THE UNIVERSITY OF DANANG

UNIVERSITY OF SCIENCE AND TECHNOLOGY

TRAN VIET THANH

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

Code: 9520201

ABSTRACT OF THE DOCTORAL THESIS IN ENGINEERING

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DA NANG – 2026

INTRODUCTION

1. Urgency of the research

Worldwide, by the end of 2024 the installed capacity of solar and wind power had reached about 1,852 GW and 1,133 GW, respectively (IRENA).

The rapid growth of RES poses operational challenges; a typical example is the 2015 solar eclipse in Europe, during which Germany lost 6,000–13,000 MW of solar power within 15 minutes, causing large voltage and frequency fluctuations.

In Vietnam, several incidents caused by the high share of RES have revealed the risk of system instability when RES development is not adequately controlled.

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:*
  + To assess the impact of solar and wind power integration on the frequency stability of the transmission grid;
  + 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 RoCoF and regulate the SOC;
  + 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;

+ To propose a Coordinated Operation Strategy (COS) for BESS – PSHP that exploits the fast response of the BESS and the large, long-duration storage capability of the PSHP to relieve line overloading, optimize power allocation, limit RES curtailment and enhance frequency stability.

3. Research methodology

- Literature review; collection and processing of Vietnamese power system operating data, source – load data and output power of solar and wind power plants;
- Theoretical analysis combined with time-domain simulation in DIgSILENT PowerFactory; multi-objective optimization using the Genetic Algorithm (GA) with the PDPAT II tool;
- Validation on the modified IEEE 39-Bus system and the actual Vietnamese grid (the 500/220 kV Central Highlands system and the Ninh Thuan area with the Bac Ai PSHP); comparison with the CBEST model and with the case without energy storage.

4. Research subject and scope

- *Research subject:* Renewable energy power plants (solar, wind, etc.), BESS, pumped-storage hydropower plants and the Vietnamese power system.
- *Research scope:* The focus is on the frequency stability of power systems with a high share of RES (frequency deviation, RoCoF, frequency nadir/zenith 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 rotor angle stability (including local and inter-area electromechanical oscillations), long-term voltage stability and the optimal BESS siting and sizing problem are not considered.

5. New contributions of the thesis

- Theoretical contributions:

+ Developed a BESS control method with cascaded control loops that reduces the average RoCoF by about 23 – 52% and improves the frequency extrema compared with the case without BESS;

+ Developed a multi-objective genetic optimization model demonstrating the superior role of pumped-storage hydropower (PSHP) in frequency stability compared with previous thermal/LNG models combined with RES;

+ Proposed a coordinated PSHP – BESS operation strategy to optimize the load profile and enhance system frequency stability, identifying the coordinating role of each source in different operating modes so as to improve the utilization of RES.

- Methodological contributions:

+ Applied a new BESS control algorithm that outperforms CBEST in frequency stability and tie-line power control;

+ Simultaneously minimized operating cost, environmental emissions and energy losses;

+ Coordinated PSHP – BESS operation, which both overcomes the limitations of each device and creates a synergistic effect for primary frequency control, long-term operation and system reliability.

- Practical contributions:

+ A BESS solution directly applicable to power systems with high RES penetration;

+ Development of guidelines and a database for consulting, design and power transmission under high RES penetration;

+ Support for power system planning and operation;

- Contributions to scientific knowledge:

+ Clarified the simultaneous role of voltage, P and Q in BESS control (unlike CBEST, which focuses only on SOC and Q);

+ Demonstrated the complementarity between BESS and PSHP;

+ Laid the foundation for further research and applications.

6. Structure of the thesis

The thesis consists of an introduction, four main chapters, conclusions and a list of published works.

Chapter 1: Overview of the integration of RES into power systems.

Chapter 2: Development of a BESS control model for enhancing frequency stability under high RES penetration.

Chapter 3: Study on the control system and power generation strategy of pumped-storage hydropower plants for enhancing power system stability under high RES penetration.

Chapter 4: Application of the solutions and control models of electrical energy storage devices to enhance power system stability.

The final part, CONCLUSIONS AND RECOMMENDATIONS, summarizes the results obtained in the thesis and provides recommendations and proposals for future research directions extending the results of the thesis.

CHAPTER 1: OVERVIEW OF THE INTEGRATION OF RES INTO POWER SYSTEMS

1.1. Introduction

1.2. Challenges of integrating RES into power systems

1.2.1. Impact on system frequency response

1.2.1.1. Inertia

The integration of large amounts of RES reduces the inertia and damping capability of the power system, causing frequency instability. A possible solution is the use of virtual inertia.

1.2.1.2. Primary frequency response

The increasing share of inverter-based resources (IBRs) reduces the natural frequency response capability, making frequency stability assurance an urgent issue.

1.2.2. Disturbances in the power grid

RES integration causes voltage fluctuations at the Point of Common Coupling (PCC) due to its variable and stochastic nature, degrading power quality and affecting equipment.

1.3. Overview of electrical energy storage devices in power systems

1.3.1. Status and trends of energy storage technologies

1.3.1.1. Energy storage technologies currently in use

Energy storage technologies are diverse: PSHP offers large capacity at low cost but depends on topography; BESS is flexible but still limited by cost and materials; Gravity Energy Storage (GES) and Compressed Air Energy Storage (CAES) are alternative solutions for large-scale storage; flywheels are suitable for short-term, high-efficiency storage; green hydrogen has long-term potential but is still under development and costly.

1.3.1.2. Development trends of energy storage technologies

PSHP will maintain its dominant role in the short term, while BESS is growing strongly with new battery technologies. CAES and flywheels are expanding into niche applications. New technologies such as solid-state batteries and green hydrogen are expected to

improve efficiency and safety. PSHP and BESS are the two dominant storage technologies, combining fast response, large-scale storage and economic operation, thereby enhancing the integration of RES.

1.3.1.3. Development of PSHP and BESS projects in ASEAN and worldwide

ASEAN countries such as Thailand, the Philippines, Indonesia and Laos are actively developing PSHP and BESS to support RES integration and enhance power system stability. Thailand stands out in PSHP, the Philippines leads in commercial BESS, while Indonesia and Laos are strengthening their roles in regional energy storage and regulation.

China, the United States, the EU, Australia and Japan are all expanding PSHP and BESS to support RES integration, enhance power system stability and achieve carbon-neutrality targets. Overall, PSHP retains its role in large-scale storage, while BESS is growing rapidly thanks to its flexibility and fast response.

1.3.2. PSHP – BESS: A comprehensive integrated solution for Vietnam's power grid

The combination of PSHP and BESS is highly complementary: PSHP provides long-term storage, while BESS offers fast short-term response, covering the full frequency regulation range. This is the most feasible solution for Vietnam, balancing cost and operational efficiency, especially under high RES variability in the South Central and Central Highlands regions. This is the main focus of the thesis.

1.4. Overview of research on the integration of high shares of RES into power systems

1.4.1. In Vietnam

RES research in Vietnam has mainly been limited to potential assessments or small-scale trials; comprehensive technical solutions regarding scale, storage, siting and control strategies are lacking, particularly studies on the optimal operation of storage systems.

1.4.2. Worldwide

Many studies have developed control algorithms and integration models of RES with storage systems, but they mostly focus on individual technologies. In practice, PSHP and BESS are the two most feasible solutions; however, studies combining both technologies are still limited and lack detailed technical analysis.

1.4.3. Remarks

RES are highly variable and affect system stability; as their share increases sharply in line with Net Zero targets, the risk of instability grows. An effective solution is the integration of storage systems, among which the coordinated PSHP – BESS model stands out in frequency regulation and power balancing.

The thesis focuses on analyzing individual control and proposing an optimal coordination algorithm to enhance power system stability.

1.5. Conclusion of the chapter

CHAPTER 2: DEVELOPMENT OF A BESS CONTROL MODEL FOR ENHANCING FREQUENCY STABILITY UNDER HIGH RES PENETRATION

2.1. Introduction

2.2. Problem formulation

The effectiveness of a BESS depends on its control strategy: the controller coordinates the DC/DC converter and the DC/AC inverter to regulate P – Q at the PCC according to frequency and voltage signals and to determine the charging – discharging mode.

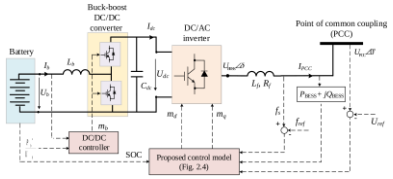


Fig. 2.1. BESS frequency response model

2.2.1. Battery system

The battery system consists of lithium-ion battery modules and auxiliary equipment connected to the grid to perform controlled charging – discharging. The DC power from the battery is regulated by the DC/DC converter before being converted to AC.

