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Study on the VFD (Variable Frequency Drive) for RCP (Reactor Coolant Pump) Motors of APR1400.

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1. Introduction

Over the past few decades, energy conservation and energy efficiency have experienced growing importance. Clearly, the electric motor is a prime candidate for a large portion of the energy savings opportunity. Electric motors can be found in almost every residential, commercial, and industrial facility around the world. It has been estimated that electric motors consume nearly half the world's electric power generation.

Therefore, most industrial facilities are continually searching for ways to reduce energy costs while increasing or maintaining current production. In terms of electric motors, Variable Frequency Drive (VFD) units represent a critical opportunity for energy savings. Currently, VFDs are used on about ten (10) percent of industrial process motors, and this percentage is increasing every year. Properly applied VFDs have been documented to save as much as fifty percent of the energy consumed by certain industrial processes.

Nuclear Power - Power plants in general and Nuclear Power Plants (NPPs) in particular are slow to adopt new technology. The nuclear power industry requires a nearly absolute demonstration through operating experience in other industries in which the new approach will result in a net improvement in plant reliability without any surprises.

Only recently has the nuclear industry begun to adapt VFD units for large motors. Specifically, there are several examples in the Boiling Water Reactor (BWR) fleet of replacing Motor-Generator (M-G) sets with VFD units for Reactor Recirculation (RR) pump motor service. At one station, VFD units were introduced upstream of the Circulating Water (CWP) pump motors to address environmental issues. They units are taking advantage of VFD technology whose benefits include increased reliability, reduction in electrical house load, improved flow control, and reduced maintenance.

RCP Application - In the case of new generation, it has been reported that the Westinghouse AP1000 will make use of VFD units for the Reactor Coolant Pump (RCP) motors. Reported advantages in using VFD units for RCP motors include:

- Relaxed reactor coolant system parameters required for start-up: low NPSH (<u>N</u>et <u>P</u>ositive <u>S</u>uction <u>H</u>ead)
- Minimized motor fatigue due to across-the-line (direct-on-line) motor start (soft start)
- Allows use of a smaller motor
- Eliminates need for anti-reverse rotation system

The proposed work for this study is to examine benefits and design considerations of VFD units and to make a recommendation regarding VFD applicability to the RCP motors on the APR1400 design.

2. Methods and Results

In this section, some of the tools and techniques are addressed to analyze applicability and feasibility of adopting VFD on RCP motors of APR1400.

<u>2.1 Electrical Analysis</u>

This study analyzed the behavior of motor starting when 2nd RCP motor starts. In other words, 1A motors has already been started. Dynamic analysis of 2A RCP motor performed for soft starting.

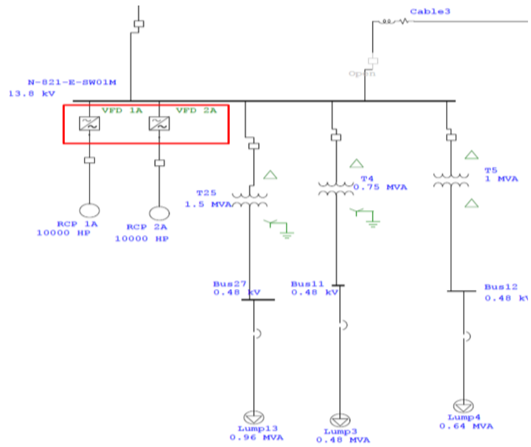

Figure. 1: Single Line Diagram particularly for RCP motors

2.1.1 <u>Starting Current</u>

Use of VFD units permits 'soft start' of motors. This is accomplished by first applying a reduced voltage and frequency to the motor terminals, greatly reducing the motor current inrush and acceleration of the driven shaft. This voltage and frequency can then be gradually increased to maintain motor currents within pre-specified limits.

