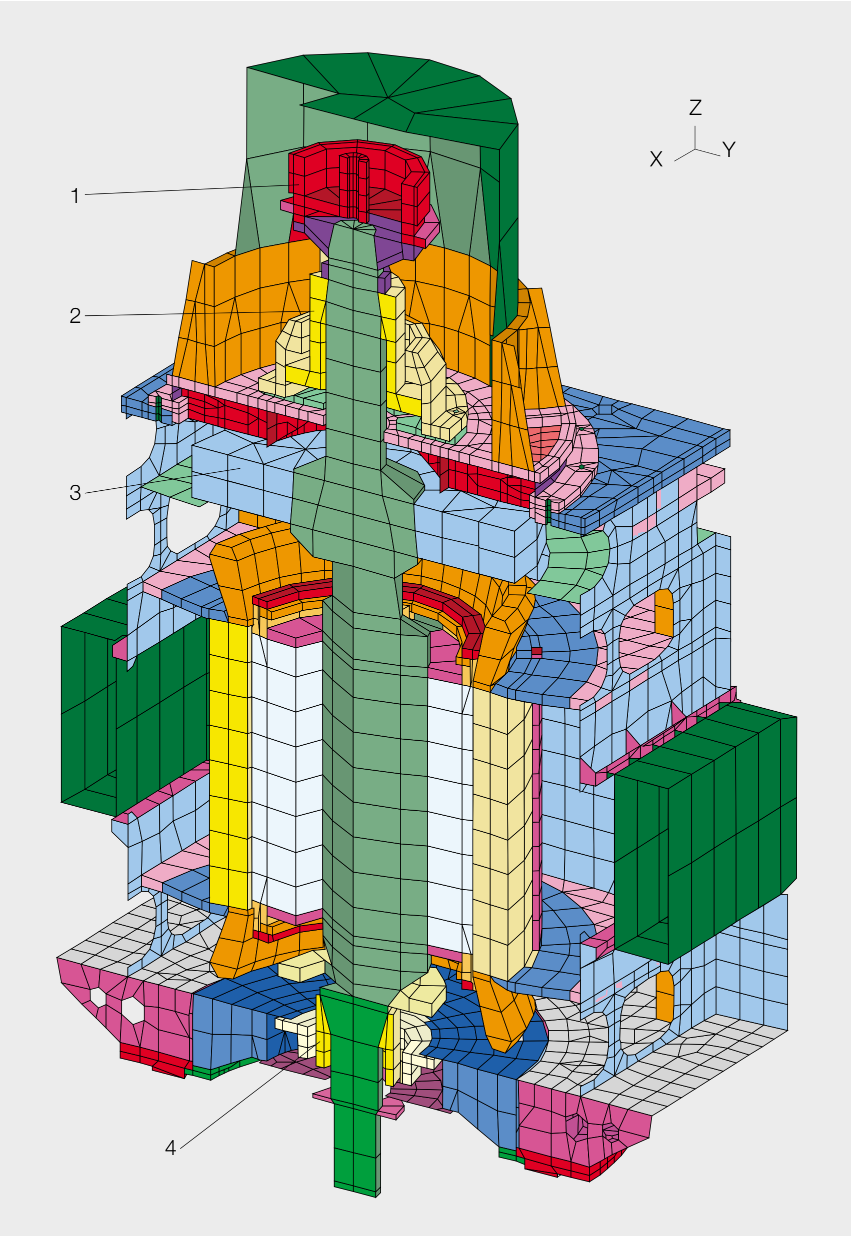
The electrical design of the motor has to allow direct on-line starting with a limited inrush current and acceleration of a high mass moment of inertia, even with a voltage dip to 75 – 80 %, against a quadratically increasing counter torque. These requirements call for a rotor cage winding exhibiting sufficient resistance, a high skin effect and high thermal capacity. The conventional way to ensure these properties is to use a deep bar winding with large cross-section, made of a high-resistance copper alloy. This leads, inevitably, to an oversized motor design with a large rotor diameter. The advantage of such a design is its intrinsically high mass moment of inertia and short rotor core length, both of which support the goal of high critical rotor speeds. As a rule, the critical speed of the motor rotor has to be 150 percent of the nominal speed.