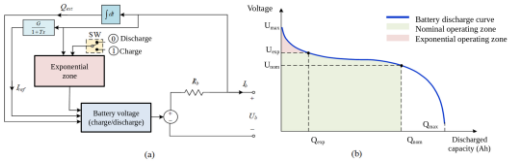


Fig. 2.2. Battery model: (a) nonlinear characteristic and (b) typical discharge curve

2.2.2. DC/DC converter

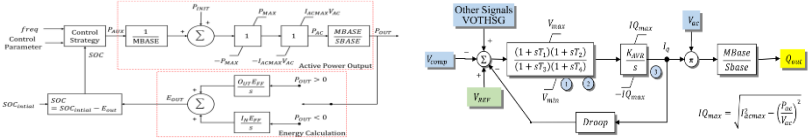
The bidirectional buck-boost DC/DC converter regulates the voltage according to the SOC and controls the charging (buck) – discharging (boost) modes through current control.

The CBEST model is commonly used owing to its simplicity, but its accuracy is limited when nonlinearities and losses are considered; it therefore needs to be analyzed and improved.

2.3. CBEST model

2.3.1. Model characteristics

2.3.2. Structure of the CBEST model



a/ BESS SOC control *b/ Reactive power control*

Fig. 2.3. Simulation of the BESS using the CBEST model

2.3.2.1. BESS SOC control

The "BESS SOC control" diagram consists of: the active power calculation block, the BESS stored energy calculation block and the BESS SOC calculation block.

2.3.2.2. Reactive power control

This block regulates reactive power to support the system voltage.

2.4. BESS control model

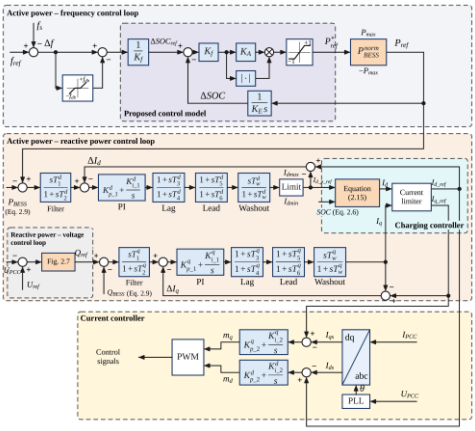


Fig. 2.4. Proposed control technique for the BESS

The BESS control strategy uses inner and outer control loops to generate the PWM signals for the inverter. Active power (d-axis) is used for frequency stabilization, while reactive power (q-axis) is used for voltage regulation.

The overall controller structure is divided into the following parts:

- Active power – frequency control loop;
- Active power – reactive power control loop;
- Reactive power – voltage control loop;
- Current controller.

2.4.1. Comparison of the adaptive nonlinear droop control method (proposed model) with conventional droop control

Table 2.1. Differences between the proposed model and conventional droop control

Criterion	Proposed model	Conventional droop control
Overshoot	Low: adaptive gains according to SOC and deviation level	High: fixed gains, prone to over-reaction
Settling time	Short: Lead/Lag and Washout blocks quickly damp oscillations	Long: lacks dynamic compensation blocks
Steady-state error	Not eliminated (intentionally): the BESS responds only during the transient; the steady-state deviation is handled by AGC, limiting SOC depletion	Steady-state error exists; the BESS keeps delivering power according to the frequency deviation, continuously depleting the SOC
Adaptability	High: the control characteristic self-adjusts with SOC, protecting the BESS	Low: SOC limits are not considered, prone to over-charging/over-discharging

2.4.2. Comparison of the proposed model with the CBEST model

Table 2.2. Differences between the proposed model and the CBEST model

Criterion	Proposed model	CBEST model
Level of detail	Full simulation of the structure and multi-level control	High-level functional blocks only
Advantages	Three loops P-f, Q-U, P-Q and a current loop; nonlinear droop with SOC feedback	Compact structure, light computation, easy to integrate into large grids
Disadvantages	Many parameters, difficult to tune and to analyze for stability	Does not reflect fast transients due to the lack of current loop and modulation
P-f control	Droop adaptive to frequency deviation and SOC	Fixed power add/subtract logic
Q-U control	Lead-Lag and Washout, fast oscillation damping	Low-pass filter, slow response
Role of SOC	Directly involved in the active power loop	Only an energy state variable
Current control	Inner current loop, instantaneous current limiting	Indirect, through P-Q limits
Field of application	Research, accurate simulation, practical applications	Preliminary simulation, quick assessment

2.5. Calculation results

2.5.1. Calculation models

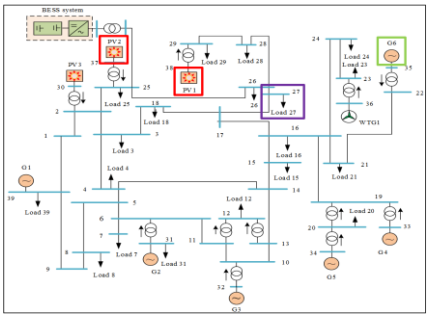


Fig. 2.5. Modified IEEE 39-Bus system with wind, solar power plants and BESS

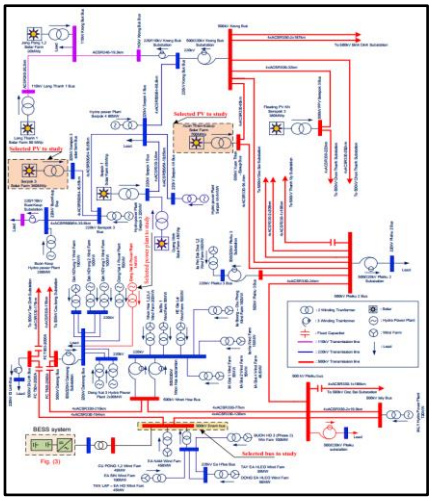


Fig. 2.6. 500/220kV Central Highlands power system

Two systems are used: the IEEE 39-bus system integrated with RES and the 500/220 kV Central Highlands system with a high share of RES, to evaluate the effectiveness of BESS control. The models are built in DIgSILENT PowerFactory 2022, in which the BESS is developed from the built-in library, with the focus on analyzing the control and operation strategies.

2.5.2. Case 1: Modified IEEE 39-Bus system

- Scenario 1: Cloud cover reduces the output of the two plants PV1 and PV2 by about 1,250 MW within 20 seconds;

- Scenario 2: Generator G6 (650 MW) has a fault and is disconnected from the system;
- Scenario 3: Load 27 (281 MW) has a fault and is disconnected from the system.

2.5.2.1. Scenario 1

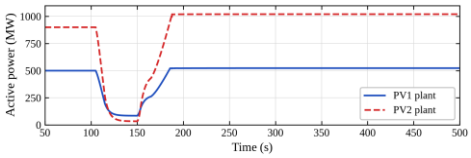


Fig. 2.7. Impact of cloud cover on the output power of PV1 and PV2

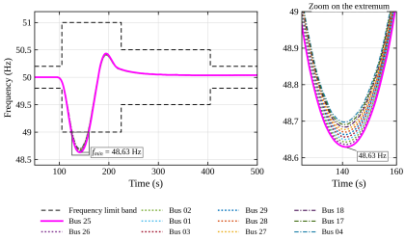


Fig. 2.8. Frequency under cloud cover affecting the PV1 and PV2

2.5.2.2. Scenario 2

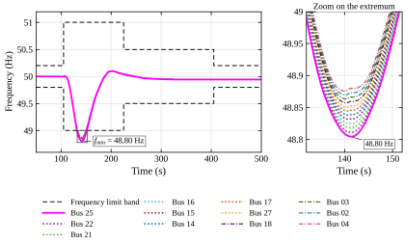


Fig. 2.9. Frequency when generator G6 is tripped, without BESS

2.5.2.3. Scenario 3

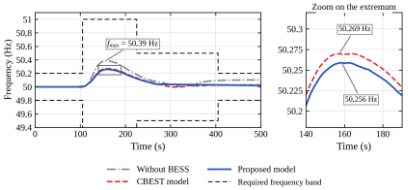


Fig. 2.10. Frequency when load 27 is lost, without BESS

2.5.2.4. Calculation results

a/ Scenario 1:

