Simplified Load Follow Schemes to Simulate Long Term Daily Load Follow Operation

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1. Introduction

Nuclear Power Plants (NPPs) are one of the choices of renewable fuel power plants to reduce emissions of greenhouse gasses [1]. Because renewal sources like wind and solar can be irregular NPPs are expected to operate under load follow to meet the grid load demand. Load follow operation is the potential for a power plant to adjust its power output as grid load demand fluctuates throughout the day. Control rods are used to achieve the sudden power level adjustment required.

The simulation of long-term daily load follow operation and base load operation would result in different burn-up and power distribution at End Of Cycle (EOC). Additionally, computer code simulation of long term daily load follow operation is very detailed and have high computational time making it almost impracticable for nuclear core designer to carry out.

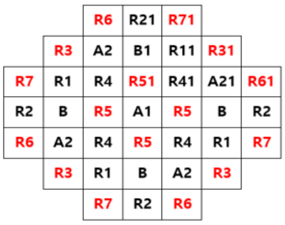
The purpose of this study is to develop a simplified load follow scheme that can simulate long term daily load follow. Both simplified load follow scheme and long term daily load follow will be simulated using MASTER code. Burn-up, assembly power and axial offset of the simplified load follow scheme and long term daily load follow will be compared at the end of the load follow operation. The RMS error and reduction of computational time of the simplified scheme will be presented and discussed. To validate the simplified load follow operation scheme, Single Control Element Assembly (SCEA) withdrawal accident will be simulated for both the long term daily load follow scheme and the simplified load follow scheme at the end of load follow operation.

2. Load Follow Models, Methods, and Tools

The nuclear reactor model used in this paper is the Korean Nuclear Fuel (KNF) proposed SMR with a thermal power of 180MW [2]. The core has 37 uranium fuel assemblies and each consists of 264 fuel rods in a 17 by 17 array. The active core height is 200 cm and is divided into 24 axial mesh sizes. The core is aimed to be boron free and use only burnable absorber and control rod for reactivity control. The enrichment is less than 5% with a cycle length of 3 years. The computer codes used are CASMO-3 [3] and MASTER [4]. The former was used to generate the cross-section library and the latter was used for load follow simulations.

OPR1000 daily load follow operation scheme employs control banks and boron for reactivity control as well as power level adjustment [5] while SMR uses only control banks. In this paper, heavy-worth banks, A2 and R1, were used to simulate load follow operation for SMR in order to achieve heavily bottom-skewed flux distribution. Critical heights of the control rods were searched with every power step change as well as every burnup step to ensure core criticality.

Table I and Figure 1 shows the CEA group worth and map respectively. The results of the simplified load follow schemes were compared to the long term daily load follow (reference scheme) for both burn-up and assembly power distributions at the end of long term daily load follow operation.



		R6	R21	R71		
	R3	A2	B1	R11	R31	
R7	R1	R4	R51	R41	A21	R61
R2	B	R5	A1	R5	B	R2
R6	A2	R4	R5	R4	R1	R7
	R3	R1	B	A2	R3	
		R7	R2	R6		

Figure 1: CEA Configuration

Table I: CEAs Groups Worth

CEA	(pcm)	CEA	(pcm)
B	3624.9	R5	1770.6
R1	3051.1	R3	1655.7
A2	3051.1	R6	1427.9
R4	2278.1	R7	1427.7
R2	2263.4	A1	293.9

2.1 Long Term Daily Load Follow (Reference Scheme)

Figure 2 shows power level maneuvering of a one-day daily load follow that was simulated for 336 days and used as the reference scheme in this paper. Power changes from 100% to 50% in 3 hours, remains constant at 50% for 6 hours and then increases to 100% for 3 hours after which it remains constant for 12 hours. OPR 1000 employs a Mode-K algorithm which uses regulation banks, boron, and heavy-worth banks to control axial power and power distributions during load follow. The reactivity control is achieved by boron and regulations banks while heavy-worth banks are used for axial power shape [6]. In this paper, however, only heavy worth CEAs R1 and A2 were used to regulate power level as well as to maintain criticality during load follow simulations. The reference scheme was simulated using MASTER code for 336 days.