The drawback of this design is that the mechanical stresses are higher and can approach the limits of the materials used. Rotors for high-output motors have to be segmented, ie they will have many more parts than a rotor core with single-piece laminations. Also, strength analyses have to be performed on the additional parts needed to press and fix the rotor core to the shaft, as these represent an additional risk factor. Finally, the oversized design leads to higher losses and lower efficiency.

Improved motor design

Electrical design

The electromagnetic design was improved by choosing a design variant with a higher flux and lower current, resulting in lower ohmic losses and a smaller rotor diameter. The smaller rotor diameter also leads to lower windage losses. A reduction in the pressure drop was achieved by optimizing the cross-



Longitudinal cross-section through the new RCP motor (FE model) **2**

1 *Anti-reverse rotational device (ARRD)*
2 *Combined thrust and guide bearing*
3 *Flywheel*
4 *Lower guide bearing*

sections of all the air ducts. This has allowed an additional reduction in the no-load losses through the use of an advanced, double-ended self-ventilation system without shaft-driven fan(s). These measures have resulted in an improvement in efficiency.

In view of the described starting conditions, the rotor was equipped with a double cage winding, ie a winding with two separate rotor cages. As a result of the high leakage reactance, the cage with the larger diameter carries almost all of the rotor current during start-up. An increase in the start-up torque was achieved by selecting a high-resistance material; the skin effect allows a further increase in torque at the beginning of the start-up period. At nominal speed, the inner cage is predominant because of the low slip frequency. The resistance of this cage is much smaller due to its bigger dimensions and the use of a highly conductive material. Low losses and high efficiency are therefore ensured.

The required thermal capacity of the rotor winding was achieved by selecting appropriate rotor bar dimensions. No unacceptably high temperatures or temperature differences between the top and bottom of the bars will occur either after consecutive starts or when the rotor is locked.

In addition, the stator winding losses were reduced by increasing the winding cross-section. Besides improving the efficiency, this also resulted in a higher surge voltage withstand capability and longer insulation lifetime. All of these measures contribute to an increase in reliability.

Mechanical design

The improved electrical design, which resulted in a longer core and a smaller rotor diameter, had several consequences for the mechanical design of the motor.

The smaller rotor diameter has the advantage that the rotor core laminations could be punched out as single pieces. Due to this design change, all of the structural elements needed for the original, segmented motor could be eliminated. The rotor core is fixed to the rotor spider by means of a shrink fit and round bar keys. This design results in low stress concentration factors, large safety margins and higher reliability.

A drawback of the smaller rotor diameter is its lower mass moment of inertia. To keep the flywheel effect (WR^2) constant, the mass of the flywheel had to be increased.

The required safety margin vis-à-vis the critical speed was guaranteed by increasing the shaft diameter. Modern Finite Element (FE) methods enable the design engineer to predict the natural frequency of the shaft, including the elasticity of the rotor suspension, much more accurately than was possible 20 years ago **3**.

The larger shaft diameter made it possible to shrink-fit the flywheel onto the shaft rather than use a key. Shrink-fitting onto a large-diameter shaft results in low stress concentration factors, resulting in a large safety margin.

Another advantage of the bigger shaft diameter is that there is a rigid connection between the rotor core and the flywheel. The result is a high torsional eigenfrequency, which lowers the stress experienced by the shaft during start-up and reclosure as well as under short-circuit conditions.

FE analyses were employed to determine the optimum shaft diameter. Other analyses also revealed that the influence of the increase in weight on the safety margin, even in the event of earthquakes, was marginal.

Another special area of concern for the designers was the limited vertical shaft movement. If the axial deflection is too large, damage could be caused to the pump seals, possibly resulting in leakage.

Much of the allowed vertical movement is already taken up by the bearing clearance, the thermal elongation of the rotor and the strain in the mechanical parts. The upper bearing bracket, in particular, has to be designed for minimum deflection as it is subject to bending forces. The FE method also proved to be a powerful tool here, and provided highly reliable results for this critical part **4**.