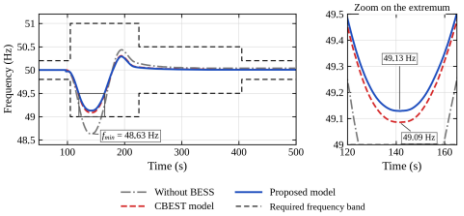
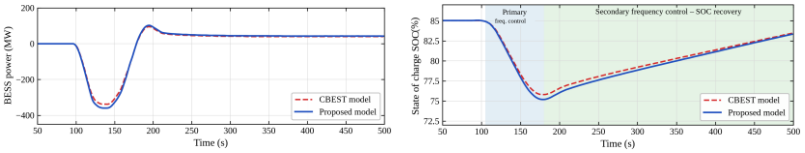


Fig. 2.11. Frequency at bus 25 – Scenario 1



(a) Generating power of BESS *(b) SOC of BESS*

Fig. 2.12. BESS frequency response – Scenario 1

b/ Scenario 2:

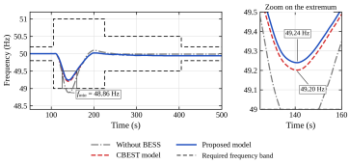
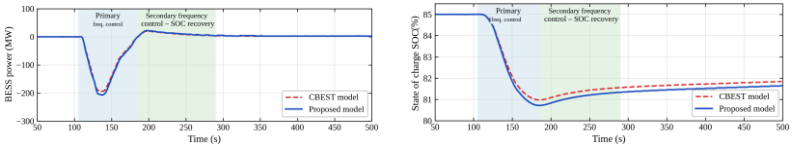


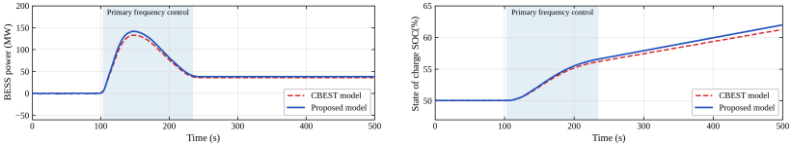
Fig. 2.13. Frequency at bus 25 – Scenario 2



(a) BESS output power *(b) BESS state of charge*

Fig. 2.14. BESS frequency response – Scenario 2

c/ Scenario 3:



(a) BESS output power *(b) BESS state of charge*

Fig. 2.15. BESS frequency response – Scenario 3

Table 2.3. Frequency extrema, average RoCoF compared with without BESS

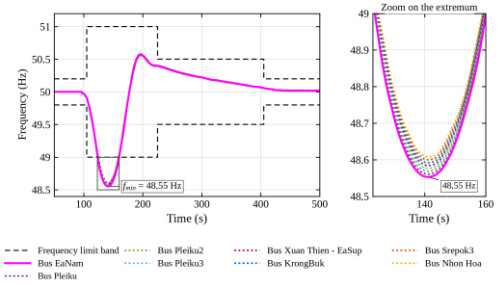
Scenario	f_{min}/f_{max} without BESS (Hz)	f_{min}/f_{max} CBEST (Hz)	f_{min}/f_{max} proposed (Hz)	RoCoF reduction – CBEST	RoCoF reduction – proposed
IEEE 39-Bus – Sc. 1	48.63	49.09	49.13	26%	30%
IEEE 39-Bus – Sc. 2	48.86	49.20	49.24	23%	26%
IEEE 39-Bus – Sc. 3	50.39	50.269	50.256	29%	23%
Central Highlands – Sc. 4	48.55	49.03	49.07	31%	30%
Central Highlands – Sc. 5	48.79	49.143	49.183	26%	31%
Central Highlands – Sc. 6	50.40	50.271	50.258	49%	52%

2.5.3. Case 2: The 500/220kV Central Highlands power system

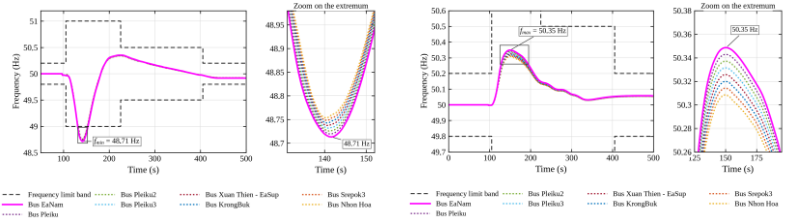
The model is applied to the 500/220 kV Central Highlands grid:

- Scenario 4: Cloud cover simultaneously affects the Xuan Thien – Ea Sup (700 MWp) and Srepok 3 (360 MWp) SPPs;
- Scenario 5: A generating unit of the Dong Nai power plant (144 MW) has a fault and is disconnected from the power system;
- Scenario 6: The 500/220 kV Pleiku transformer has a fault and is disconnected from the system.

2.5.3.1. Calculation results

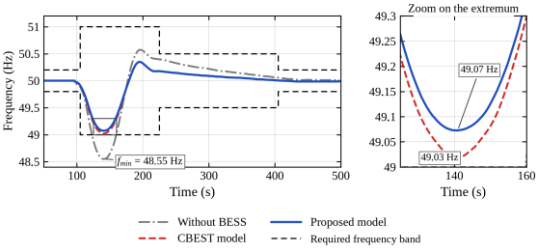


(a) Scenario 4

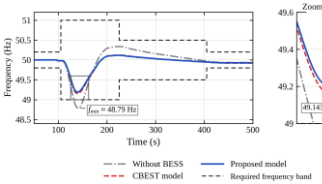


(b) Scenario 5 *(c) Scenario 6*

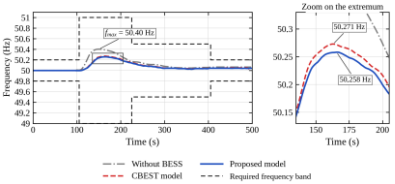
Fig. 2.16. Frequency response at selected buses of the studied system



(a) Scenario 4



(b) Scenario 5



(c) Scenario 6

Fig. 2.17. Frequency response at the EaNam bus with BESS

2.6. Conclusion of the chapter

CHAPTER 3: STUDY ON THE CONTROL SYSTEM AND POWER GENERATION STRATEGY OF PUMPED-STORAGE HYDROPOWER PLANTS FOR ENHANCING POWER SYSTEM STABILITY UNDER HIGH RES PENETRATION

3.1. Introduction

3.2. Optimal control model of the PSHP

3.2.1. Development of the variable-speed PSHP control model

The thesis selects and develops a control model for a variable-speed pumped-storage hydropower plant (VS-PSHP).

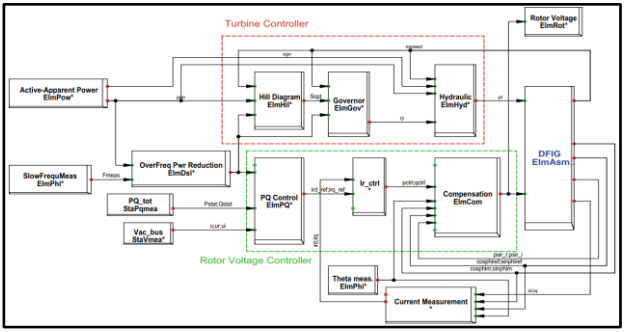


Fig. 3.1. Diagram of the VS-PSHP control model

3.2.2. Multi-objective optimal operation using the Genetic Algorithm

Having established the control model, the thesis develops a multi-objective Genetic Algorithm to determine the appropriate operating power of the Bac Ai PSHP according to three optimization objectives: (1) minimizing fuel cost; (2) reducing CO_2 emissions; (3) reducing energy losses.

3.2.2.1. Basis for selecting the multi-objective Genetic Algorithm

The genetic algorithm was selected because it is well suited to nonlinear, multi-objective optimization problems with many complex constraints. Compared with conventional algorithms, it offers better global search capability and limits convergence to local optima in systems integrating multiple RES and PSHP.

