

Simulation-based Verification of Voltage and Frequency Compliance for EDG Intermediate Load Sequencing in a Westinghouse-type Onsite Power System

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1. Introduction

Emergency Diesel Generators (EDGs) serve as essential emergency power sources in nuclear power plants (NPPs), ensuring safe shutdown and residual heat removal during a Loss of Offsite Power (LOOP). Since the Fukushima accident, enhancing the reliability of EDG power supply has emerged as a central priority in nuclear safety.

Simulation-based verification methods have been increasingly recognized as effective tools for assessing severe conditions that are difficult to reproduce in conventional field tests. These methods enable systematic evaluation of a broad range of scenarios, including extended or non-standard operating conditions that are impractical to replicate on-site. However, in Westinghouse-type (WH-type) plants, the absence of dedicated ETAP models for governor and exciter systems has made such simulations infeasible, resulting in heavy reliance on field tests with limited reproducibility. Consequently, comprehensive assessments of EDG compliance and opportunities for design optimization have remained insufficient.

To address these limitations, this study developed ETAP-based control models for the EDG governor (Woodward 2301) and exciter (IEEE AC8B), and analyzed intermediate load sequencing conditions in which the Containment Spray Pump (CSP) is initiated earlier than in the normal sequence. Voltage and frequency characteristics were evaluated in accordance with U.S. NRC Regulatory Guide 1.9 [1].

Unlike previous works that applied generic exciter models and were limited to Loss of Voltage (LOV) conditions [3], this study evaluated 16 optimized scenarios, identified non-compliant cases, and demonstrated the feasibility of achieving stable performance across all conditions. Through this expanded verification, the study strengthens the technical credibility of EDG performance assessment and provides practical guidance for design improvements, maintenance strategies, and regulatory evaluations.

2. Methods and Modeling

2.1. System Modeling

- Analysis Tool: ETAP (Load Flow, Transient Stability Module), MATLAB
- Target System: WH-type 4.16 kV Class 1E power system and EDG Load Sequence
- Major Components: EDG, Class 1E buses, circuit breakers, major safety pumps
- EDG Exciter Models: IEEE AC8B[2]
- Governor Model: Woodward Governor 2301

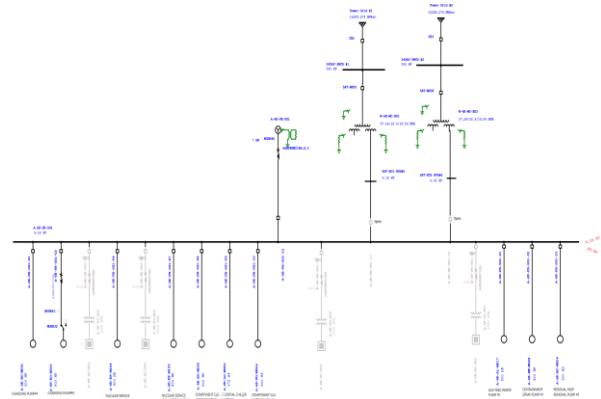


Figure 1. ETAP One-Line Diagram

Table 1. Load List and Sequence

Step	Time (Sec)	Equipment	Rating (HP)
1	0	EDG	
2	1	Charging Pump	300
3	5	Residual Heat Removal Pump	300
4	15	Component Cooling Water Pump #1	800
5	19	Nuclear Service Cooling Water Pump #1	900
6	28	Aux Feed Water Pump	800
7	36	Nuclear Service Cooling Water Pump #2	900
8	46	Component Cooling Water Pump #2	800
9	51	Essential Chiller Water Pump	472

Table 2. Intermediate load sequence including CSP insertion

Step	Time (Sec)	Equipment	Rating (HP)
3-1	8	Containment Spray Pump	600
5-1	22		
7-1	39		

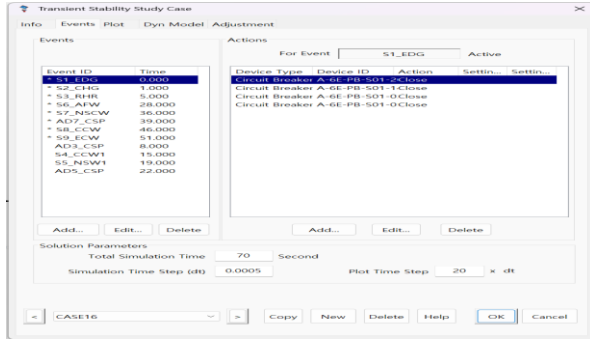


Figure 2. ETAP Transient Stability Study Case

2.2. Simulation Scenarios

- Total: 16 cases with varying load patterns, sequencing intervals, and exciter models
- Conditions: Base load sequence and CSP intermediate-insertion at Steps 3, 5, and 7)

Table 3. Scenario Definitions

No.	Equipment	Scenarios							
		1	2	3	4	5	6	7	8
1	EDG	o	o	o	o	o	o	o	o
2	CHG	o	o	o	o	o	o	o	o
3	RHR	o	o	o	o	o	o	o	o
3-1	CSP					o		o	o
4	CCW #1	o		o		o	o	o	
5	NSCW #1	o	o			o	o	o	o
5-1	CSP						o		
6	AFW	o	o	o	o	o	o	o	o
7	NSCW #2			o	o				
7-1	CSP							o	
8	CCW #2		o		o				o
9	ECW	o	o	o	o	o	o	o	o