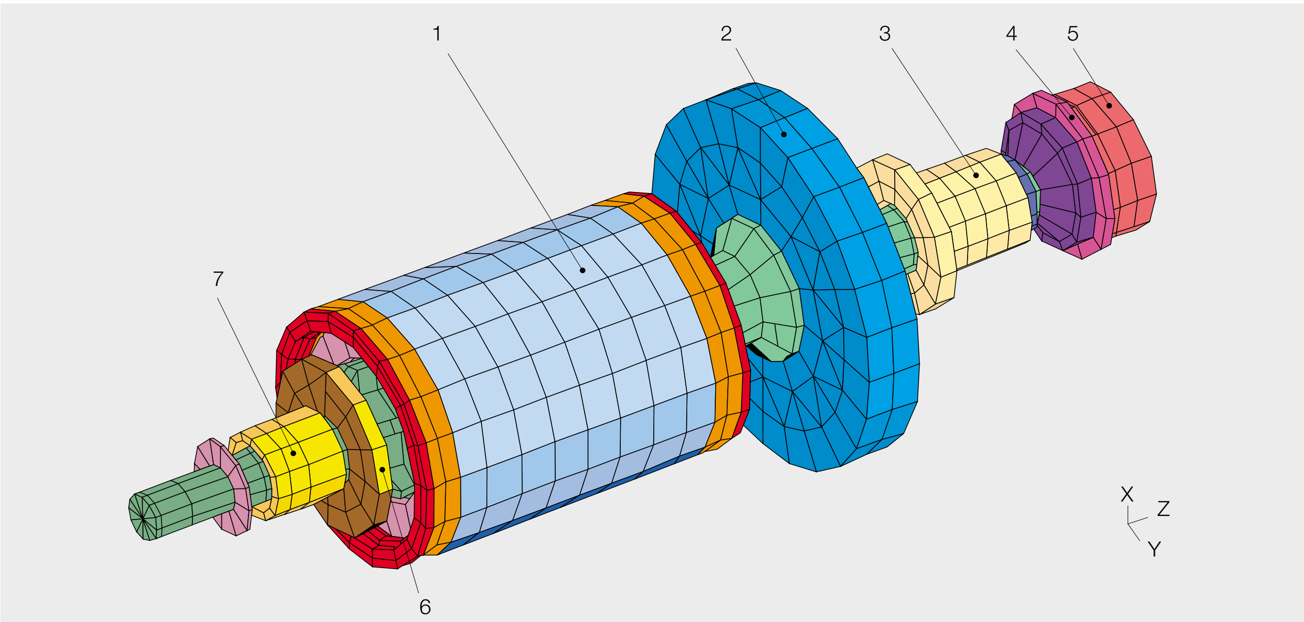
The design of the thrust bearing was also modified. Instead of a conventional plate-type tilting pad bearing, a tilting pad bearing with circular pads was chosen **5**. The circular shape of the pads results in an increase in the specific load capacity, so that the diameter of the bearing, and therefore the average circumferential speed, can be reduced. Losses are consequently lower with this type of bearing than with a conventional design. The modifications allowed the losses to be lowered in spite of the higher rotor weight.

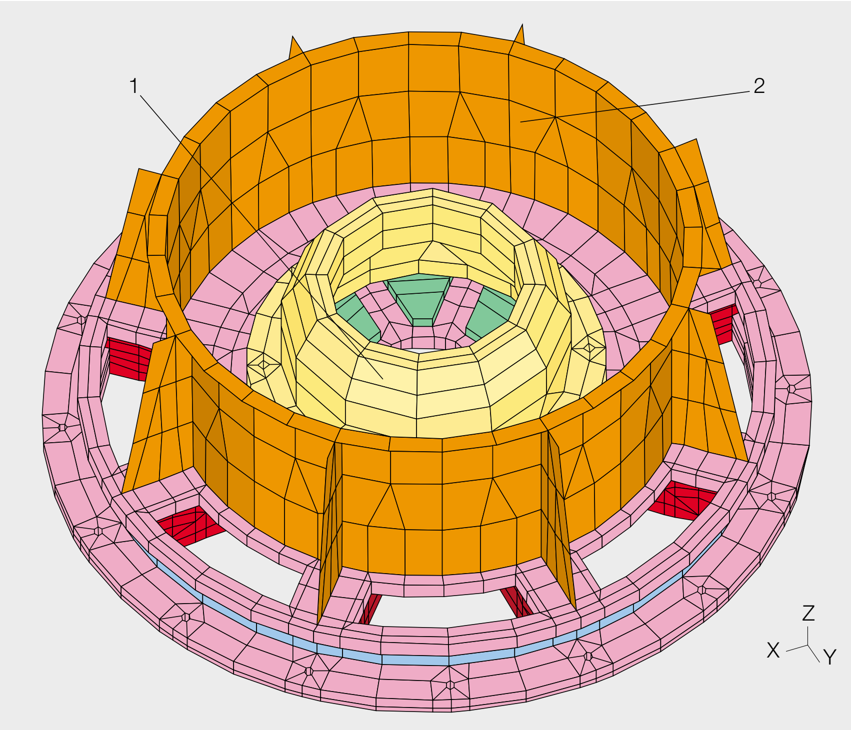
There was, however, still one design problem to resolve: In the existing motor, the oil pressure produced by the thrust bearing was used to lubricate the ARRD and to circulate the lubricating oil through external oil/water coolers. Since the new thrust bearings exhibit only low losses, they do not produce enough pressure for this. It was therefore decided to replace the external coolers by an internal cooler. Also, the lubricating oil for the ARRD is supplied by the upper guide bearing instead of by the thrust bearing. This design change required optimization of the oil piping connecting the upper guide bearing to the ARRD.