3.2.2.2. Optimal operation of the PSHP

a) Multi-objective optimization problem with the Genetic Algorithm:

The problem is formulated as a multi-objective optimization in which feasible solutions are evaluated against several criteria simultaneously to determine the Pareto-optimal set. The genetic algorithm searches for optimal solutions through selection, crossover and mutation, gradually improving solution quality towards the Pareto-optimal set. Solutions are classified into dominated and non-dominated ones; the non-dominated set forms the Pareto front, reflecting the trade-offs among the objectives. The two main GA operators, crossover (combining parent solutions) and mutation (introducing random variations), expand the search space and avoid local optima. The multi-objective GA is superior to conventional methods owing to its ability to handle complex constraints, avoid local optima and improve the chance of finding the global optimum.

b) Algorithm model and methodology:

❖ *Algorithm model:*

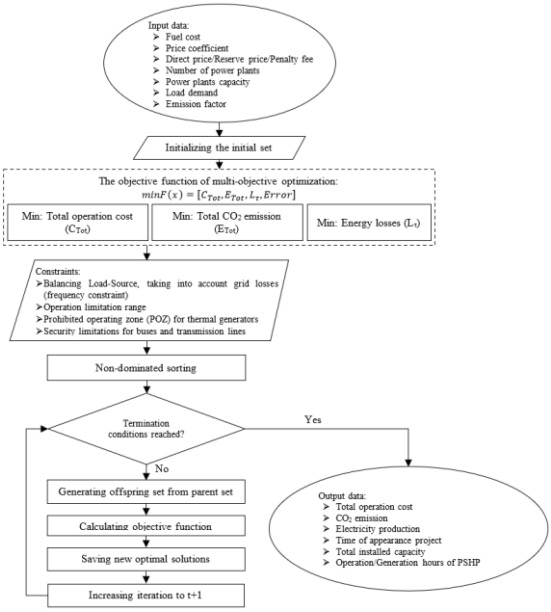


Fig. 3.2. Flowchart of the multi-objective optimization problem of the PSHP

❖ *Methodology:*

A scenario-based simulation method is used to analyze the supply – demand balance, load variations, generation commissioning schedule and fuel costs. The system is divided into 6 regions interconnected through the 500/220 kV grid. After selecting the alternative with PSHP, its operation is simulated chronologically, giving results on power, energy, dispatch timing and pumping – generating modes.

❖ *Calculation scenarios:*

The thesis compares three alternatives: A1 – without PSHP, using existing coal-fired and LNG plants; A2 – with the Bac Ai PSHP (1,200 MW); A3 – a new LNG plant of the same capacity. TCO is the present value of annual costs over 20 years (2026 – 2045): $TCO_i = \Sigma\, Z_{i,t}/(1+r)^t$, where $Z_{i,t} = CAPEX_i \cdot CRF_i + OPEX_i + C_{CO2,i} + C_{fuel,i,t}$; r = 10%/year (according to Circular 12/2025/TT-BCT); The substituted energy is E_{tt} ≈ 1,181 GWh/year.

c) Algorithm flowchart procedure:

The optimization objective function is formulated as follows:

$$minF(x) = [C_{Tot}, E_{Tot}, L_\tau, Error]$$

$$C_{Tot} = \sum_{i=1}^{N_g} \left(a_i \cdot {P_i}^2 + b_i \cdot P_i + c_i\right)$$

$$E_{Tot} = \sum_{j=1}^{N_g} \left(\frac{\sum_i FC_{i,m,y} \cdot NCV_{i,y} \cdot EF_{CO_2,i,y}}{EG_{m,y}}\right) \cdot {EG_j}^{N_g} \qquad (3.1)$$

$$L_\tau = \sum_{i=1}^{N_g} P_i + P_{PSHP} - P_{Load}$$

$$Error = \omega_1|\Delta f| + \omega_2|\Delta U| + \omega_1|\Delta P_{PSHP}|$$

Where: $F(x)$ is the multi-objective function; C_{Tot} is the total operating cost function; E_{Tot} is the total CO_2 emission function; L_τ is the operating loss function; $Error$ is the operating error function.

3.3. Calculation results

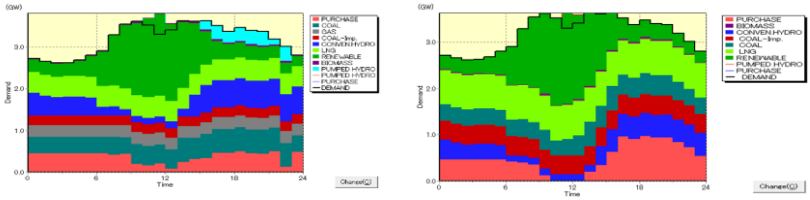
3.3.1. Economic operation results

Objective "Minimizing the total operating cost (C_{Tot})".

3.3.1.1. Economic efficiency evaluation of the three alternatives

Table 3.1. Cost components and TCO of the three alternatives (r = 10%)

Component	A1	A2	A3
CAPEX (million USD)	0	1,044	744
Economic life (years)	–	40	25
CAPEX·CRF (million USD/year)	0.0	106.8	82.0
OPEX (million USD/year)	50.9	10.4	27.8
C_{CO2} (million USD/year)	16.0	0.0	8.0
Fixed cost (million USD/year)	66.9	117.2	117.8
20-year present value of fixed costs (million USD)	569	998	1,003
20-year present value of fuel costs (million USD)	145,682	145,436	148,344
TCO (million USD)	146,251	146,433	149,347



a/ Operating chart, May 2027 (P_{max}) – with PSHP

b/ Operating chart, May 2027 (P_{max}) – without PSHP

Fig. 3.3. Daily operating chart for the peak load of May 2027 (P_{max})

3.3.1.2. Evaluation of the influence of the discount rate on the alternatives:

Table 3.2. Influence of the discount rate r on the TCO difference (million USD)

r (%/year)	$TCO_{A1} - TCO_{A2}$	$TCO_{A3} - TCO_{A2}$	Alternative with the lowest TCO
6	199	4,309	PA2
7	86	3,891	PA2
7.84 (break-even)	**0**	**3,577**	**A1 = A2**
8	−15	3,523	PA1
9	−104	3,199	PA1
10 (base)	−182	2,913	PA1
11	−252	2,661	PA1
12	−313	2,436	PA1

Table 3.3. Energy balance of the South Central region in 2027 (Results for the 3 calculation scenarios)

Month		1	2	3	4	5	6	7	8	9	10	11	12	Total (GWh)	Installed capacity (MW)
Demand		1,515	1,272	1,628	2,108	2,223	2,243	2,219	2,213	2,078	1,652	1,559	1,593	22,302	0
Import	Alternative 1	-579	-1,286	-1,701	-842	-428	-468	-587	-685	-653	-645	-721	-966	-8,152	0
	Alternative 2	-414	-1,169	-1,554	-692	-263	-361	-432	-512	-503	-500	-585	-808	-6,384	0
	Alternative 3	-414	-1,169	-1,554	-692	-263	-361	-432	-512	-503	-500	-585	-808	-6,384	0
RES		614	489	828	715	424	498	729	710	594	321	440	616	6,977	3,022
Conventional hydropower		369	400	461	675	1,064	1,066	920	1,040	1,015	842	610	695	9,157	2,319
Pumped-storage hydropower	Alternative 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Alternative 2	105	76	101	96	105	68	99	110	96	92	87	100	1,136	1,200
	Alternative 3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gas		12	386	481	300	17	17	16	16	17	15	141	138	1,556	750
Imported coal		29	24	29	41	41	41	41	41	41	32	33	31	427	3,232
Coal	Alternative 1	78	364	601	233	93	71	83	87	78	71	69	74	1,901	3,600
	Alternative 2	25	326	551	185	40	37	33	32	30	25	26	24	1,333	3,600
	Alternative 3	25	326	551	185	40	37	33	32	30	25	26	24	1,333	3,600
LNG	Alternative 1	970	864	874	957	982	989	987	974	957	992	963	982	11,491	1,500
	Alternative 2	917	826	824	909	929	955	938	919	909	946	920	932	10,923	1,500
	Alternative 3	1,022	902	925	1,005	1,034	1,023	1,037	1,029	1,005	1,038	1,007	1,032	12,059	2,700
Biomass		22	31	54	29	30	29	30	30	29	24	24	23	358	43
Total generation		2,094	2,558	3,329	2,950	2,651	2,711	2,806	2,898	2,731	2,297	2,280	2,559	31,864	16,266
Pumping	Alternative 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Alternative 2	-165	-117	-147	-150	-164	-107	-155	-173	-151	-146	-136	-157	-1,768	0
	Alternative 3	0	0	0	0	0	0	0	0	0	0	0	0	0	0

3.3.2. CO_2 emission results

Objective "Minimizing the total CO_2 emissions (E_{Tot})".