The RCP motors are the largest motors found in the APR1400 and starting currents are large. The duration of the current inrush is exacerbated by the RCP flywheel which greatly increases the mass moment of inertia of the pump-motor shaftline. The large amount of inertia significantly increases the starting time and current draw versus time. Unless the motor has substantial and robust design to accommodate this starting scenario, motor insulation life will be greatly shortened by each RCP start.

In addition, an 'across-the-line' start introduces a significant angular acceleration on the motor shaft increasing mechanical stress and the potential for crack initiation and growth.

Thus soft start for the RCP motor is examined using ETAP modeling and analysis.

Accelerating rotating machinery with a heavy load torque or high mass moment of inertia imposes large stress on the electrical supply network and on the mechanical parts of the shaft string. A direct-on-line started electric motor can cause starting currents of up to six times the nominal current. This will cause a voltage drop that is likely to disturb the process, especially if the supply network is weak.

In addition, for components with a very large mass moment of inertia like the RCP, the start time is significantly extended resulting in a much longer time for high starting currents to be experienced.

<u>Soft starting benefits:</u>
(1) No process disturbance due to voltage drops, no trips of other electrical devices connected to the same bus
(2) No excessive thermal or mechanical stress on the motor, resulting in a longer lifetime
(3) Controlled and smooth start-up in driven system process parameters

<u>Starting Current Comparison</u>

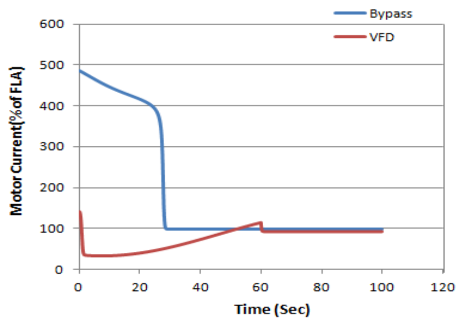

Figure 2: Comparison of starting current
[FLA: Full Load Ampere]

ETAP results comparing the two pump start cases are illustrated in Figure 2 above. Due to line voltage drop, the across the line starting current for the baseline RCP peaks at ~500% or five (5) times the running current (rather than the standard value of approximately six (6) times). Note the very long duration for high starting currents (~30 seconds) required to accelerate the flywheel to running speed.

For the case with soft start from the VFD unit, the peak starting currents are very small, even less than the full load current. Because of voltage drop (about 20%) when starting, the starting current is less than five times of rated current. VFD Reduces starting current, that is, we can expect the benefits such as no voltage drop and less stress on motor.

The currents for the soft start case are only 30% of the baseline case but correspond to relatively high values of torque, while for the across-the-line start case, high starting currents do not necessarily correspond to similar high relative values of torque.

Co-relation between torque and current can be explained with a formula.

$P = \omega T$, $\omega = 2\pi f$
(P: power (watt), ω : angular velocity (rad/sec), T: Torque(N-m))

P= $I^2 Rt$
(P: power (watt), I: current (Amp), t: time (sec))

Power is proportional to square of currents, not correspond to similar high relative values of torque.

2.1.2 <u>Motor Torque Comparison</u>

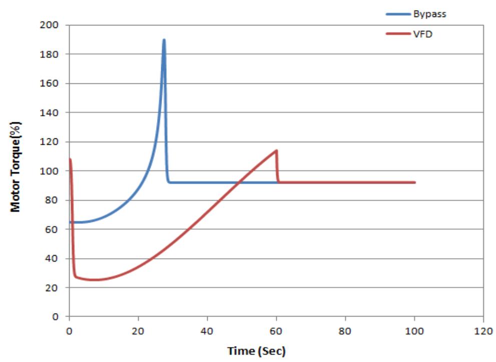

Figure 3: Soft Start Comparison of Motor Torque

Figure 3 presents ETAP results comparing motor torque. Note that the peak torque for the soft start case is within

