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Modelling a fixed-speed pumped hydro storage system for reactive power management in power grids with high penetration of inverter-based resources: A case study of Aotearoa New Zealand

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Abstract
The increasing penetration of inverter-based renewable energy resources (IBRs) presents significant challenges to power system voltage stability and reactive power management due to the declining contribution of conventional synchronous generation. This study investigates the reactive power support capability of a fixed-speed pumped hydro storage (FS-PHS). A dynamic FS-PHS model was developed in MATLAB/Simulink based on a validated Sandia National Laboratories model and adapted to Aotearoa New Zealand operating conditions. The validated model was integrated into a modified IEEE 9-bus system operating at 220 kV transmission voltage. Load flow and electromagnetic transient studies showed that the FS-PHS unit provided effective voltage support and dynamic reactive power compensation under varying reactive loading conditions. The system successfully responded to changing network requirements while maintaining stable operation and acceptable bus voltage profiles. The findings demonstrate that FS-PHS can provide valuable ancillary services beyond energy storage, including voltage regulation and reactive power support. The technology represents a promising option for strengthening weak renewable-rich regions, such as Aotearoa New Zealand, where future system strength and voltage stability are expected to become increasingly important.

Keywords: Fixed-speed pumped hydro storage; Reactive power support; Voltage stability; Inverter-based resources

1. Introduction

Aotearoa New Zealand is at the forefront of an ambitious energy transition, targeting 100% renewable electricity generation by 2030 and net-zero greenhouse gas emissions by 2050 (Transpower, 2022). Central to achieving these goals is the widespread deployment of inverter-based renewable energy sources (IBRs), such as wind and solar photovoltaic (PV) systems. These technologies offer scalability, declining costs, and environmental benefits, making them pivotal to sustainable development (Herath et al., 2023). However, this transition introduces significant technical challenges to the stability and resilience of power systems, particularly due to the declining presence of conventional synchronous generators.

Unlike their synchronous counterparts, IBRs do not inherently provide inertia, fault current, or reactive power support. These functions are essential for maintaining voltage profiles, frequency stability, and dynamic system response. The Future Security and Resilience (FSR) report warns that the displacement of synchronous generation and increasing reliance on IBRs will fundamentally change system frequency behaviour and voltage regulation. This is especially critical in electrically weak regions of New Zealand, such as Northland, where long transmission distances, low fault levels, and limited local generation exacerbate system vulnerability (Transpower, 2025).

Traditionally, reactive power compensation has been delivered through capacitor banks, synchronous condensers, and static VAR compensators. While these technologies have served well, they often lack the dynamic flexibility and fast response needed in modern grids with high shares of renewable generation. Pumped hydro storage (PHS), long used for load balancing and frequency support, is now being recognised for its ancillary service potential, including voltage regulation. This study presents the development and validation of a dynamic fixed-speed pumped hydro storage (FS-PHS) model in MATLAB/Simulink as the foundational baseline for investigating reactive power management in grids with high IBR penetration.

1.1. Objective of the study

The increasing penetration of inverter-based renewable energy sources in Aotearoa New Zealand presents substantial challenges to grid stability, particularly in regions with low system strength and declining synchronous inertia. Fixed-speed pumped hydro storage (FS-PHS) has emerged as a promising candidate, offering enhanced frequency and voltage regulation.

The research study aims to systematically model and evaluate the reactive power capabilities of FS-PHS systems to enhance voltage stability. By focusing on reactive power, this study contributes to a detailed understanding of how next-generation storage technologies can support secure and stable electricity systems.

The objectives of this study are:

- To develop a dynamic model of a fixed-speed pumped hydro storage system in MATLAB/Simulink, incorporating governor, hydraulic turbine, synchronous machine, and excitations.
- To validate the model against expected synchronous machine behaviour under varying active and reactive power loading conditions.

2. Literature review

This study adopts a thematic, technically focused literature review approach, guided by the goal of evaluating FS-PHS as a reactive power resource in weak, IBR-rich power systems. The review identifies relevant technological advances, modelling approaches, and New Zealand-specific grid challenges to build a robust foundation for simulation modelling.

