Development of ROVER-K code to Determine Regional Overpower Trip Setpoint in CANDU 6 Reactor

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1. Introduction

The CANDU 6 regional overpower protection (ROP) system for shutdown system (SDS) 1 and SDS 2 has 34 and 24 detectors respectively arranged in triplicate safety channels of equal or near equal number of detectors. To determine ROP trip setpoint (TSP) for each ROP detector, a computer code based on a probabilistic method had been proposed and developed by AECL in 1982. It was named as ROVER/REFORM encoded by APL workspaces.[1] ROVER/ REFORM had replaced ROVER-F 1.0 except two key functions – REFORM and DLO - by J. Pitre with standard FORTRAN77 language at March 1997. Two years later, ROVER-F 2.0 was released where those missed functions were encapsulated in only at the least incomplete.[2] And finally AECL released ROVER-F 2.03-01a to treat regional channel-random uncertainty caused by the plant aging and hardware unavailability for more robust TSP evaluation using FORTRAN 90 language. [3]

ROVER/REFORM was used to assess the ROP TSP of Wolsung Unit 1 at 1995 when whole existing 57 ROP detectors should be replaced as new ones. From the results, total number of ROP detectors was increased from 57 to 58 and final TSP was set as 124% for all detectors. After that assessment, it has been gradually known that CANDU 6 reactor has aging effects caused by pressure tube thermal creep and magnetite transport phenomena, etc. It means that it is required to re-determine ROP TSP according to the amount of aging of thermal-hydraulic system. That is why AECL has developed ROVER-F code instead of the upgrade of ROVER/REFROM. Since Wolsong Unit 1 was also required to assess TSP affected by the plant aging, KEPRI had been transferred ROP analysis technology including ROVER-F 2.0 source/execution file from AECL at 1999. But for ROVER-F 2.03-01a, KEPRI have the execution file only which is slow and has bugs such as stack overflow in some cases. Therefore, it is required to develop a new computer code, ROVER-K, to deal with unlimited region specific channel–random uncertainties and to compute TSP faster than the current ROVER-F version. It will be a good tool for more realistic and robust ROP analysis against CANDU 6 reactors in KOREA.

2. Probabilistic Approach for ROP TSP

A ROP system should protect CANDU 6 reactor from fuel failures caused by OID (Onset of Intermediate Dryout) on fuel cladding. Since it is impossible to measure or catch OID occurrences, the ROP system checks detector readings and triggers trip signals when detector readings exceed a specific value, trip setpoint. Therefore, it must be known the relationship between detector reading and channel power in advance. Equation (1) shows how trip probability (TP) is calculated from given several hundred flux shapes and detector readings;

$$0.95 < TP = \min_k \left[1 - \int_0^\infty P_{NT}(x,k) Q_{CM}(x,k) dx \right] \quad (1)$$

where $P_{NT}(x,k)$ means the shutdown system non-trip probability of k'th reactor condition and $Q_{CM}(x,k)$ represents the common-mode channel random probability density corresponding to k'th core flux shape. Because a ROP system has triplicate safety channels, $P_{NT}(x,k)$ should reflect each 58 detector's non-trip probability. Probability functions used in TSP calculation are based on the Gaussian function with a proper variance from the uncertainty analysis for each main variable, i.e., detector reading, channel power and critical channel power. For example, a detector non-trip probability function can be written by equation (2);

$$P_{NJ}^k(x) = \frac{1}{N} \sum_n erf_c \left(\left(\frac{x \cdot \Phi_J(k)}{TSP} - 1 \right) \frac{1}{\sigma_{\det}} \right), \quad (2)$$

where N is the number of measured power shapes in sites, $\Phi_J(x)$ means J'th detector relative reading at real situation, and $\sigma_{\det}$ is the standard deviation for detector probabilistic function. As for other functions, one can refer to Ref. [1] ~ [3]

3. Development and Verification of ROVER-K

At first, to understand the concept of probabilistic approach and numerical method, ROVER-F 2.0 source file was investigated. Then, a new computer code was encoded with more efficient algorithm for ROP TSP through FORTRAN 90 language. Several subroutines were eliminated and modified so that it resulted in more compact program. To avoid memory conflict during running ROVER-K, all vector and matrix type variables are dynamically allocated at the first stage. Since there are 380 channels, 58 detectors, about six hundred flux shapes and nearly two hundred flux distributions measured in a site, ROVER-K has to deal with over 10^5 probability functions. To reduce computing time, ROVER-K eliminates an error function subroutine in ROVER-F and replaces it with efficient conditional sentences. And SETDTADJ algorithm where the final TSP fulfilling target trip probability is determined by iterative method was modified to reduce the computing time about 50% with the same accuracy.

