

Techno-Economic Assessment of Nuclear Power Integration into Uganda's Power Grid

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1. Introduction

Uganda is pursuing nuclear power development to strengthen energy security, satisfy increasing electricity demand, and support industrialization. The country's power system is currently characterized by a relatively weak and hydro-dominated generation fleet, with hydropower contributing approximately 80% of total generation. This dependence exposes the system to hydrological variability and associated supply uncertainty [1].

The introduction of large scale conventional nuclear generation into such a system may therefore create technical challenges because the existing transmission infrastructure must accommodate the additional power injected while system demand and generation must maintain acceptable system operating conditions [2]. Small Modular Reactors (SMRs) provide a potential alternative because their smaller unit capacity allows nuclear generation to be introduced in scalable stages [3].

This study evaluates the technical and economic feasibility of integrating a 680 MW Innovative Small Modular Reactor (i-SMR) into Uganda's projected 2040 grid system. Additionally, a comparative analysis was used to evaluate the economic performance of the i-SMR against a 1400 MW conventional large nuclear reactor for Uganda's case.

2. Methods and Results

2.1 Technical Analysis

A simplified representation of Uganda's major generation and transmission network was developed in DIGSILENT PowerFactory. The model incorporated a 680 MW i-SMR together with the projected 2040 generation mix and demand profile. Major grid stations were modelled using information obtained from the Uganda Grid Development Plan 2018–2040 by UETCL [4].

The load flow analysis employed a balanced positive sequence AC Newton-Raphson formulation. A maximum of 50 iterations was specified, with convergence obtained when the load flow errors were below 1 kVA for nodes and 0.1% for the model equations. Line and cable resistances were evaluated at a reference temperature of 20°C. The model converged successfully and had an installed capacity of approximately 5800MW, total generation was 3298.2 MW while system demand was 3210 MW with grid losses of 88.2MW and spinning reserve of 954.1MW.

An N-1 contingency was subsequently performed to evaluate system performance following the loss of the 680 i-SMR. An 80% loading limit, 100% overload threshold and minimum acceptable voltage of 0.95 p.u. were adopted. The system remained satisfactory under the pre-contingency conditions, however the sudden loss of the i-SMR resulted in localized thermal and voltage violations particularly within the central transmission network. This indicates that although the projected system can accommodate the i-SMR during normal operation, additional transmission reinforcement may be required to improve its resilience to major generation contingencies.

Transient stability analysis was evaluated following the sudden disconnection of the i-SMR at 1.0s. The 680 MW generation loss produced an immediate reduction in system frequency reaching a nadir of approximately 0.979 p.u. (48.95) Hz on a 50 Hz base before recovering towards 0.998 p.u. (49.9) Hz within 40s. This was possible because of the response of the remaining generators and activation of the Under Frequency Load shedding (UFLS) system based on the Uganda grid code requirements.

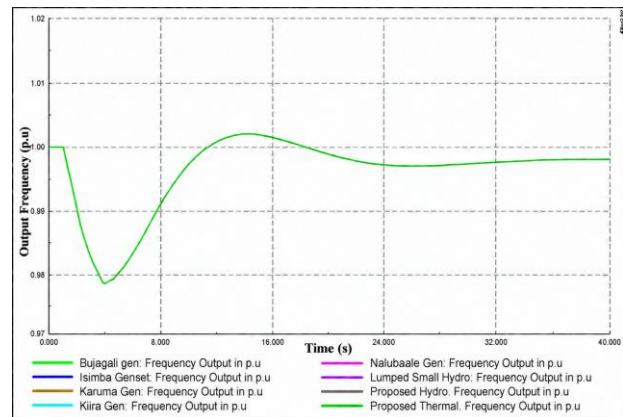


Fig. 1. System frequency response following the i-SMR trip

Generator rotor angles initially deviated following the disturbance but subsequently damped toward a steady state regaining synchronism within approximately 20 s.