Table 3.4. Forecast CO_2 emissions from coal-fired and LNG power plants, 2026 – 2045

Year	A2 vs. A1			A2 vs. A3	
	Coal 600 MW (MWh/year)	Gas 600 MW (MWh/year)	CO_2 (tCO_2/year)	Gas 1,200 MW (MWh/year)	CO_2 (tCO_2/year)
2026	362,000	362,000	184,388	724,000	232
2027	568,000	568,000	289,316	1,136,000	365
2028	644,500	644,500	328,282	1,289,000	414
2029	645,500	645,500	333,375	1,309,000	420
2030	687,500	687,500	350,184	1,375,000	441
2035	747,500	747,500	380,746	1,495,000	480
2040	772,500	772,500	393,480	1,545,000	496
2045	805,500	805,500	410,289	1,611,000	517

3.3.3. Energy loss results of plant operation

The objective "Minimizing power losses (Lτ)" is achieved by optimizing the PSHP operating mode. The results show that the optimal schedule comprises about 9 hours of pumping and 7 hours of generating per day, with the exact timing depending on the season and the level of RES surplus.

3.3.4. Application to plant operation for system frequency stabilization

3.3.4.1. Cloud-cover scenario

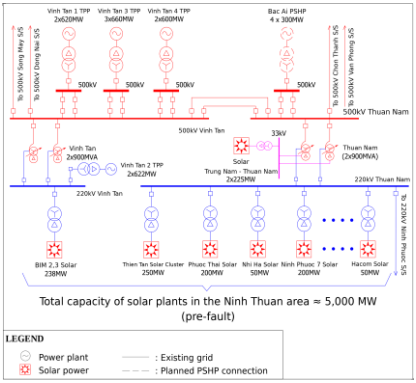


Fig. 3.4. Reduced diagram of the 500/220 kV grid in the Ninh Thuan area

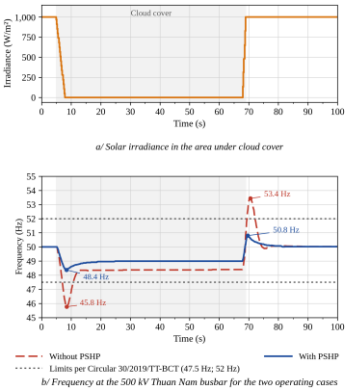


Fig. 3.5. Frequency oscillation in the Bac Ai PSHP area during the incident

3.3.4.2. Fault scenario

- Option 1: Fault on the 500 kV Bac Ai PSHP – Ninh Son line;
- Option 2: Fault on the 500 kV Ninh Son – Chon Thanh line.

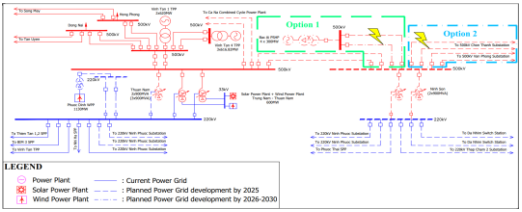


Fig. 3.6. Faults on the 500 kV Bac Ai PSHP – Ninh Son and 500 kV Ninh Son – Chon Thanh lines

a) Daytime pumping mode:

➢ Option 01:

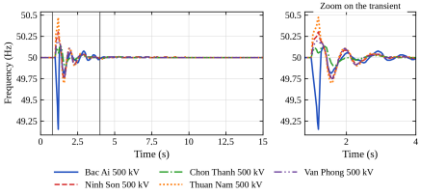


Fig. 3.7. Frequency oscillations at the 500kV Bac Ai PSHP busbar and other 500kV busbars in the area during the fault

➢ Option 02:

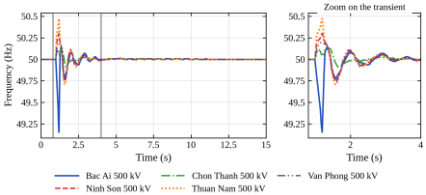


Fig. 3.8. Frequency oscillations at the 500kV Bac Ai PSHP busbar and other 500kV busbars in the area during the fault

b) Night-time generating mode:

➢ Option 01:

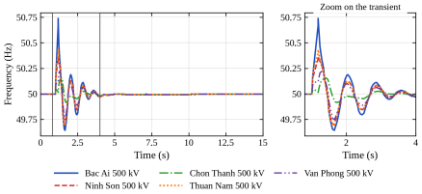


Fig. 3.9. Frequency oscillations at the 500kV Bac Ai PSHP busbar and other 500kV busbars in the area during the fault

➢ Option 02:

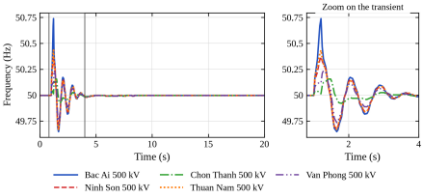


Fig. 3.10. Frequency oscillations at the 500kV Bac Ai PSHP busbar and other 500kV busbars in the area during the fault

c) Conclusion:

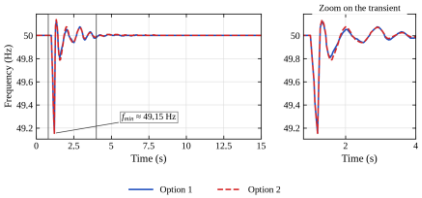


Fig. 3.11. Frequency oscillations at the 500kV Bac Ai PSHP busbars in daytime pumping mode in the rainy season during the fault

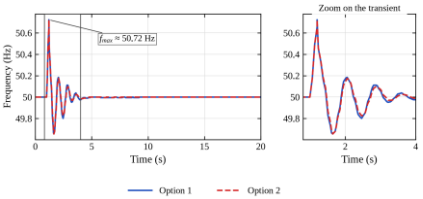


Fig. 3.12. Frequency oscillations at the 500kV Bac Ai PSHP busbars in night-time generating mode in the rainy season during the fault

3.4. Conclusion of the chapter

CHAPTER 4: APPLICATION OF THE SOLUTIONS AND CONTROL MODELS OF ELECTRICAL ENERGY STORAGE DEVICES TO ENHANCE POWER SYSTEM STABILITY

4.1. Introduction

4.2. Coordinated Operation Strategy for PSHP – BESS

4.2.1. Coordinated Operation Strategy (COS)

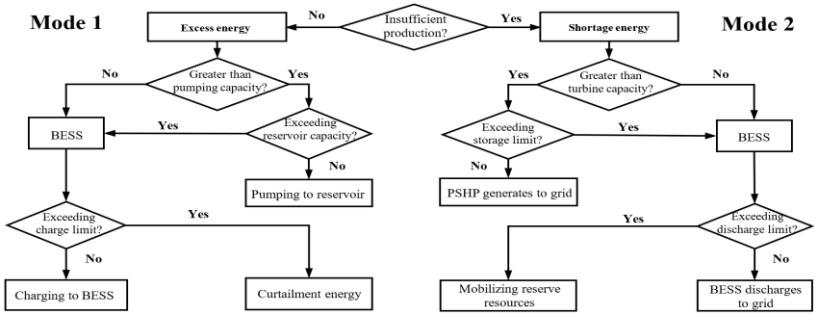


Fig. 4.1. Coordinated Operation Strategy for PV–wind–PSHP–BESS system

4.2.1.1. Mode 1: Sufficient energy supply to Load – Excess energy E_{ex} stored in PSHP, BESS, or both

Since the storage cost of PSHP is very low, surplus energy will be prioritized for storage in the Upper Reservoir (UR) according to the following equation:

$$E_p(t) = min\left[\rho \cdot g \cdot \mu_{psh} \cdot W_p(t) \cdot H(t); E_{ex}\right] \quad (4.1)$$
$$UR_{min} < UR(t) < UR_{max}$$

Where: $E_p(t)$ is Energy pumped to the UR in period *t*; $W_p(t)$ is Water flow from the pump (m^3/s); $H(t)$ is Head of the UR (m); μ_{psh} is Overall efficiency of PSHP, assumed to 80%; ρ is Water density (kg/m^3); g is Constant of gravitational acceleration (m/s^2).

In cases where the UR is already full but E_{ex} still remains, or when further pumping is not possible due to technical constraints of the PSHP (e.g., E_{ex} < 20% of the allowable pumping capacity), the remaining excess energy will be stored in the BESS according to the following equation:

$$E_b(t) = E_b(t-1) + E_{ch}$$
$$E_{ch} = \left[E_{res}(t) - E_p(t) - \frac{Load(t)}{\eta_{inv}}\right] \cdot \eta \quad (4.2)$$
$$E_{bmin} < E_b(t) < E_{bmax}$$

Where: $E_b(t)$ is the state of charge (SOC) of the BESS; E_{ch} is the energy charged into the BESS; $E_{res}(t)$ is the total energy generated by the RES; η_{inv} is the inverter efficiency; η is the BESS efficiency; E_{bmax} is the maximum allowable charge of the BESS; E_{bmin} is the minimum allowable charge, assumed to be 20% of E_{bmax}.