20% of the running torque. For the across-the–line start case, peak torque is nearly twice the running torque.
It looks like that Integration of [torque × time] is the same for both cases. To verify this, we did integration with time and torque data. As a result, the integration value is the same when base line reaches around 40 seconds on Bypass mode, not 30 seconds, as VFD mode's one while it takes 60 seconds. Energy to accelerate the flywheel can be obtained by multiplication Torque and Speed

2.1.3 Short Circuit

Standard VFD design topology does not permit reverse current flow from the driven motor to the line in the event of a short circuit upstream of the VFD. Depending on the auxiliary electrical system design, this has the potential to significantly reduce short circuit currents. Reduced short circuit current has the potential to beneficially affect the sizing for auxiliary electrical system components such as switchgear, non-segregated bus duct design, and circuit breaker sizing.

ETAP modeling and analysis is used to determine the benefit to the design short circuit current from introducing VFD units for the RCPs.

In most designs, VFD units are designed with full electrical bypass capability to maintain operations in the event the VFD unit becomes inoperable. This mode is not included in the RR (Reactor Recirculation) pump applications for BWRs since pump speed controls reactivity. However, if such a bypass were included in Pressurized Water Reactor (PWR) designs for RCPs (e.g., such as for the AP1000 design), there is no benefit in the design of auxiliary electrical systems for short circuit.

Soft start capability of the VFD units permits the RCP motors to be sized for the full speed duty when the reactor coolant is hot This permits a reduction in motor size of ~30% but is only true is VFD bypass is not employed. This motor size is modeled in the ETAP analysis with VFD units.

3-phase fault is most severe case among the faults. In other words, the fault current is extremely high, comparing to other faults. 3-phase fault study is performed per the ANSI C37 Standard. This study calculates momentary symmetrical and asymmetrical rms, momentary asymmetrical crest, interrupting adjusted symmetrical rms short-circuit currents at faulted buses. The short circuit of the case N-821-E-SW01M 13.8kV BUS Fault is evaluated as described below.

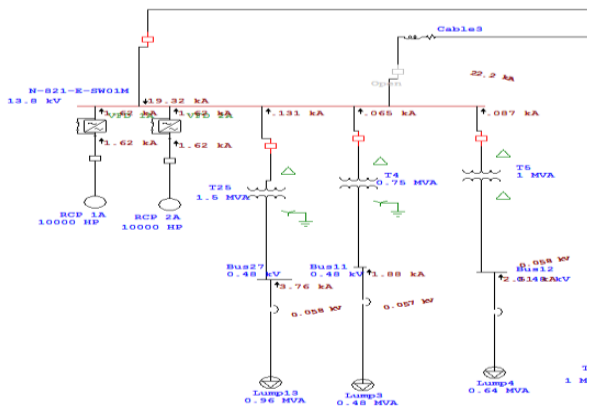

Figure 4: Single Line Diagram for Short Circuit Analysis in Bypass MODE

From the short circuit report, we can confirm the effect of the VFD installation. This may make it possible to use lower level equipment, such as circuit breaker, cables, and so on. From Table 1, reducing short circuit current is about 2[kA], so it can give a margin for circuit breaker when selecting the Circuit Breaker. VFD can provide a margin for rated short circuit current.

The rated short circuit breaker has six (6) capabilities from Table 2. During 1/2 cycle, VFD mode's short circuit current is only 19.8589[kA] while Bypass mode's short circuit current is 22.201[kA]. Usually we consider 15% margin when selecting circuit breakers. According to Table 1, we can select the lower grade of short circuit breaker, so it can make cost saving possible.

Table 1: Comparison Short Circuit Current between Bypass and VFD MODE

MODE	1/2 Cycle	1.5 to 4 Cycle
Bypass	22.201[kA]	20.591[kA]
VFD	19.589[kA]	18.841[kA]
Difference	2.3421[kA]	2.177[kA]

Table 2: Power Circuit Breaker Characteristics

Nominal ANSI Voltage Class (kV)	Rated Short Circuit Current (Maximum Interrupting Capability) (kA)
13.8	20
	25
	31.5
	40
	50
	63

2.2 FMEA and Safety Analysis (Licensing Impact)

2.2.1 Application of VFD Units - Failure Modes

Use of VFD units upstream of RCP motors has several identified advantages. However, the introduction of these components also presents new failure modes for system operation.