No.	Equipment	Scenarios							
		9	10	11	12	13	14	15	16
1	EDG	o	o	o	o	o	o	o	o
2	CHG	o	o	o	o	o	o	o	o
3	RHR	o	o	o	o	o	o	o	o
3-1	CSP			o			o		
4	CCW #1			o	o	o			
5	NSCW #1	o							
5-1	CSP	o			o			o	
6	AFW	o	o	o	o	o	o	o	o
7	NSCW #2		o	o	o	o	o	o	o
7-1	CSP		o			o			o
8	CCW #2	o					o	o	o
9	ECW	o	o	o	o	o	o	o	o

2.3. Data Analysis Method

- Export of ETAP transient results as CSV files [5]
- MATLAB-based post-processing for voltage/frequency profile quantification [6]
 - Evaluation at representative points within each load-step interval [1]
 - Automated calculation of recovery times, extrema, and out-of-limit durations
- Compliance verification against NRC Regulatory Guide 1.9 ($\pm 10\%$ voltage, ± 2 Hz frequency) [1]

3. Results and Discussion

The analysis confirmed that the selection of governor and exciter models has a significant impact on the voltage and frequency responses of EDGs.

Initially, a total of 32 scenarios were considered; however, several scenarios represented unrealistic or non-essential conditions, such as those leading to failure of safe shutdown or residual heat removal. These cases were excluded from the transient analysis. Consequently, 16 representative scenarios were ultimately selected. The application of the IEEE AC8B exciter and the Woodward 2301 governor models demonstrated satisfactory performance across all 16 scenarios, with voltage and frequency deviations consistently remaining within the regulatory acceptance limits.

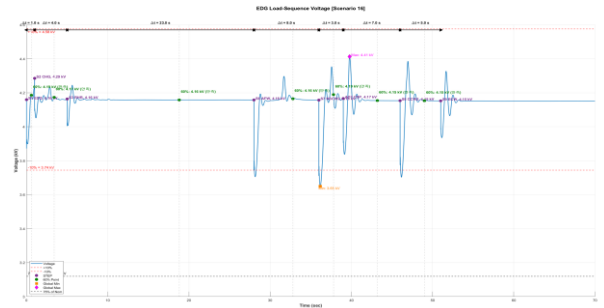


Figure 3. Voltage Profile Analysis

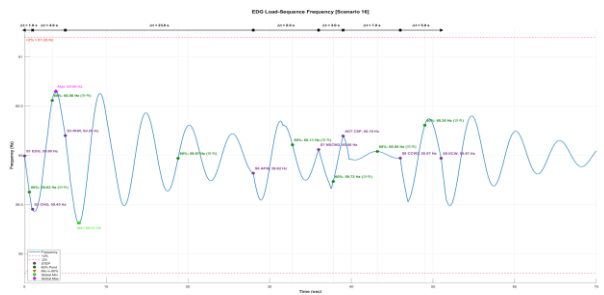


Figure 4. Frequency Profile Analysis

4. Conclusions

This study applied ETAP-based dynamic modeling combined with MATLAB post-processing to evaluate the voltage and frequency compliance of EDG

intermediate load sequencing in a WH-type onsite power system.

The IEEE AC8B exciter and Woodward 2301 governor models satisfied all regulatory acceptance criteria across 16 representative scenarios, including early CSP insertion, and demonstrated stable performance. This outcome extends beyond the limitations of previous studies, which were confined to normal load sequencing and single generic models, by incorporating expanded operating conditions and optimized control models.

Compared with earlier works—Hur and Roh [3], which verified normal sequencing of OPR-type plants using a generic exciter model, and Lee et al. [4], which analyzed improvements in load-sequence control logic—this study distinctly demonstrates that the inclusion of intermediate load sequencing and optimized control models in WH-type plants ensures both regulatory compliance and operational reliability of EDG performance.

The findings confirm not only compliance with regulatory requirements but also a substantive contribution to enhancing EDG operational reliability. These results provide a robust technical basis for future design improvements and reliability verification.

REFERENCES

- [1] U.S. NRC, Regulatory Guide 1.9, Selection, Design, Qualification, and Testing of Emergency Diesel Generator Units, Rev. 4, 1993.
- [2] IEEE Std 421.5, IEEE Recommended Practice for Excitation System Models, IEEE Power Engineering Society, 2005.
- [3] J.-S. Hur and M.-S. Roh, “Verification of voltage/frequency requirement for emergency diesel generator in nuclear power plant using dynamic modeling,” AIP Conf. Proc., vol. 1584, pp. 15–21, 2014.
- [4] K. Lee, H. Jang, and Y. Cho, “Verification of improved load sequence logic of emergency diesel generator,” Proc. IEEE Power & Energy Society General Meeting, Boston, MA, USA, 2016.
- [5] ETAP User Guide, Operation Technology Inc., 2023.
- [6] MATLAB Documentation, MathWorks, 2023.