This allows maximum utilization of the energy produced by RES and reduces the waste of surplus energy. If the PSHP/BESS is saturated but RES power is still in surplus, the system curtails power according to the equation:

$$E_{curtailment}(t) = E_{ex}(t) - \left[E_p^{max}(t) + E_{ch}^{max}(t)\right] \quad (4.3)$$

Where: $E_{curtailment}(t)$ is the curtailed energy; $E_p^{max}(t)$ is the maximum energy stored by the PSHP at time t; $E_{ch}^{max}(t)$ is the maximum energy charged into the BESS at time t.

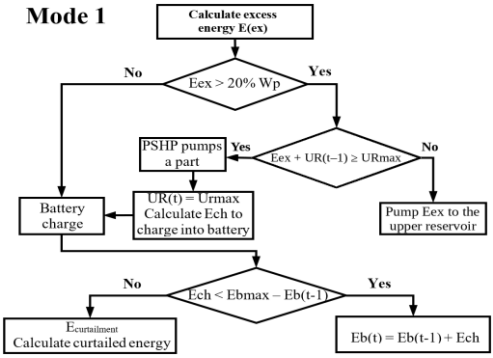


Fig. 4.2. Mode 1: Excess energy is charged into the BESS and PSHP

4.2.1.2. Insufficient energy supply to Load (E_{sh})

The system calculates the energy shortage (E_{sh}) and commands one of the storage systems (or both simultaneously) to promptly meet the load demand. After the system has checked the response capability

of the PSHP and ensured that it can fully compensate E_{sh}, discharging starts according to the following equation:

$$E_g(t) = min\left[\rho \cdot g \cdot \mu_{psh} \cdot W_g(t) \cdot H(t); E_{sh}\right] \quad (4.4)$$

Where: $E_g(t)$ is the energy delivered to the grid during time t; $W_g(t)$ is Water flow from the turbine (m^3/s)

If full compensation is not possible, the PSHP generates only part of the energy to compensate E_{sh}. The remainder is supplied by the BESS according to:

$$E_b(t) = E_b(t-1) - E_{dch}$$
$$E_{dch} = \left[\frac{Load(t)}{\eta_{inv}} - E_{res}(t) - E_g(t)\right] \cdot \eta \quad (4.5)$$

If the PSHP cannot meet E_{sh} due to the reservoir SOC or turbine power limits, the BESS acts as the last reserve to compensate the power deficit. If the total power from RES, PSHP and BESS is still insufficient to meet the load, the system must perform load shedding or dispatch reserve sources from the grid:

$$E_{deficit}(t) = E_{sh}(t) - \left[E_g^{max}(t) + E_{dch}^{max}(t)\right] \quad (4.6)$$

Where: $E_{deficit}(t)$ is the energy deficit to be met; $E_g^{max}(t)$ is the maximum energy generated by the PSHP at time t; $E_{dch}^{max}(t)$ is the maximum energy discharged by the BESS at time t.

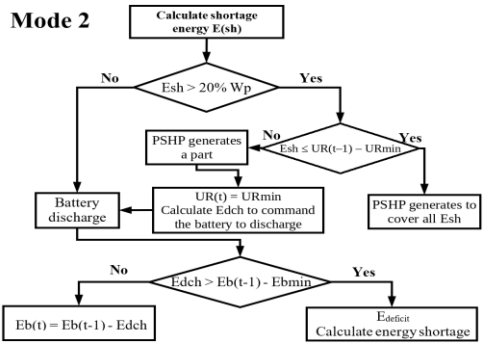


Fig. 4.3. Mode 2: PHSP–BESS system supplies power to meet Load demand

4.2.2. Energy management model

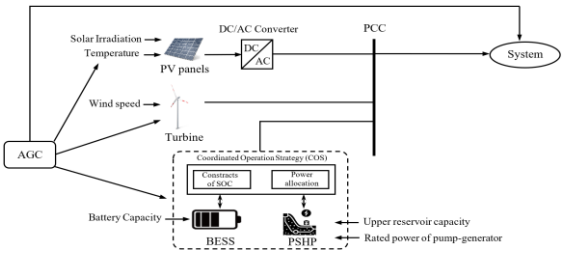


Fig. 4.4. Block diagram of the combined PV – Wind – BESS – PSHP system

4.3. Models and calculation scenarios

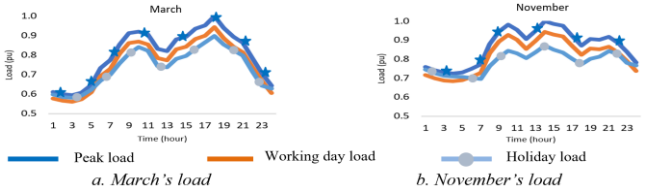
4.3.1. Calculation models

4.3.1.1. Load model

The national load is divided into 6 load regions:

Table 4.1. Load data for each region (P_{max}) – Unit: MW

Year	Northern	North Central	Central	South Central	Central Highlands	Southern
2025	25,577	3,970	3,063	3,018	1,784	24,668
2030	37,917	6,204	4,692	4,934	2,796	36,244
2035	50,618	9,073	6,362	7,095	3,812	47,972
2040	61,827	12,040	7,898	9,288	4,754	58,117
2045	70,616	14,839	9,176	11,325	5,543	65,865
2050	77,934	17,575	10,309	13,298	6,245	72,159



a. March's load *b. November's load*

Fig. 4.5. Typical load profiles (calculations use March and November data)

4.3.1.2. RES models

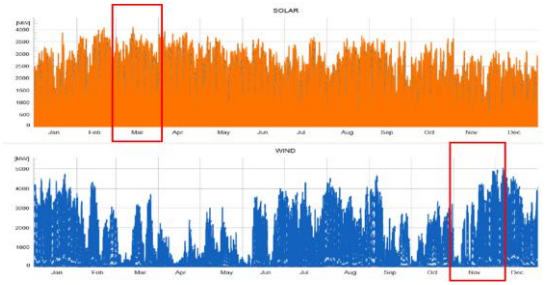


Fig. 4.6. Annual output power of the RES

Output power and energy of the RES (project area), with March and November as typical months:

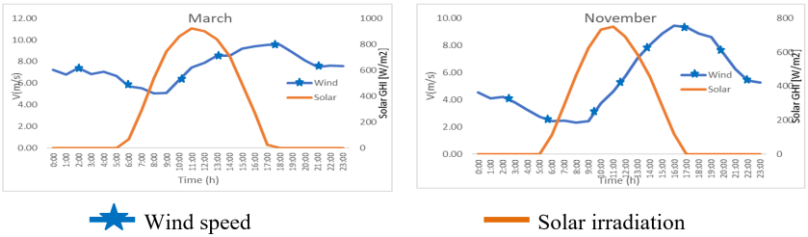


Fig. 4.7. Calculation data of the RES in Ninh Thuan area

4.3.1.3. Grid model

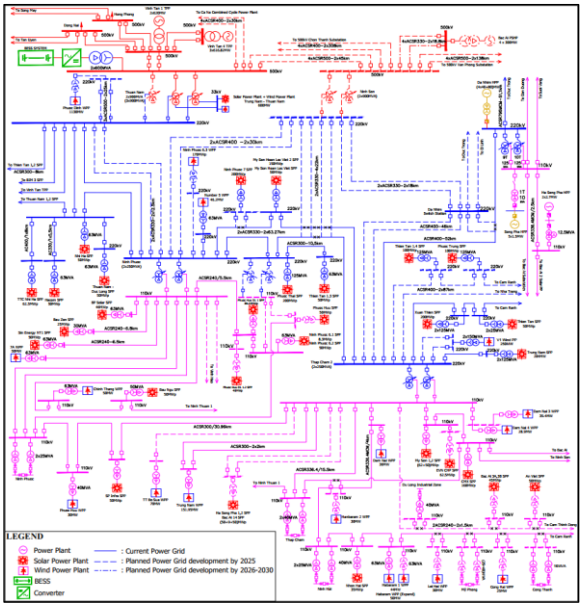


Fig. 4.8. Ninh Thuan grid diagram used for simulation in DIgSILENT

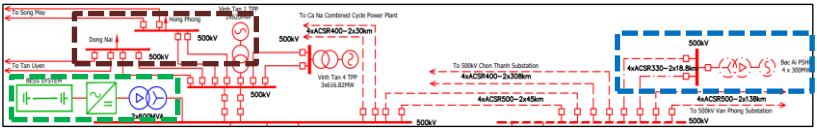


Fig. 4.9. The two studied 500 kV lines (brown), the BESS (green) and the Bac Ai PSHP (dark blue) (extracted from Fig. 4.8)