In the existing motor, the lubrication of the upper bearing is supervised by measuring the oil flow in the exter-

FE model of the rotor of the new RCP motor **3**

1 *Rotor core and winding*
2 *Flywheel*
3 *Upper guide bearing journal*
4 *Thrust bearing runner*
5 *ARRD*
6 *Balancing disc*
7 *Lower guide bearing journal*





FE model of the upper thrust and guide bearing bracket **4**

1 *Upper guide bearing* 2 *ARRD flange*

nal coolers. As the new motor has an internal cooler, special oil loops had to be designed which simulate the external oil flow and enable the same type of supervisory instruments to be used.

Upthrust tilting pad bearing with circular pads **5**

Motor fabrication, testing and site installation

The motor design was approved in stages during 1994 and early 1995, and coordinated by means of a master schedule for the fabrication which also included all the items relevant for the design verification and motor tests.

Before being assembled, the rotor was dynamically balanced and subjected to an overspeed test to prove the mechanical integrity of the construction and the materials. In addition, the stator winding underwent rigorous multistage testing during the fabrication, after assembly and after impregnation.

Early 1995 saw the first motor ready for extensive performance testing. The results of the electrical tests, which were carried out to IEEE 112A [2], confirmed the pre-calculated performance values. The same procedure was subsequently used for the second motor.

The mechanical tests covered bearing performance, the lubrication of the ARRD assembly and vibration behaviour. The bearings were subjected to a full-scale heat run with a water inlet temperature that corresponded to site conditions. The test results showed that the bearing temperatures were close to the expected values.

The tests on the ARRD oil supply showed that the oil pipes connecting the upper guide bearing to the ARRD needed adjusting to ensure sufficient lubrication of the latter.

Following successful no-load tests at the ABB factory, both the motors were shipped from Switzerland to the SCE facilities **6**.

The two motors were run at the Edison facilities under no-load conditions prior to acceptance by SCE. Subsequently, one motor was installed in San Onofre Unit 3 in August, 1995, contingency plans having been put into place to allow the old motor to be re-installed should unforeseen problems arise. Only minor modifications were necessary during the installation of the motor, and these could be carried out on site. After successful completion of the pre-operational and post-operational tests, the motor was certified for operation. Service commissioning took place in September, 1995.

Summary

The *Southern California Edison Company* has shown considerable foresight with this programme, which will secure continued operation of San Onofre Units 2 and 3 in the event of an RCP motor failure during the remaining lifetime of the units. By adding two spare RCP motors to the Edison inventory, SCE can accommodate degradation and/or failure of a motor in each unit with only minimal impact on plant operation while replacement is taking place.

Due to the improved supervision, SCE can now evaluate the internal conditions of RCP motors in more detail and is in a position to implement the RCP motor refurbishment programme should degradation of the existing motors indicate that it would be prudent to do so.

The project showed the importance of teamwork in a programme of this kind. The success of the project has made a major contribution to securing the future competitiveness of SCE's nuclear resources.

References

[1] Code of Federal Regulations (10 CFR Energy, Part 50, Appendix B)
[2] IEEE 112A Standard

RCP motor ready for shipping to San Onofre **6**

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