NEW CONTRIBUTIONS OF THE THESIS

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

Major: Electrical Engineering

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

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The use of electrical energy storage devices to enhance the stability of power systems with integrated renewable energy sources (RES) is attracting the attention of scientists, engineers and experts in Vietnam and worldwide, because the share of these sources in power systems is increasing rapidly, while technical solutions ensuring frequency stability, power quality and operational security of the grid against the variability and limited predictability of RES are still lacking. On the theoretical side, the thesis analyzes the mechanisms of inertia reduction and frequency instability in power systems with a high share of RES and develops control models for two types of electrical energy storage devices, the battery energy storage system (BESS) and the pumped-storage hydropower plant (PSHP), together with a coordinated operation strategy for them. On the practical side, the models are validated on the modified IEEE 39-Bus test system and the actual Vietnamese grid (the 500/220 kV Central Highlands system and the Ninh Thuan area with the Bac Ai PSHP), providing a reference for the consulting, planning and operation of power systems with a high share of RES. The main contributions of the thesis are as follows:

1. Theoretical contributions

The first theoretical contribution of the thesis is the development of a BESS control model based on adaptive nonlinear droop with state-of-charge (SOC) feedback, using cascaded control loops: active power – frequency, active power – reactive power, reactive power – voltage, and the current loop. The control characteristic varies with the frequency deviation and the SOC, so that the BESS responds strongly to large frequency deviations and avoids unnecessary charging/discharging during small oscillations. The model reduces the average rate of change of frequency (RoCoF) by about 23 – 52% compared with the case without BESS.

The second theoretical contribution of the thesis is the development of a control model for a variable-speed pumped-storage hydropower plant (VS-PSHP) combined with a multi-

objective optimization problem solved by the Genetic Algorithm (fuel cost – CO_2 emissions – energy losses) to determine the optimal pumping/generating schedule of the Bac Ai PSHP. This clarifies the peak-shaving, valley-filling and frequency-support roles of the PSHP compared with alternatives using coal-fired and LNG power plants.

The third theoretical contribution of the thesis is the proposal of a Coordinated Operation Strategy (COS) for BESS – PSHP based on the excess (Es)/shortage (Ed) energy of the RES, which assigns roles to the two devices by time scale: the BESS handles fast, short-term fluctuations, while the PSHP handles energy balancing over longer cycles and frequency recovery after disturbances.

2. Methodological contributions

The first methodological contribution of the thesis is the implementation and simulation of the proposed BESS control model in DIgSILENT PowerFactory, compared with the CBEST model and the case without BESS on the modified IEEE 39-Bus system and the 500/220 kV Central Highlands grid in six scenarios (cloud cover over solar power plants, generator outage, load loss and transformer outage). The proposed model yields better frequency extrema than the CBEST model in all six scenarios and meets the requirements of Circular 25/2016/TT-BCT.

The second methodological contribution of the thesis is the simultaneous combination of three objectives – fuel cost, CO_2 emissions and energy losses – in a multi-objective optimization problem solved by the Genetic Algorithm, determining the Pareto-optimal set instead of optimizing each objective separately. In addition, the economic efficiency is evaluated by the total cost of ownership (TCO), expressed as the present value over 20 years, with a sensitivity analysis with respect to the discount rate.

The third methodological contribution of the thesis is the simulation of the COS on a model of the Ninh Thuan area grid in DIgSILENT PowerFactory using hourly load and RES data for two typical months (March and November) and a temporary short-circuit scenario at the 500 kV Ninh Son busbar, allowing the role of the BESS – PSHP to be assessed simultaneously with respect to transmission line loading and frequency stability.

3. Practical contributions

The first practical contribution of the thesis is that the proposed BESS control model, together with the SOC operating range of 20 – 85% and the SOC feedback mechanism, can serve as a reference when developing or updating grid-connection and operation regulations for BESS and when issuing dispatch instructions to BESS, especially in areas with high rates of change of frequency due to large-scale RES integration.

The second practical contribution of the thesis is the set of calculation results for the Bac Ai PSHP: an optimal operating 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 that of a new LNG plant of the same capacity (discount rate 10%/year) and close to that of the alternative using existing thermal power plants; and, when cloud cover reduces about 5,000 MW of solar

power in the Ninh Thuan area, the PSHP keeps the frequency within 48.4 – 50.8 Hz (45.8 – 53.4 Hz without the PSHP). These results provide a reference for consulting, planning and dispatch entities when preparing generation dispatch schedules.

The third practical contribution of the thesis is that the COS applied to the Ninh Thuan area grid 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 due to grid overloading; 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. The results can serve as a reference for other areas with a high density of RES, such as the Central Highlands and the South Central region.

4. Contributions to scientific knowledge

The first contribution of the thesis to scientific knowledge is the clarification of the role of voltage, active power P and reactive power Q, in addition to SOC, in BESS control (the CBEST model considers only SOC and Q), providing a basis for BESS control models that closely reflect actual operating characteristics.

The second contribution of the thesis to scientific knowledge is the clarification of the complementary mechanism between the BESS and the PSHP in terms of both energy and time: on a typical day, the PSHP absorbs about 85% of the stored surplus energy, while the BESS handles the small remainder and short-term fluctuations. During a disturbance, the BESS reaches its maximum power of 417.3 MW within about 5 ms to slow down the frequency decline, and the PSHP reaches 742.1 MW after about 0.56 s to restore the frequency. This division of roles overcomes the limitations of each technology when operating alone.

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