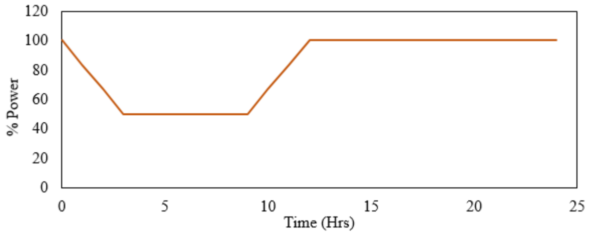


Figure 2: Daily load follow operation of OPR1000 [5]

2.2 Simplified load follow schemes

Unlike daily load follow where power level changes few number of times in a day, simplified load follow schemes power level changes a few number of times in a month as shown in Figure 3. The simplified load follow schemes were also simulated for 336 days using MASTER code.

2.2.1 Simplified load follow scheme requirement

The simplified load follow schemes are determined to have the same energy production as the long term daily load follow (reference scheme). Equation (1) expresses this requirement using two variables, time and power. After fixing two power levels, two time intervals are later determined to satisfy Equation (1). *E(MWhr)* in the equation represents the total energy production from the reference daily load follow operation and n is the number of power level maneuvering pattern in a load follow simulation.

Three power levels are considered in the simplified load follow schemes, 50% which is the minimum power level used in Figure 2, 75% as the averaged power level of the power reduction or increase slope in Figure 2, and lastly 100% the maximum power level of Figure 2.

$$E(MWhr)=\sum_{i=1}^{n}(T_1\times P_1+T_2\times P_2)_i \qquad (1)$$

2.2.2 Power level maneuvering patterns in simplified load follow schemes

Figure 3 below shows simplified load follow scheme 1 for 28 days only, and this pattern was repeated 12 times to simulate long term load follow operation of 336 days. Scheme 1 is an exception to simplified load follow schemes requirements operating at low power level of 63% and a maximum of 100%. This was due to constrained T1 and T2 in Equation (1) which was set to be equal.

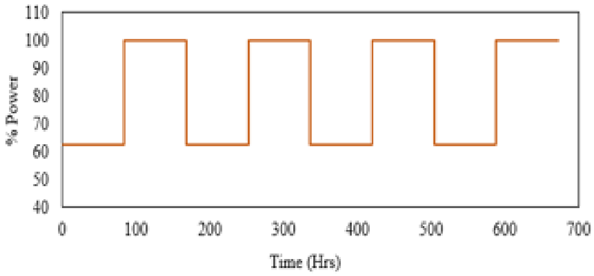


Figure 3: Simplified load follow scheme 1 for 28 days

Simplified load follow scheme 2 and 3 are shown in Figure 4. Scheme 2 operates at low power level of 50% while scheme 3 at a low power level of 75%. Both schemes operate at a maximum power level of 100%. Figure 4 and Figure 5 also shows simplified load follow schemes for 28 days only, and these patterns were repeated 12 times to simulate long term load follow operation of 336 days.

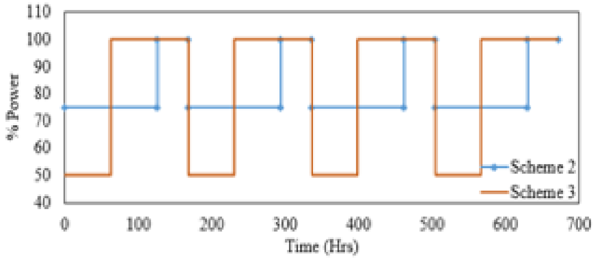


Figure 4: Simplified load follow scheme 2 and 3 for 28 days

Simplified load follow of scheme 4 and 5 are the most simple changing power level only twice in 336 days. Scheme 4 and scheme 5 operates at a low power level of 75% and 50% respectively, and both operate at a maximum power level of 100%.