Specific symptom based failures include the following:

VFD or controller failure which results in

1) Increase of RCP speed and flow for one or more RCPs,
2) Decrease of RCP speed and flow for one or more RCPs,
3) trip of one or more RCPs due to VFD malfunction.

These failures all require review and analysis and must be addressed in the licensing per the Safety Analysis Report (SAR). However, since VFD technology is licensed and operating at several BWR units in the U.S.A., and since these failures result in a greater response Neutronic and thermal response for BWRs than for PWRs, it is expected that licensing for PWRs will not present unsolvable licensing issues.

Increase in RCP Speed

- A controller failure which increases RCP speed will not produce a rapid or severe transient. The increase in flow will be gradual due to the high mass moment of inertia of the RCP flywheel.

Further, core power is not particularly sensitive with respect to the temperature coefficient for entering reactor coolant. Core response should be within existing reactivity transients and protected by the core protection system.

In addition, if the APR1400 were to employ VFD units on RCP motors for Modes 1 and 2, it is expected that diverse and redundant instrumentation and controls would be employed to trip RCPs on high speed using sensors, controls, and signals that are currently used in the standard APR1400 design. New trip logic must be designed and added to the existing RCP controller system.

Decrease in RCP Speed

- A controller failure which decreases RCP speed will not produce a rapid or severe transient. The decrease in flow will be gradual due to the high mass moment of inertia of the RCP flywheel. Further, this transient is bounded by the RCP trip event which is a part of the licensing basis. Core response should be within existing core thermal transients and protected by the core protection system. If the APR1400 were to employ VFD units on RCP motors for Modes 1 and 2, it is expected that no additional instrumentation and controls beyond the existing system to detect RCP trip would be required.

Trip of RCP

- A controller failure which results in the trip of one or more RCPs would be covered by the existing licensing design basis. Not further evaluations would be required.

Other Failure

1) VFD Overheating

This fault is usually caused by problems with cooling air circulation over the VFD heat sink or within the VFD chassis. It may also be caused through a combination of big motor load and high ambient temperature. Failure would result in loss of power and RCP trip. This is part of the current licensing basis and is addressed in the system design.

2) Loss of Control Loop

If VFD is using a 4-20 mA source for speed reference, the VFD will normally monitor for a reference value below 4 mA. If this occurs, the VFD may respond by tripping, as it understands that the control loop has been lost and is therefore out of control. This will usually be caused by broken external cabling or a control instrument failure.

3) DC Bus Over Voltage

This problem can have several causes; regeneration from high inertia loads, excessively fast deceleration speeds, open circuiting contactors or other types of switches between the motor and VFD, and regeneration from high inertia loads. This fault would potentially result in equipment damage but nuclear safety implications are bounded by the RCP trip case.

4) Instantaneous Over Current

This fault may be caused for various reasons; Motor phase to phase short circuit, Short circuit between two or more motor cables, Closing switches between VFD and motor while VFD still running, Acceleration rate too fast. This fault would potentially result in equipment damage but nuclear safety implications are minor and can be addressed with minor upgrades to the RCP monitoring and control system.

5) Ground Fault

This fault will be reported if either the motor or motor cables have become shorted to earth. Most VFDs monitor the current balance between all three-phases and at maybe 40% imbalance on one phase, the VFD will trip and report ground fault. Ground fault may result in equipment damage but nuclear safety implications are not substantially different from any other ground fault.

6) Open Circuit Output Phase
Many VFDs do not allow the motor to run with an open circuit on one of the phases to the motor. If the currents flowing in each phase do not balance to a reasonable level, the VFD will trip.

