ABSTRACT OF DOCTORAL THESIS

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II. Major: Electrical Engineering

III. Code: 9520201

IV. Scientific supervisors: 1. Assoc. Prof. Dr. Nguyen Huu Hieu

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V. Thesis title: Research and proposal of control solutions for energy storage systems to enhance power system stability in the presence of renewable energy integration

VI. Training institution: University of Science and Technology – The University of Danang

VII. Summary of thesis content

1. Rationale of the thesis

The development of renewable energy sources (RES) is an inevitable trend for all countries. By the end of 2024, the worldwide installed capacity of solar and wind power had reached about 1,852 GW and 1,133 GW, respectively (IRENA). In Vietnam, wind and solar power reached 21,447 MW, about 26% of the total installed capacity. Under Power Development Plan VIII, the share of RES will continue to grow to about 29% by 2030 and 44% by 2045.

The rapid integration of RES has created many difficulties for power system operation and stability: during the 2015 solar eclipse, Germany lost 6,000–13,000 MW of solar power within about 15 minutes; in Vietnam, on 11/10/2020 the system frequency rose to 50.5 Hz due to surplus generation, and on 18/10/2020 about 1,500 MW of solar power had to be curtailed because of low load. As the share of RES increases, the reduction of system inertia makes frequency stability the most prominent issue, while overloading of interconnecting lines forces the curtailment of RES output.

Electrical energy storage devices, especially battery energy storage systems (BESS) and pumped-storage hydropower plants (PSHP), are feasible solutions to these problems. However, domestic studies have mostly been limited to potential assessments or small-scale trials, and international studies usually focus on individual technologies; studies on the simultaneous coordination of BESS – PSHP remain very limited. These considerations establish the urgency and the scientific and practical significance of the research topic.

2. Research objectives

General objective: To investigate the impact of large-scale solar and wind power plants on power system frequency stability; to develop control models for two electrical energy storage devices, namely BESS and PSHP, together with a coordinated BESS – PSHP operation strategy, applied to the IEEE 39-Bus test system and the actual Vietnamese power grid.

Specific objectives:

i. To assess the impact of solar and wind power integration on the frequency stability of the transmission grid.

ii. To propose a BESS control model based on adaptive nonlinear droop combined with state-of-charge (SOC) feedback, in order to limit frequency oscillations, improve the rate of change of frequency (RoCoF) and regulate the SOC.

iii. To propose a control model for a variable-speed pumped-storage hydropower plant (VS-PSHP) whose optimal pumping/generating schedule is determined by a multi-objective Genetic Algorithm (fuel cost – CO_2 emissions – energy losses), thereby clarifying the peak-shaving, valley-filling and frequency-stabilizing roles of the Bac Ai PSHP.

iv. To propose a Coordinated Operation Strategy (COS) for BESS – PSHP to relieve line overloading, optimize power allocation, limit RES curtailment and enhance frequency stability.

3. Research subject and scope

3.1. Research subject

Renewable energy power plants (solar, wind, etc.), battery energy storage systems (BESS), pumped-storage hydropower plants and the Vietnamese power system.

3.2. Research scope

The focus is on the frequency stability of power systems with a high share of RES (frequency deviation, RoCoF, frequency extrema and frequency recovery) and on BESS and PSHP control solutions operating individually and in coordination. In addition, the thesis examines the transient stability of the PSHP under short circuits on the 500 kV grid and its ability to relieve overloading of interconnecting lines; small-signal stability, long-term voltage stability and the optimal BESS siting and sizing problem are not considered. The study grids are the modified IEEE 39-Bus system, the 500/220 kV Central Highlands grid and the Ninh Thuan – South Central grid.

4. Research methods

Literature review; collection and processing of Vietnamese power system operating data and source – load data; theoretical analysis combined with modelling and time-domain simulation in DIgSILENT PowerFactory; multi-objective optimization using the Genetic Algorithm (GA) with the PDPAT II tool; validation on test and actual grids, with comparison against the CBEST model and the case without energy storage.

5. Scientific and practical significance of the thesis

The novelty and scientific significance of the thesis can be summarized as follows:

- *First,* a BESS control model based on adaptive nonlinear droop with SOC feedback and cascaded control loops (P – f, P – Q, Q – U and the current loop) is developed, reducing the average RoCoF by about 23 – 52% compared with the case without BESS and giving better frequency extrema than the CBEST model.
- *Second,* a VS-PSHP control model combined with a multi-objective genetic optimization problem (fuel cost – CO_2 emissions – energy losses) is developed, clarifying the peak-shaving, valley-filling and frequency-support roles of the PSHP compared with coal-fired and LNG alternatives.
- *Third,* a Coordinated Operation Strategy (COS) for BESS – PSHP based on the excess/shortage energy of RES is proposed, assigning roles by time scale: The BESS handles fast, short-term fluctuations, while the PSHP handles long-cycle energy balancing and frequency recovery after disturbances.