Measured pressure tube creep rates are very important factor for reflecting thermal-hydraulic aging effect on CCP and for treating region specific channel-random uncertainty. Therefore, some variables and a subroutine to deal with them were added in ROVER-K. Actually channel-wise creep rates for 41 channels of Wolsong Unit 1 were measured. They had been used for determining a new ROP TSP. ROVER-K code also introduced hardware unavailability for each detector, safety channel and shutdown system respectively obtained from PSA (Probabilistic Safety Analysis) outcomes for Wolsong Unit 1 and 2. Finally, automatic single detector assembly failure moudle was added as a unique function of ROVER-K.

To verify the performance and accuracy of ROVER-K, it has been applied to total 22 cases of standard test-matrix for current ROVER-F version and 61 TSP cases for Wolsong Unit 1 including single detector failure cases for given hardware unavailability data. Some results are summarized in Table 1 and 2. RORVER-K and ROVER-F 2.03-01a show the very same TSPs. In all test cases, the detail outputs obtained from two codes also revealed as identical.

4. Conclusion

KEPRI has developed ROVER-K to determine regional overpower protection trip setpoint for CANDU 6 reactor and to replace current ROVER-F 2.03-01a AECL made. ROVER-K shows the same accuracy bur four times faster than the current ROVER-F version. REFORM and DLO function based on an optimization theory will replace the current incomplete functions.

REFERENCES

[1] A. D. Falkoff and K. E. Iverson, “Design of APL,” *IBM J. RES. DEVLOP*. (1973)

[2] R.D. McArthur, “Verification Report: Porting of ROVER-F Version 2-00, for HP” Y2K-03514-225-010, Report P17, Revision 0, March 1999.

[3] V. Caxaj, “ROVER-F Version 2-03-01a Manual,” CW-117390-MAN-001, Rev. 2 Sep. 2004.

Table 1. The comparison of various TSP cases

CASE	ROVER-F		ROVER-K	
	TSP	CPU (sec)	TSP	CPU (sec)
98%[1)], 23[2)]	1.0865	526	1.0865	136
95%, 23	1.1119	502	1.1119	134
SDF[3)]-1G	1.1117	496	1.1117	125
SDF-2G	1.1118	495	1.1118	125
SDF-3G	1.1119	499	1.1119	125
SDF-4G	1.1119	498	1.1119	125
SDF-5G	1.1119	496	1.1119	125
SDF-6G	1.0985	504	1.0985	128
SDF-7G	1.1119	505	1.1119	125
SDF-8G	1.1119	506	1.1119	125
SAF[4)]-1V	1.1119	499	1.1119	120

98%, 95% : Target Trip Probability
23: 2 out of 3 trip logic
SDF: the single detector failure case
SAF: the single detector-assembly failure case

Table 2. The comparison of Test-matrix cases

TEST CASE	ROVER-F		ROVER-K	
	TSP	CPU (sec)	TSP	CPU (sec)
T01	1.0381	3	1.0381	0.5
T02	1.0381	3	1.0381	0.5
T03	1.0381	3	1.0381	0.6
T04	1.1558	3	1.1558	0.5
T05	1.0383	3	1.0383	0.5
T06	1.0381	3	1.0381	0.6
T07	0.9888	4	0.9888	0.5
T08	0.9905	5	0.9905	0.5
T09	0.9905	4	0.9905	0.6
T10	1.2124	5	1.2124	0.8
T11	1.2020	7	1.2020	0.6
T12	10.3693	34	10.3693	1.4
T13	0.1037	33	0.1037	1.4
T14	1.1406	39	1.1406	1.4
T15	0.9332	37	0.9332	1.4
T16	1.1337	2	1.1337	0.5
T17	1.0983	2	1.0983	0.5
T18	1.0493	3	1.0493	0.5
T19	0.9598	5	0.9598	0.5
T20	1.1255	2	1.1255	0.5
T21	1.0910	1	1.0910	0.3
T22	1.2024	20	1.2024	0.9
Total CPU time		256		17.5