7) DC Bus Fuse Open Circuit
Most VFDs have a fuse located in the DC bus circuit. This fuse is usually a high speed semi-conductor protection fuse and is designed to protect the input bridge rectifier in the event of a major failure on the VFD output stage. If the fuse has become open circuit, it should not be replaced without first checking the VFD power devices. It is unlikely that the fuse will have blown without some major component having failed elsewhere.

2.2.2 Licensing Impact

Review of Westinghouse AP1000 Design

To examine the licensing impact regarding VFD unit application on RCP motors, the AP1000 DCD (design control document) was reviewed. AP1000 DCD contents that are related with VFD units on RCP motor are as below;

1) DCD, Ch 5.4.1.2.1 Design Bases
Each pump motor is driven by a variable speed drive, which is used for pump startup and operation when the reactor trip breakers are open. When the reactor trip breakers are closed, the variable frequency drives are bypassed and the pumps run at constant speed.

2) DCD, Ch 5.4.1.2.2 Description of Operation
The variable frequency drives enable the startup of the reactor coolant pumps at slow speeds to decrease the power required from the pump motor during operation at cold conditions. The variable frequency drive provides operational flexibility during pump startup and reactor coolant system heatup. During a plant startup, the general startup procedure for the pumps is for the operator to start the pumps at a low speed. During reactor coolant system heatup, the pumps are run at the highest speed that is within the allowable motor current limits. As the reactor coolant temperature increases, the allowable pump speed also increases. Before the reactor trip breakers are closed, the variable frequency controllers are bypassed and the pumps run at constant speed.

During all power operation (Modes 1 and 2), the variable frequency drives are bypassed and the pumps run at constant speed.

3) DCD, Ch 16, LCO 3.4.1.c
RCS total flow rate 301,670 gpm and greater than or equal to the limit specified in the COLR. (MODE).
COLR: core operation limit report

4) DCD, Ch 16, LCO 3.4.4
Two RCS loops shall be OPERABLE with four Reactor Coolant Pumps (RCSs) in operation with variable speed control bypassed. (MODE 1, 2 and MODE 3, 4, 5 whenever the reactor trip breakers are closed)

According to the Technical Specifications of the AP1000, the RCS total flow rate should be maintained greater than or equal 301,670 gpm which is 95% of design flow during power operation (MODE 1).

Since any decrease in RCS flow could result in a degradation of core heat transfer, the RCS flow rate should be maintained at the design value. It gives many restrictions on using the VFD units on RCP motors.

Actually for AP 1000, the use of VFD units on RCP is only allowed when the plant startup conditions are satisfied and, the reactor trip breakers are closed.

VFD units are used for “soft-start” of the RCPs during plant shutdown condition. Once rated RCP speed is achieved, the VFDs are bypassed and the RCPs are fed from grid power prior to the reactor trip circuit breakers being closed.

Preparation of APR1400 SSAR revision

According to AP1000 DCD review result, to use the VFD unit for the “soft-start” of RCP, a draft SAR revision plan for licensing input is prepared as below.

Table 3: ARP1400 SSAR revision plan

Section	Before	After
5.4.1.2 Description	None	Each pump motor is driven by a variable speed drive, which is used for pump startup and operation when the reactor trip breakers are open. When the reactor trip breaker is closed, the variable frequency drives are bypassed and the pumps run at constant speed.
16.3.4.4 RCS Loops (Mode 1 and 2)	Two RCS loops shall be operable and in operation	Two RCS loops shall be operable and in operation with variable speed control bypassed.

2.3 Simulation for increasing Flywheel Mass

Use of VFDs eliminates the across-the-line start associated with the existing design and permits a 'soft' start. The soft start reduces: (1) in-rush currents, (2) thermal and mechanical stress on the motor core and windings, and (3) mechanical stress on the pump-motor shaft line associated with acceleration of the flywheel to operating speed.

VFD units thus permit the consideration of specific change to the APR-1400 design which we would like to examine using simulation program (WIN NPA).