The practical contributions of the thesis are as follows:

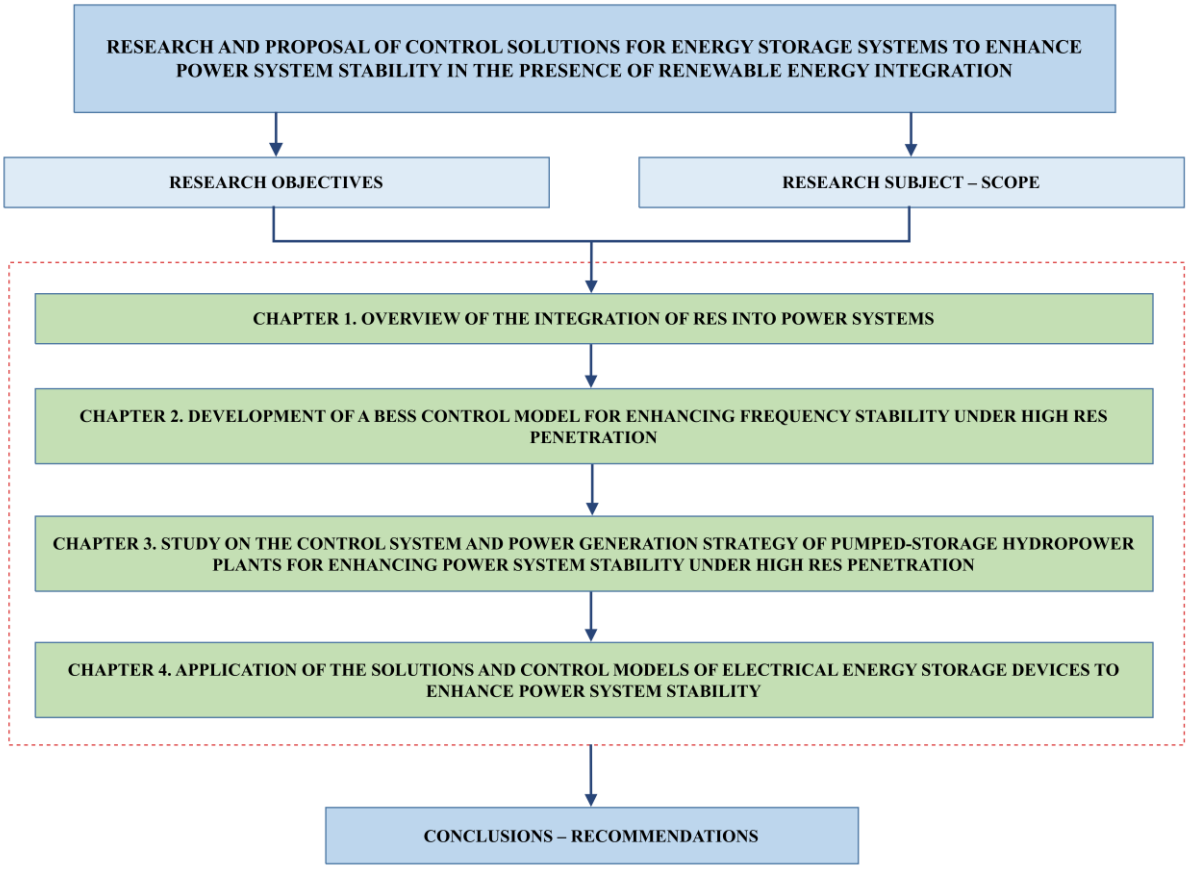
(1) The proposed BESS control model, together with the SOC operating range of 20 – 85%, can serve as a reference for grid-connection and operation regulations and for dispatch instructions for BESS.

(2) For the Bac Ai PSHP: An optimal schedule of about 9 hours of pumping and 7 hours of generating per day. A 20-year TCO about 2,913 million USD lower than a new LNG plant of the same capacity; and, when cloud cover reduces about 5,000 MW of solar power, the PSHP keeps the frequency within 48.4 – 50.8 Hz (45.8 – 53.4 Hz without the PSHP).

(3) The COS reduces the maximum loading of the two 500 kV lines Vinh Tan – Dong Nai and Vinh Tan – Hong Phong from 111 – 117.8% to no more than 91.5%, limiting RES curtailment. During a temporary short circuit, the frequency nadir rises from 49.891 Hz to 49.903 Hz and the settling time is shortened from about 1.0 s to 0.4 s.

6. Structure of the thesis

The thesis consists of an introduction, four main chapters, conclusions and recommendations, a list of published works, references and appendices. The structure of the thesis is summarized in the following diagram:



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