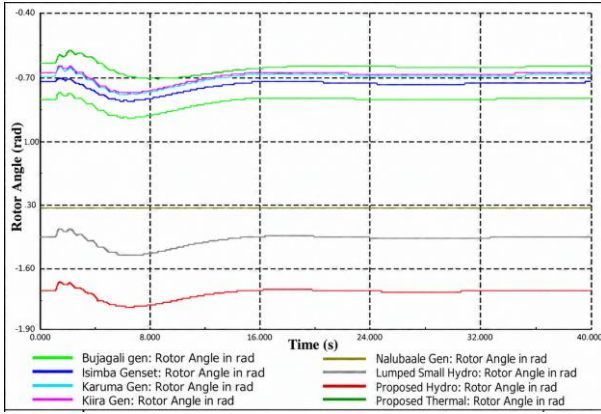


Fig. 2. Generator rotor-angle response following the i-SMR trip

2.2 Economic Analysis

PLEXOS was used to evaluate the economic performance of a 680 MW i-SMR and a 1400 MW conventional large reactor under the defined 2040 Uganda generation mix and demand conditions. The 2040 demand and non-nuclear generation fleet were maintained consistently for both scenarios, while nuclear generation was introduced in 2040. The i-SMR configuration comprised of four 170 MW modules whereas the conventional option represented a single 1,400 MW unit. The analysis assumed a 5% discount rate annualised over the project's economic life.

Table I: Summary of key nuclear assumptions

Parameter	i-SMR	Large Reactor
Unit capacity (MW)	170	1400
Max units built	4	1
VO&M Charge (\$/MWh)	2.5	2.38 [5]
FO&M Charge (\$/kW/yr.)	95.48	122.26 [6]
Build cost (\$/kw)	10,000	6870 [5]
Economic life (yr.)	60	60 [6]

Build costs were taken from Idaho National Laboratory (INL) reference conservative estimates, applying a 0.64 nuclear scaling exponent to the 170MW and 1400 MW [5].

Table II: PLEXOS economic and generation results

Parameter	i-SMR	Large Reactor
LCOE (\$/MWh)	92	74
Annual generation (GWh/yr.)	5400	11000

Nuclear generation cost (\$ million/yr.)	70	142
Total system cost (\$ million/yr.)	1,165	1,493

The results indicate that the large reactor has a lower levelized cost of electricity (LCOE) of 74 \$/MWh compared with the 92 \$/MWh for the i-SMR. This difference is associated with the higher unit investment cost of the smaller modular configuration. However, under the assumed 3300MW 2040 annual demand, the non-nuclear generation sources contribute approximately 670 \$million/yr in both scenarios so the system total cost difference is attributed to nuclear integration, 495 \$million/yr for the i-SMR against 823 \$million/yr for the large reactor representing 39.85% reduction in annual generation costs with the i-SMR.

This indicates that, despite its high LCOE, the i-SMR provides a more economically suitable capacity addition under the assumed demand and generation mix for Uganda by complementing the existing renewable resources rather than the large reactor that may result in over generation thereby reducing the dispatch of other available generation resources.

3. Conclusions

The technical and economic feasibility of integrating a 680 MW i-SMR into Uganda's projected 2040 power system was assessed using DigSILENT PowerFactory and PLEXOS. The load flow model successfully converged, and the major transmission corridors remained within acceptable thermal limits under normal operating conditions.

The N-1 assessment showed that the loss of the 680 MW i-SMR produces localized thermal and voltage violations particularly within the central transmission network. The transient stability analysis showed that the system maintained generator synchronism following the nuclear unit trip, although the frequency decreased to approximately 48.95 Hz before recovering toward 49.9 Hz in approximately 40s.

The PLEXOS analysis showed that although the i-SMR has a higher LCOE, its smaller capacity offers a scalable deployment pathway into Uganda's evolving renewable generation mix. The i-SMR therefore serves the same projected 2040 demand at a lower total system cost, making it cost competitive compared to the large scale reactor.

Nonetheless, as demand, transmission capacity and regional interconnections continue to develop, additional nuclear capacity including larger reactors may be successfully deployed. These findings can support Uganda's future nuclear technology selection in terms of unit sizing, grid expansion planning and investment decisions.

AFFILIATION

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