Flywheel Mass - Reduced mechanical stress during pump start permits consideration of a larger flywheel with a higher mass moment of inertia. This will improve thermal margins in the core following pump trip.

In the limiting case, loss-of-offsite-power (LOOP), the reactor and RCP pump motors will trip on low voltage on the station auxiliary electrical buses. RCP flow will experience a 'coast-down' and continue to deliver flow to the reactor core for some period.

From the simulation, we would like to understand core thermal margins and the adequacy of the flywheel mass moment of inertia. We would also like to examine operation with low and high level of MMI (Mass Moment of Inertia)

Table 4: Cases for Simulation

Case	Core Power (%)	RCP Flow/ Speed	Flywheel MMI
4A	100	100	Baseline
4B	100	100	125% Baseline
4C	100	100	25% Baseline

As expected, coast-down flow following pump trip will be reduced as inertia increases. This below graph shows increased MMI guarantees slow coast-down, so flow to the reactor core is maintained for longer period than small MMI.

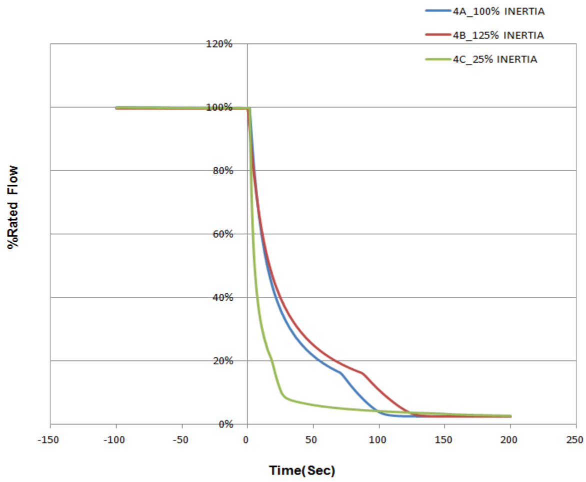

Figure 5: Pump flow coastdown

2.4 Cost benefit analysis

By applying VFD units to RCP motors, the motor size can be reduced from 13,500 HP to 10,000 HP. During heatup, the RCP allowable speed is then based on reactor coolant temperature to remain within the motor rating.

During plant startup and shutdown, energy consumption of RCPs can be reduced with the VFD application. However, considering nuclear power plant operation characteristics, plant startup and shutdown occurs only once every 18 months, this amount of cost savings would be very small.

During normal operation (hot condition), new motors (10,000 HP) should operate at a higher load factor than old ones (13,500 HP), but there is almost no substantial difference at motor efficiency (estimated below1%).

In conclusion, in spite of application of VFD units on RCP motors, almost no operational cost savings are expected for the APR1400.

3. Conclusions

3.1 Benefit doesn't work for APR1400 RCP motor

VFD has a variety of benefits such as energy savings, soft start, precise flow and pressure control, et cetera. Before examining VFD, these benefits looked great; however, it turned out VFD for RCP doesn't have many benefits because of as follows:

1) VFD is only applicable when starting up.

- MODE 1, 2 (Power Output) cannot be used; all of the safety issues should be reviewed. That will bring huge impact on the existing system.

2) Cannot expect energy savings with high efficiency
3) Starting time is not long. Moreover, starting and shutdown frequency is very rare. If doesn't have any problem, it occurs every 1.5years or 2years.
4) Thermal and mechanical stress reduction with VFD enables RCP to have a bigger flywheel. Bigger flywheel can improve the safety of coolant flow coast-down. This effect is not that so much. APR1400 has been designed to endure at the current circumstance.
5) Smaller motor with VFD has almost same efficiency characteristics, comparing with current motor.
6) From the short circuit analysis, we can expect short-circuit duty improvement, however, it only works on the critical situation at which electrical equipment has a small portion of margin.
7) If adopting VFD on RCP of APR1400, almost all VFD companies need step up transformer because market demanding is pretty much rare for 13.8kV motor. It makes VFD cost up about 30%.