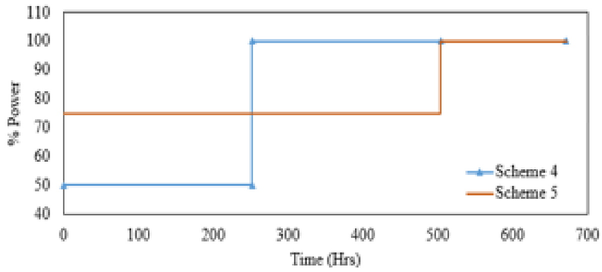


Figure 5: Simplified load follow scheme 4 and 5 for 28days

3. Results

In this section burn-up and assembly power distribution errors of the simplified load follow schemes are presented and discussed. A nuclear power plant reactor operating cycle is typically longer than 336 days. A simulation of 336 days continuous daily load follow using MASTER code had about 810 minutes in computational time, whereas the simplified load follow schemes had less than 2 minutes in computational time as shown in Table II.

The axial offsets of the simplified schemes were predicted less negative than that of the reference scheme. The highest RMS error and absolute maximum error in all the planes across the core at the end of load follow operation are shown in Table II. Scheme 3 showed good agreement in burnup distribution with the reference, and the worst results in assembly power distribution. Schemes 4 showed better results in assembly power distribution than scheme 3 but worse burnup distributions than scheme 3. It is speculated that higher control rod critical height of scheme 3 causes a bigger error in power distribution. Scheme 3 used the minimum and maximum power level of the reference scheme as well as many power level maneuverings which could have led to reasonably low errors of burnup distribution. Scheme 4 also used same power level as the reference scheme which could have led to low assembly power distribution errors, however the high burnup could have been caused by less power level maneuverings Scheme 1, 2 and 5 all used low power level higher than the minimum of the reference scheme 50% which could be the cause of higher assembly power and burnup distribution errors.

Table II: Axial plane comparison summary of the reference scheme and simplified schemes at the end of load follow operation

Scheme	Reference	1	2	3	4	5
Time (Seconds)	48598	105	110	99	27	26
EOLF AO	-0.5101	-0.4688	-0.4847	-0.4564	-0.5027	-0.4972
Highest RMS error of Assembly Burnup	-	6.55	12.87	1.96	11.02	11.04
ABS Max error of Assembly Burnup	-	10.07	18.13	3.31	16.03	11.46
Highest RMS error of Assembly Power	-	19.97	12.04	25.42	6.60	10.85
ABS Max error of Assembly power	-	38.59	23.05	49.03	13.5	22.17
CRCH at EOLF (cm)	118.5	125	123	127	122	124

***EOLF = End Of Load Follow**
***CHCR = Critical Height of Control Rods**

2.1 Burnup and assembly power at end of load follow operation

Figure 6 shows how the RMS error of axial plane burnup distribution of scheme 3 varies along the active core height at the end of load follow operation, as well as the critical height of control rods at the end of load follow operation. Scheme 3 shows RMS errors of plane-wise assembly burnup lower than 2% across the core height at the end of load follow operation. Sharp change in error in Figure 6 is observed around core height of 115 cm, where steep flux gradient is observed and produces steep burnup and power gradients at the end of load follow operation. The max/min curve represents the largest error deviation from the reference scheme at every axial plane/mesh. The largest errors across the active core height at the end of load follow operation was in the range of ±3 which is reasonably low.

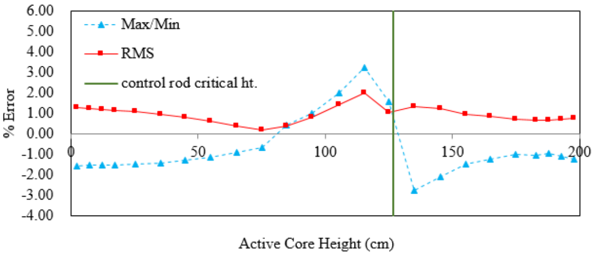


Figure 6: Simplified load follow scheme 3 axial plane burnup distribution error at the end of load follow operation

Figure 7 shows how the RMS error of axial plane assembly power distribution of scheme 4 varies along the active core height at the end of load follow operation, as well as the critical height of control rods at the end of load follow operation. Scheme 4 shows RMS and max/min errors of plane-wise assembly power distribution lower than 7% and 14% respectively at the end of load follow operation. The RMS and a maximum error of power distribution in scheme 4 show a similar trend as errors in burnup distribution around critical height in Figure 3. This is due to the control rod effect.