4.3.1.4. Frequency control model

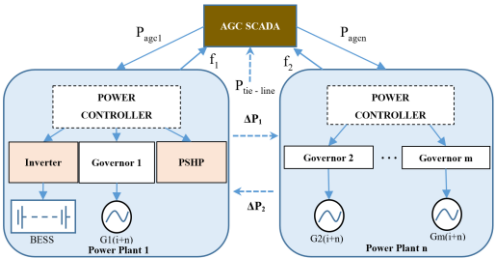


Fig. 4.10. AGC model for frequency control of the BESS – PSHP system

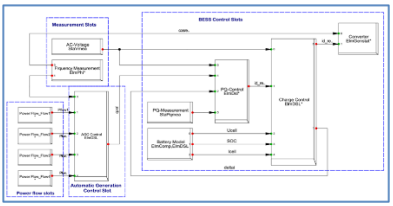


Fig. 4.11. AGC model of the BESS in DIgSILENT

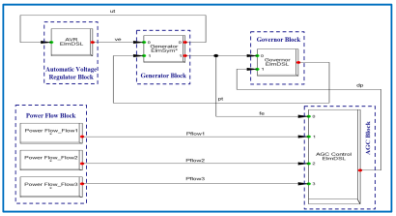


Fig. 4.12. AGC model of the PSHP in DIgSILENT

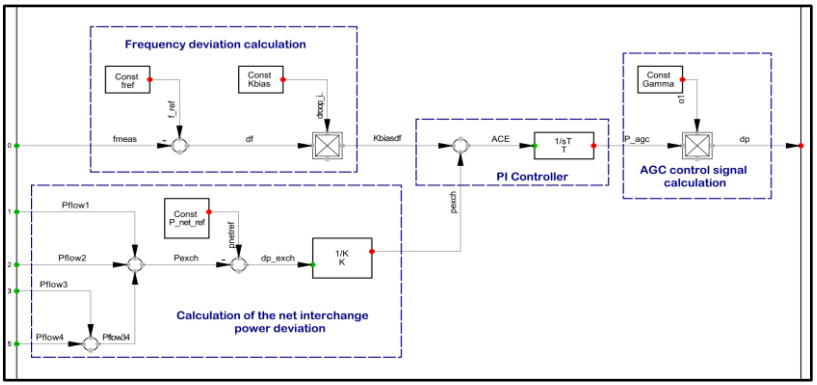


Fig. 4.13. Block diagram of the AGC model in DIgSILENT

4.3.1.5. BESS control model

The thesis uses the BESS control model presented in Chapter 2.

4.3.1.6. PSHP control model

The thesis uses the PSHP control model presented in Chapter 3.

4.3.2. Calculation scenarios

- **Scenario 1 – Grid operation with RES integration:**

❖ Without BESS – PSHP participation;

❖ With BESS – PSHP participation;

- **Scenario 2 – Temporary short-circuit fault at the 500 kV Ninh Son busbar:**

❖ Without BESS – PSHP coordination;

❖ With BESS – PSHP coordination;

4.4. Calculation results

4.4.1. Role of coordinated operation in the load profile

4.4.1.1. Results for Scenario 1

a) Without BESS and PSHP participation

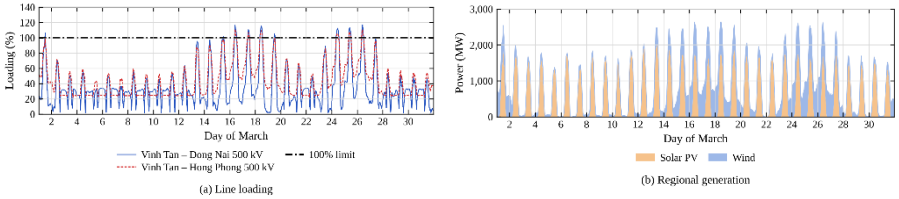


Fig. 4.14. Without BESS and PSHP – line overloading – March

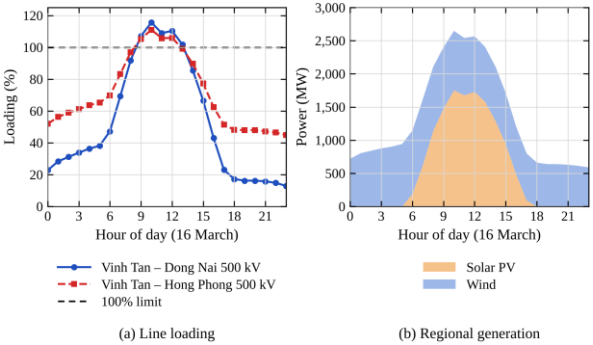


Fig. 4.15. Loading of the two studied 500kV lines – March

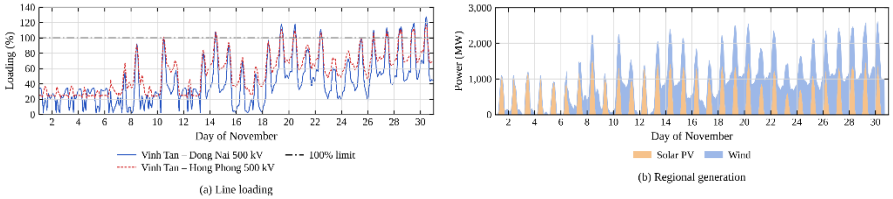


Fig. 4.16. Without BESS and PSHP – line overloading – November

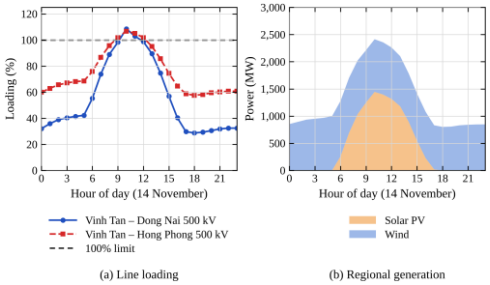


Fig. 4.17. Loading of the two studied 500kV lines – November

b) With BESS and PSHP participation

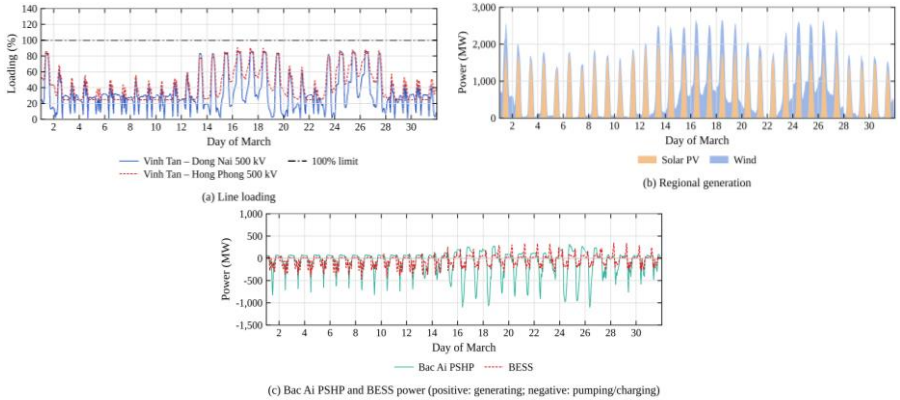


Fig. 4.18. With BESS and PSHP – no line overloading – March

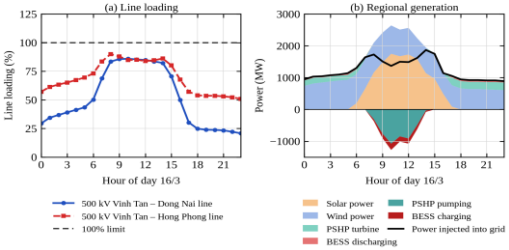
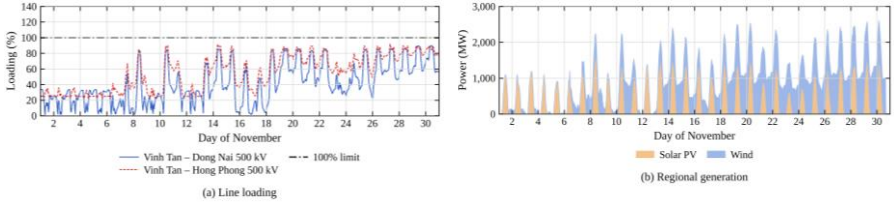


