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Simplified load follow schemes to simulate long-term daily load follow operation

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ABSTRACT

Simulation of Daily Load Follow Operation (DLFO) for a whole cycle has long computation time as well as tedious lengthy input files. The purpose of this study is to reduce the computation burden associated with long-term DLFO simulation by developing a Simplified Load Follow Scheme (SLFS) simulation that can reproduce the core characteristics of long-term DLFO simulation (reference scheme) at End of Cycle (EOC). To achieve this aim, the SLFS employs two constraints: energy production and cycle length must equal those of the reference scheme. The solution variables in a SLFS then becomes operation time and power level satisfying the two constraints. In this paper, low power levels of 50%, 63%, 75%, and a maximum power level of 100% are employed for the SLFSs. Operation times are determined to satisfy the two constraints for the given power level. The reference scheme in this paper employs OPR1000 Mode-K daily load follow scheme for the Small Modular Reactor (SMR).

The results show the SLFSs can predict Core Radial Plane Burnup (CRPB) and Core Radial Plane Power (CRPP) distributions of a long-term DLFO with errors lower than 6% across the core height. Axial Offset (AO) and Control Element Assembly (CEA) critical height of the SLFSs are also comparable with the reference scheme with low errors of 1.5% and 4.5% respectively at EOC. The computational time of the simplified schemes is reduced by more than 29 times than that of the reference scheme. Single Control Element Assembly (SCEA) Ejection is simulated to validate the applicability of the simplified schemes. The SCEA ejection simulations also show CRPP distribution errors less than 6%. In conclusion, the SLFSs can be used to simulate long-term DLFO with marginal errors of less than 6%.

1. Introduction

As part of the drive to reduce greenhouse emissions, nuclear power together with other renewable sources is an alternative for sustainable energy generation (World Nuclear Association, 2011). Renewal energy sources such as wind and solar can be irregular thus cannot be utilized to supply peak load demands. Nuclear power which emits low greenhouse gases is a favorable and viable option to meet the grid peak load demand by operating under load follow (Locatelli et al., 2014). Load follow operation is the potential of a power plant to adjust power output as grid load demand fluctuates throughout the day. Conventionally, Nuclear Power Plants (NPPs) use control rods to achieve the sudden power level adjustment required during load follow operation.

Power level maneuvering of a long-term Daily Load Follow Operation (DLFO) used in this study decrease from 100% to 50% in 3 h; remain constant at 50% for 6 h; increases from 50% to 100% in 3 h; and remains constant at 100% for 12 h every day. This daily power level maneuvering requires frequent insertion and withdrawal of control rods which leads to a different nuclear core burnup and power distributions compared to when operating at base-load power. The simulation of a long-term DLFO has tedious input code and long computation time compared to base-load power operation. This is mainly because; at base power operation all control rods are withdrawn for the whole cycle. Therefore, there exist significant differences in core burnup and power distribution between base-load power operation and long-term DLFO at the End of Cycle (EOC).

The purpose of this study is to reduce the computation burden associated with long-term DLFO simulations by developing a

Abbreviations: Abs, Absolute; AO, Axial Offset; CEA, Control Element Assembly; CHCEA, Critical Height of CEA; CRPB, Core Radial Plane Burnup; CRPP, Core Radial Plane Power; DLFO, Daily Load Follow Operation; EOC, End Of Cycle; FA, Fuel Assembly; KNF, Korean Nuclear Fuel; NPP, Nuclear Power Plant; PWR, Pressurized Water Reactor; RMS, Root Mean Square; SCEA, Single Control Element Assembly; SLFS, Simplified Load Follow Scheme; SMR, Small Modular Reactor.

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Simplified Load Follow Scheme (SLFS) simulation that can reproduce the core characteristics of a long-term DLFO simulation at EOC. The SLFS employs two constraints: total energy production and total operation time should equal that of a long-term DLFO. The simulation of the SLFS has less detailed input code, show a reduced computation time and predicts a core state similar to the simulation of a long-term DLFO at EOC.

Both the SLFS and long-term DLFO are simulated with CASMO-3 (Endenius and Forssen, 1991) and MASTER (Cho, 2004). “CASMO-3 is the lattice calculation code to generate fuel assembly cross section library. MASTER (Multi-purpose Analyzer for Static and Transient Effects of Reactors) is a nuclear design code that has the capability of static core design, transient core analysis, and operational support” (You et al., 2007).

The nuclear reactor model used in this study is the proposed Korean Nuclear Fuel (KNF) Small Modular Reactor (SMR) with a thermal power of 180 MW (Kang et al., 2015). A comparison between the Axial Offset (AO), Core Radial Plane Burnup (CRPB) and Core Radial Plane Power (CRPP) distribution of the long-term DLFO simulation and SLFS simulation is used to evaluate the efficacy of the proposed scheme. Computational time, CRPB and CRPP distribution errors of the SLFS are presented and discussed in the later sections. To validate the SLFS, Single Control Element Assembly (SCEA) ejection accident is simulated for both the long-term DLFO scheme and the SLFS at EOC.