2.1. Review approach

In line with guidelines from Tranfield et al. (2003), the review process follows a structured protocol involving problem formulation, literature identification, screening, extraction, and synthesis. Inclusion criteria focus on recent studies involving dynamic modelling, control of hydro storage, and reactive power in weak or renewable-heavy grids. Exclusion criteria eliminate purely economic or market-based studies that lack a technical component. This methodology ensures that the literature review is grounded in empirical evidence and contributes directly to simulation-based system modelling.

The review draws on both academic literature and grey literature (technical reports, government documents, and industry publications). Databases used include IEEE Xplore, ScienceDirect, Scopus, and Google Scholar, using keywords such as "Fixed-speed pumped hydro storage," "reactive power support," "inverter-based resources," "weak grids," and "voltage stability." The use of these databases is consistent with best practices for systematic literature reviews in engineering (Kitchenham and Charters, 2007).

2.2. Impacts of high IBR penetration on grid strength and voltage control

While these resources offer low-cost, clean energy, their intermittent, volatile, and unpredictable nature poses significant challenges to the reliable and stable operation of the power grid (Ye et al., 2021). One of the primary impacts of high IBR penetration is the reduction in system inertia (Maharjan et al., 2023). Conventional synchronous generators inherently provide inertia, which helps maintain grid frequency stability. However, IBRs are connected to the grid via power electronic converters, which decouple them from the host AC system and prevent them from inherently contributing to inertial response (Reigstad and Uhlen, 2021). This reduction in synchronous generation leads to a decrease in grid strength, making the grid weak (Saleem et al., 2023).

Weak grid conditions present several critical issues:

- Voltage Stability: Under weak grid conditions, the grid voltage becomes sensitive to active and reactive power disturbances, potentially leading to voltage stability issues and risks of voltage collapse (Adetokun and Muriithi, 2021). The depletion of synchronous generators directly relates to a decrease in the grid's short-circuit level, which can compromise voltage stability. Studies show that increased IBR penetration and their location can affect grid strength and voltage stability (Saleem et al., 2023).
- Frequency Stability: The reduction in inertia directly degrades frequency stability, as the system loses its natural ability to quickly respond to power imbalances (Vasudevan et al., 2021).
- Reactive Power Management: High renewable power penetration affects reactive power, provoking steady-state voltage and dynamic or transient stability issues. Adequate reactive power reserve is imperative for a stable and reliable power grid (Sarkar et al., 2018).

2.3. Pumped hydro storage – fundamentals for grid support

Pumped hydro storage (PHS) is a mature, commercially available, and proven technology that has been integral to power systems for many years (Koritarov et al., 2022). It represents the largest utility-scale energy storage capacity in the United States, accounting for approximately 22 GW, or 93% of all utility-scale energy storage in 2021 (Jimenez Aparicio et al., 2022). Globally, PHS systems represent 3% of total installed electricity generation capacity and 99% of electricity storage capacity (Nikolaos et al., 2023).

The fundamental principle of PHS (see Figure 1) involves using an upper and a lower reservoir to store water. In pumping mode (low demand periods), electrical energy is absorbed from the grid to pump water from the lower to the upper reservoir, storing energy as gravitational potential energy. In generating mode (high demand periods), water flows from the upper to the lower reservoir, driving a hydro turbine to generate electricity (Nasir et al., 2015). PHS plants can operate in an open-loop configuration, utilising a naturally flowing water body as a lower reservoir, or in a closed-loop configuration with two independent reservoirs (Nikolaos et al., 2023).

PHS provides a multitude of benefits and services to the grid, including:

- Energy Storage: PHS offers large amounts of energy storage to store surplus variable renewable energy (VRE) generation and provide energy generation when needed (Koritarov et al., 2022). PHS systems boast exceptional operational efficiency, with a round-trip efficiency of 70–85% and generally negligible self-discharge (Nikolaos et al., 2023).
- Frequency Regulation: PHS contributes to frequency regulation, especially important as synchronous generation decreases (Nobile et al., 2018). It offers fast response capabilities to rectify temporary power imbalances (Muljadi et al., 2021).