Fig. 4.19. Loading of the two studied 500kV lines – March



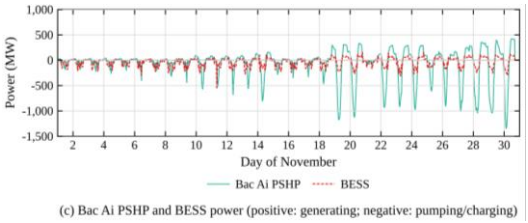


Fig. 4.20. With BESS and PSHP – no line overloading – November

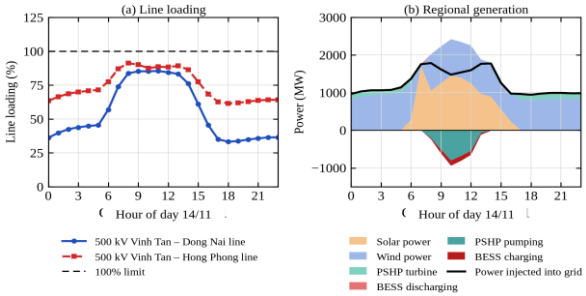


Fig. 4.21. Loading of the two studied 500kV lines – November

4.4.2. Role in grid frequency stability

4.4.2.1. Results for Scenario 2

a) Without BESS – PSHP coordination

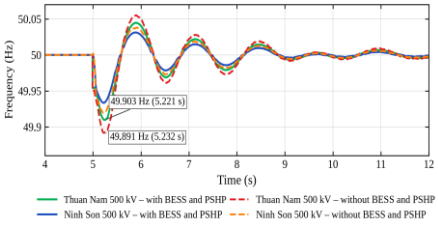


Fig. 4.22. Frequency oscillations at the 500kV busbars (up to 12 s)

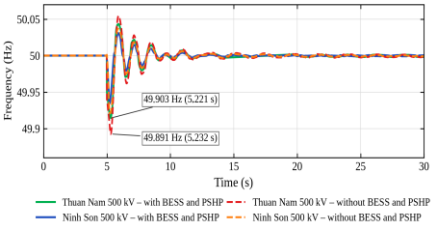


Fig. 4.23. Frequency oscillations at the 500kV busbars (up to 30 s)

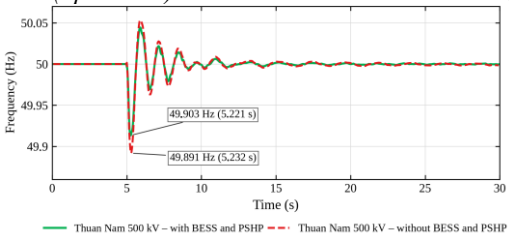
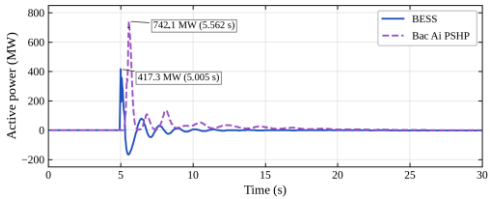
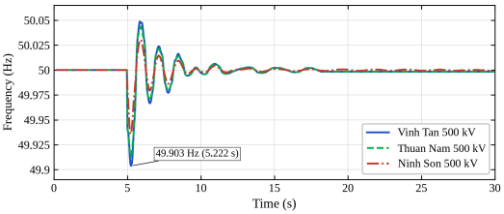


Fig. 4.24. Frequency oscillations at the 500kV Thuan Nam busbar

b) With BESS – PSHP coordination





a/ Frequency oscillations at the 500kV busbars

b/ Coordinated frequency regulation by the BESS – PSHP system

Fig. 4.25. Frequency response during frequency regulation by the BESS – PSHP

4.5. Conclusion of the chapter

CONCLUSIONS AND RECOMMENDATIONS

1. Conclusions

The thesis has studied the stable operation of power systems with a high share of RES, focusing on the effective use of two important storage types: BESS and PSHP. The main results are as follows:

- Regarding the objective of assessing the impact of RES integration on the transmission grid and frequency stability: Chapter 1 analyzes the impact of RES on system inertia, RoCoF and frequency stability, and clarifies the role of energy storage systems.
- Regarding the objective of studying solutions and control models to enhance power system stability:
  - Chapter 2 proposes a BESS control model based on adaptive nonlinear droop with SOC feedback, reducing the average RoCoF by 23 – 52%, outperforming CBEST in frequency extrema and SOC management.
  - Chapter 3 develops a multi-objective optimization algorithm and a control model for the Bac Ai PSHP to reduce operating costs and CO_2 emissions and to improve RES utilization.
  - Chapter 4 proposes the BESS – PSHP COS, eliminating the overloading of two 500 kV lines (maximum loading ≤ 91.5%) and improving the frequency response during short circuits.

The research results fully meet the stated objectives and provide a scientific and practical basis for the effective development and integration of RES in the Vietnamese power system.

Further research directions: battery capacity degradation; validation with actual operating data and HIL considering communication delays and RES forecast errors; the effect of ramp rate on the PSHP; optimal BESS siting – sizing combined with economic assessment.

2. Recommendations

Recommendations for NSMO: (i) refer to the proposed BESS control model when updating BESS grid-connection and operation regulations; (ii) incorporate the SOC operating framework and SOC feedback into BESS dispatch instructions; (iii) use the optimal pumping/generating schedule of the Bac Ai PSHP when preparing generation dispatch schedules; (iv) implement automatic BESS – PSHP coordination according to the COS in areas with high RES density such as Ninh Thuan.

Based on the results of this thesis, the following further research directions are proposed:

- Integration of other storage technologies such as hydrogen, CAES and supercapacitors.
- Application of AI and deep learning in BESS – PSHP control to increase efficiency and reduce losses.
- Study of the integration of nuclear power plants into the Vietnamese grid and assessment of their impact when operating in parallel with RES.
- Assessment of the impact of hierarchical control models on the national grid, especially in areas with high RES density such as the Central Highlands and the South Central region.

LIST OF PUBLISHED WORKS

1. **Tran Viet Thanh**, Dinh Thanh Viet, Le Cao Quyen, Le Van Dai, Nguyen Trong Hieu, *A Solution to Enhance Operational Effectiveness of the Renewable Energy Sources and Power System Transmission Lines in Vietnam*, 2022 6th International Conference on Green Technology and Sustainable Development (GTSD 2022), 29-30 Jul. 2022, Nha Trang City, Vietnam; doi: 10.1109/GTSD54989.2022. 9989150.
2. **Tran Viet Thanh**, Dinh Thanh Viet, Le Cao Quyen, Le Van Dai, Tran Quoc Tuan, *New method for secondary frequency by battery energy storage system on Viet Nam power system*, 2023 IEEE Asia Meeting on Environment and Electrical Engineering (EEE-AM), 13-15 Nov. 2023, Hanoi, Vietnam; doi: 10.1109/EEE-AM58328.2023.10395758.
3. **Tran Viet Thanh**, Dinh Thanh Viet, Le Cao Quyen, Nguyen Huu Hieu, Le Van Dai, Tran Ngoc Thao Nguyen, Le Ngo Tri Toan, *Optimal Operation of Pumped Storage Power Plant to Improve the Stability of Vietnamese Power System*, in Lecture Notes in Network and Systems, 2nd ed., vol. 1199, P. H. Yo, J. W. Wen, L. G. Hieu, and H. Q. An, Eds., NY, USA: Springer Nature, 2024, pp. 173–188. doi: 10.1007/978-3-031-76232-1_16.
4. **Tran Viet Thanh**, Le Cao Quyen, Dinh Thanh Viet, Nguyen Huu Hieu, and Le Van Dai, *Advanced frequency control strategy for power systems with high renewable energy penetration: A battery energy storage system approach,* in An International Journal of Optimization and Control: Theories & Applications ISSN: 2146-0957 eISSN: 2146-5703 (2025). doi: 10.36922/ijocta025150076.
   https://doi.org/10.36922/IJOCTA025150076.

5. **Tran Viet Thanh**, Le Cao Quyen, Tran Quoc Tuan, Le Tien Khai, Le Ngo Tri Toan, Nguyen Huu Hieu, *Coordinated operation strategy of BESS and Pumped Storage Hydropower Plant for Load curve optimization and Frequency regulation in power systems.* 2025 IEEE Asia Meeting on Environment and Electrical Engineering (EEE-AM), 05 - 07 Nov. 2025, Hanoi, Vietnam. Doi:10.1109/EEE-AM66675.2025.11473767.