2. Load follow schemes, methods, and tools

The SMR employed in this study is a Pressurized Water Reactor (PWR) which has 37 uranium Fuel Assemblies (FAs). Each FA has 264 fuel rods in a 17 by 17 array. The average enrichment of the FAs is less than 5%. The core height is 200 cm and is divided into 24 axial mesh sizes. The core height is measured from the bottom (0 cm) to the top (200 cm) of the core. The SMR has a cycle length of 40 months as shown in Fig. 1 by the Critical Boron Concentration (CBC) curve. Fig. 1 shows the required CBC when the SMR operates at full power throughout the cycle. To simulate DLFO, the core is aimed to operate with no soluble boron, and use burnable absorber and control rods for reactivity control. Load follow simulation is performed from day 60 to day 536 (17 months), this is depicted in Fig. 1 by scheme 1 and scheme 4.

The CEA map of the SMR is shown in Fig. 2 and the reactivity worth of the CEA groups is shown in Table 1. The CEAs of the SMR are classified into 9 groups and each group consists of 4 CEAs except for the A group which has 5 CEAs. One CEA consists of 24 control rods. OPR1000 reactor employs Mode-K algorithm (Lee et al., 2012) which use regulating CEA groups, boron, and heavy-worth CEA groups to control axial power and power distribution during DLFO. The reactivity control is achieved by boron and regulating CEA groups while heavy-worth groups are used for axial power shape (Lee et al., 2012). The SMR used in this study employs only heavy-worth CEA groups, A2 and R1 in Fig. 2 to achieve criticality and heavily bottom-skewed flux distribution during DLFO simulation. Critical height of the CEAs is searched with every power level change and every burnup step during DLFO simulation to ensure core criticality.

In this section, the power level maneuvering of a long-term DLFO called the reference scheme, is described in one day, and will be repeated every day in the same manner. The basic principle of transforming a reference scheme into a SLFS is explained using two variables, reactor power level, and time interval.

2.1. Long-term daily load follow operation

Fig. 3 shows a one day OPR1000 power level maneuvering of long-term DLFO based on the load demand pattern in Korea (Choi et al., 1992). Power decreases from 100% to 50% in 3 h, remains constant at 50% for 6 h, increases to 100% in 3 h, and remains constant at 100% for 12 h. This one-day power level

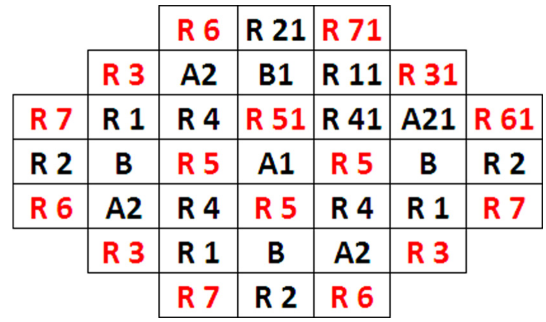

Fig. 2. SMR CEA configuration.

Table 1
CEA Group Worth.

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

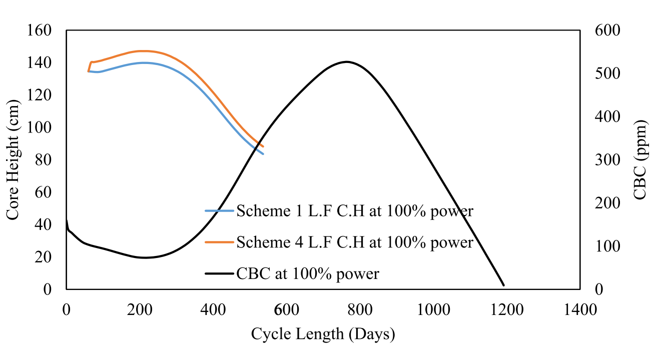

Fig. 1. Loading pattern CBC, scheme 1 and scheme 4 critical height at 100% power. *L.F = Load Follow, C.H = Critical Height.

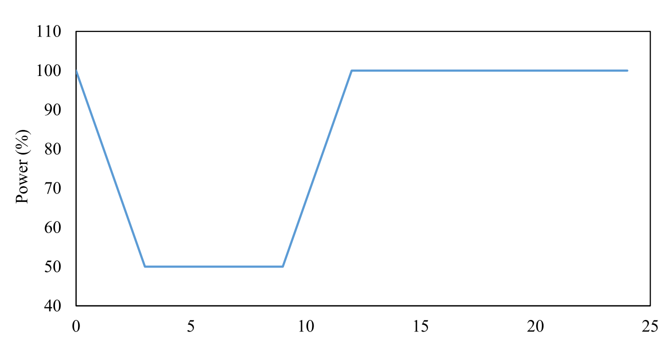

Fig. 3. Daily load follow operation scheme of OPR1000 (Lee et al., 2012).