- Reactive Power Support and Voltage Regulation: PHS can provide reactive power compensation and voltage support (Ye et al., 2021).
- Renewable Energy Integration: PHS acts as a force multiplier for other renewable power generation sources, enabling larger penetration of VRE by compensating for their variability and uncertainty (Muljadi et al., 2021).

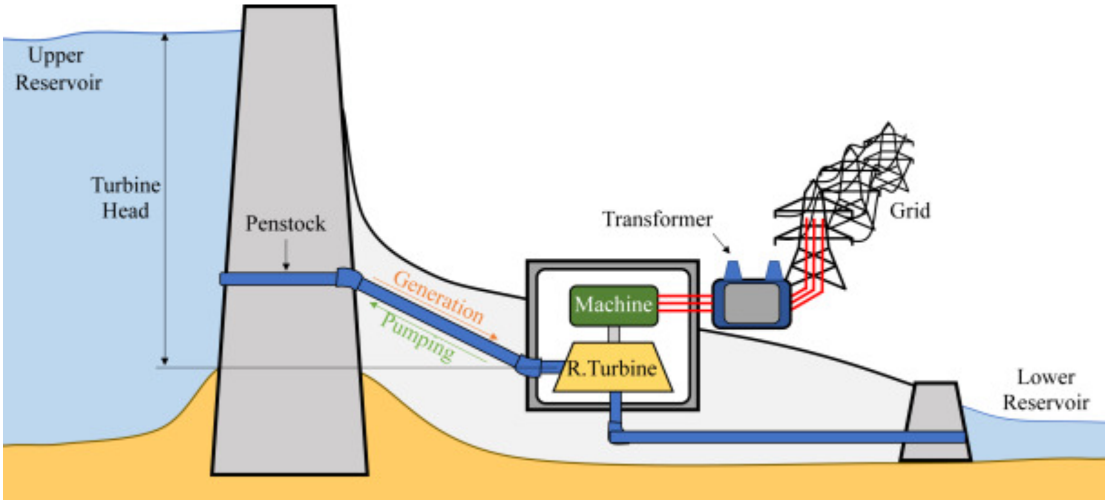

Figure 1. Schematic configuration of a pumped hydroelectric plant
(Source: García et al., 2022)

2.4. Fixed-speed pumped hydro storage characteristics

A typical FS-PHS plant consists of a hydraulic turbine, governor, excitation system, and synchronous generator. The governor regulates the mechanical power delivered by the turbine, while the excitation system controls the generator terminal voltage through adjustment of rotor field current. In generating mode, the governor contributes to active power and frequency regulation, whereas the excitation system enables reactive power support and voltage regulation (Muljadi et al., 2021). The direct connection of the synchronous machine to the power system enables FS-PHS units to contribute electromechanical inertia, fault current support, voltage regulation, and reactive power control, which are valuable in modern power systems experiencing higher penetration of inverter-based renewable generation. Unlike inverter-based generation, synchronous machines inherently store kinetic energy within their rotating masses. This stored energy provides inertia that helps resist rapid frequency changes during disturbances. Furthermore, synchronous generators contribute significant short-circuit current during fault conditions, improving protection system performance and enhancing system strength (Rezkalla et al., 2018).

Reactive power capability is one of the most important characteristics of synchronous generators and plays a fundamental role in maintaining voltage stability within electrical power systems. Unlike inverter-based resources, which often require additional control systems to provide voltage support, synchronous generators can inherently generate or absorb reactive power through excitation control (Muljadi et al., 2021). The reactive power output of a synchronous generator depends primarily on the level of field excitation. Increasing the field current increases the internal generated voltage of the machine, causing it to operate in an over-excited condition and supply reactive power to the network. Conversely, reducing field excitation causes the machine to operate in an under-excited condition, resulting in reactive power absorption from the grid. The operating limits of a synchronous generator are commonly represented by a capability curve, which defines the permissible combinations of active and reactive power output. These limits are constrained by stator current ratings, rotor field current limits, armature heating effects, and steady-state stability requirements (Flores et al., 2023). Alizadeh Bidgoli et al. (2020) demonstrated that conventional synchronous-machine-based pumped hydro plants can provide substantial reactive power support within their operational limits. This capability allows FS-PHS facilities to contribute not only to energy storage and active power balancing but also to voltage regulation and ancillary service provision.