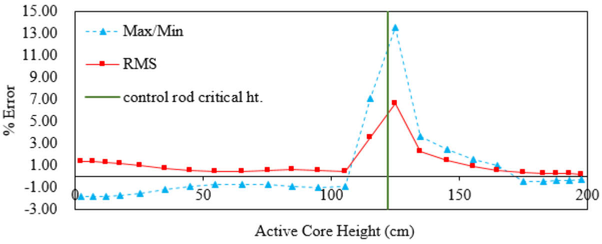


Figure 7: Simplified load follow scheme 4 axial plane assembly power distribution error at the end of load follow operation

2.2 Single Control rod Element Assembly (SCEA) ejection

To validate the simplified load follow schemes, single control element assembly (SCEA) ejection accident was simulated at the end of load follow operation for both the simplified and the reference scheme. Two CEAs R11 and A21 in Figure 1 were used to simulate CEA ejections. Because CEA ejection does not affect burn-up distribution, only power distribution is discussed in this paper. Scheme 4 was used to carry out SCEA simulations since it showed low assembly power error as shown in Table II and Figure 7. Plane assembly power distribution of both the simplified and reference scheme is compared by RMS error calculation at every plane across the core height after SCEA.

SCEA simulation of R11 and A21 gave the same assembly power RMS error results when CEA. The RMS error increased to 16% around the critical height of the control rods. The two vertical lines in Figure 10 shows the critical height of control rods at the end of load follow operation for both the reference scheme and scheme 4. The increased errors around 120 cm in Figure 8 is caused by the difference of reference scheme and scheme 4 critical height of control rods.

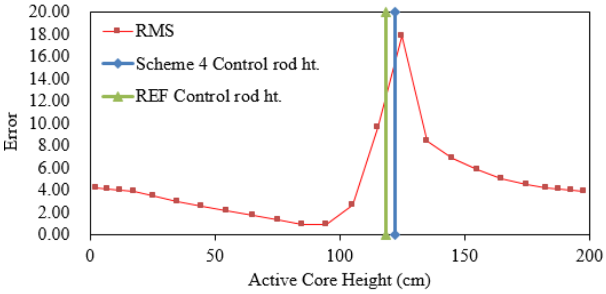


Figure 8: Long term daily load follow and simplified load follow single CEA ejection at the end of load follow operation

4. Conclusions

It has been revealed in this study that burn-up and assembly power distribution of long term daily load follow can be estimated by simplified load follow schemes, to reduce tedious input preparations and computational time associated with long term daily load follow simulations. The simplified scheme 3 have burnup distribution errors lower than 2%, but higher assembly power distribution errors. Simplified scheme 4 have assembly power errors lower than 13.5%. The SCEA simulation of scheme 4 gave errors as low as 16%. The simplified load follow schemes with further developments can be used to simulate long term daily load follow operation. The challenge encountered was to reduce the critical control rods height difference of the simplified schemes and the reference scheme at end of load follow operation, which led to an increased error towards the critical control rod height.

REFERENCES

[1] Locatelli, G., Boarin, S., Pellegrino, F. & Ricotti, M. E., 2014. Load following with Small Modular Reactors (SMR): A real options. Energy.

[2] Kang J.K., Hah C.J, Cho S.J. & Seong K.B., 2015, The effects of stainless steel radial reflector on core reactivity for small modular reactor. NUSTEC

[3] Endenius, M. & Forssen, B., 1991. CASMO-3, A FUEL ASSEMBLY BURNUP PROGRAM USER'S MANUAL. NYKOPING: STUDSVIK NUCLEAR.

[4] Cho, J.-Y., 2004. MASTER 3.0 USER's MANUAL. Taejon: KAERI

[5] Lee, K., Choe, J. & Lee, D., 2012. Application of Load Follow Operation to Equilibrium Cycle of OPR1000. Transactions of the Korean Nuclear Society Autumn Meeting.

[6] Choi, J.I., Oh, S.J., Song I.H. & Hah Y.J., 1992. Advanced Load Follow Operation Mode for Korean Standardized Nuclear Power Plants. Korean Nuclear Society, Volume 24, p. 183.