3.2 Review VFD Benefit based on AP1000 benefits

In case of AP1000 design, Westinghouse pursued to enhance the safety of sealing of motor, making a sealess motors.

For the seal-less motor, it is imperative to adopt canned motor with VFD which can provide both smaller motor size and less mechanical and thermal stress.

AP1000 promises 60 years maintenance free, but it has a lot of doubt. For example, smaller freewheel's friction with water is not good on the view of stress while freewheel rotate in the air APR1400.

Westinghouse compromised many things to accomplish lower CDF (Core Damage Frequency) such as poor coastdown flow, parasite power, and maintenance about pump and motor.

These AP1000 designs have not been proven yet. No one can assure it lasts for 60 years with no maintenance.

Table 5: Comparison different models of motor

Classification	Model	APR1400 (General motor)	AP1000 (Canned motor)
Design	RCP Motor Size	Big - Cold water	Small - Hot
	Mechanical seal	Yes	No(Canned Motor)
	Proven Design	Equivalent Palo Verdi	No
	Anti-reverse Rotation Mechanism	Required	Not required
	Short circuit duty	Standard	Improved a little
Operation	RCS Flow/MWt	Very Good (484kgpm/4000MW)	Poor (316kgpm/3420MW)
	Coast down following trip	Excellent	Poor
	Parasitic Power(Flywheel)	~0[Mwe]	~2.5[Mwe](4x625 kW)
	Soft start (VFD)	No	Yes
	Standby RCP power consumption	High	Low
Nuclear Safety	Shutdown seal	Applicable	No
	Loss-of-thermal barriers-LOCA	Yes	No
Maintenance	60 year Maintenance Free	No	Yes
	Motor removal	Easy	Very hard
	Pump Internal Rebuild	Easy	Very hard

3.3 Summary of Conclusion

Canned motor using VFD has some benefits. The benefits don't work much to application of APR1400. It has already had its own robust system, which is optimized to other related parts or systems.

3.4 Recommendation for APR 1400

To enhance the safety related to a leakage of motor's seal in case of LOOP (Loss of Offsite Power), SB-LOCA (Small break Loss of Coolant Accident), and SBO (Station Black Out), shutdown seal can be adopted for APR1400.

Based on current the PRA (Probabilistic Risk Analysis) results, RCP seal LOCA scenarios are dominant contributors to risk of many PWRs.

SDS (Shutdown Seal) reduces risk of LOCA from the seal leakage. Installation SDS will improve overall plant safety margin. Eliminating RCP seal leakage can achieve the reduction of CDF (from as low as 5% to as high as 80%). With SDS, we can expect 5% reduction of CDF.

3.5 Future Study

Even though VFD is not appropriate to RCP motor the APR1400 model, it has a bunch of benefits which are widely used in industrials.

One of the strongest advantages of VFD is energy savings. By employing VFD, the energy bill can be reduced by as much as 50 percent.

Therefore, we need to consider the application to Condensate or Circulating Pump. These pumps need accurate flow control frequently.

Condensate or Circulating Water Pump

If adopting VFD on condensate pumps, we can expect benefits of VFD Units results in

1) Throttling can be eliminated by use of VFD improving plant efficiency
2) Valve station can be eliminated
3) Response to pump trip can be improved
4) Startup is simplified, simplified minimum flow control
5) Short circuit duty on electrical power system can be reduced

6) CP motors can be started with 'soft' start, extending motor life

Shutdown seal

Instead of adopting VFD on RCP motor, shutdown seal could be used to enhance the safety related to CDF. The shutdown seal improves Mitigating System Performance Index (MSPI) margin by reducing RCP seal cooling vulnerabilities and decreasing Core Damage Frequency by up to 50 percent. Currently, the U.S. Nuclear Regulatory Commission (NRC) has approved 24-hour survivability of the SHIELD seal under station blackout (SBO) conditions for regulatory applications.

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