Voltage regulation in fixed-speed pumped hydro storage plants is achieved through the excitation system associated with the synchronous generator. The excitation system controls the generator field current and therefore directly influences both terminal voltage and reactive power output. In a conventional FS-PHS plant, the Automatic Voltage Regulator (AVR) continuously measures terminal voltage and compares it with a predefined reference value. Any deviation between the measured voltage and reference voltage generates an error signal that adjusts the excitation voltage supplied to the field winding. An increase in excitation results in a higher internal electromotive force, enabling the machine to generate additional reactive power and support system voltage. Conversely, a reduction in excitation decreases reactive power output and may cause the machine to absorb reactive power from the network (Muljadi et al., 2021).

2.5. Fixed-speed pumped hydro storage in the context of New Zealand

Aotearoa New Zealand's electricity sector is undergoing a significant transformation driven by ambitious climate change goals: reaching net zero for long-lived gases by 2050 and an aspirational target of 100% renewable electricity by 2030. This commitment entails increasing renewable generation and reducing reliance on fossil fuels, which will lead to a substantial growth in electricity demand (Transpower, 2023).

New Zealand's power system stretches over a long transmission network, with potential renewable energy resources often located in remote regions (e.g., Northland, Taranaki, Wairarapa, Hawkes Bay, West Coast, Southland). This geographical characteristic imposes challenges when incorporating high penetration of IBRs. Many connection points in these regions are considered weak, posing stability challenges for IBR integration. The Northland region is highlighted as a perfect study case due to its reliance on generation transmitted from other regions, limited local generation, and existing need for reactive power compensation (Transpower, 2023). Transpower's Future Security and Resilience (FSR) Programme identifies potential security and resilience opportunities and challenges arising from future changes in technologies and system use. Investigations are being carried out to understand the performance of different inverter technologies (grid-following vs. grid-forming) in the Aotearoa New Zealand power system context (Transpower, 2025).

Although modern inverter-based resources can provide reactive power support through converter control, their performance is ultimately constrained by converter ratings, current limits, and operating conditions. So, maintaining adequate sources of dynamic reactive power support remains an important requirement for future system operation. The ability of synchronous generators to generate or absorb reactive power makes FS-PHS a valuable technology for supporting voltage regulation in renewable-rich regions of the country. Through AVR-based excitation control, FS-PHS plants can respond dynamically to changing network conditions and assist in maintaining bus voltages within acceptable operating limits (Alizadeh Bidgoli et al., 2020).

3. Research methods

This section presents the methodology adopted to develop, validate, and assess a fixed-speed pumped hydro storage (FS-PHS) system for reactive power support applications. The study involved the development of an FS-PHS model in MATLAB/Simulink, validation through reactive power capability assessment, and integration into a modified IEEE 9-bus network to evaluate its impact on voltage regulation and reactive power management under varying operating conditions.

3.1. Research approach

This research adopted a simulation-based methodology to investigate the reactive power support capability of a fixed-speed pumped hydro storage (FS-PHS) system and evaluate its effectiveness in improving voltage regulation under varying network conditions. MATLAB/Simulink was selected as the primary simulation platform due to its extensive library of power system components and its ability to perform both steady-state and electromagnetic transient (EMT) studies. The study was conducted in three main stages. First, a fixed-speed pumped hydro storage model was developed based on a previously validated model reported by Sandia National Laboratories. Then, the reactive power capability of the developed FS-PHS model was assessed using a test network connected to an infinite bus. Finally, the FS-PHS system was integrated into a modified IEEE 9-bus transmission network to evaluate its performance under representative grid operating conditions.

3.2. Development of the fixed-speed pumped hydro storage model

The FS-PHS model developed in this study is based on the fixed-speed pumped hydro storage model presented by Jimenez Aparicio et al. (2022). The model consists of hydraulic, mechanical and electrical subsystems representing the dynamic behaviour of a conventional fixed-speed pumped hydro storage plant (see Figure 2).

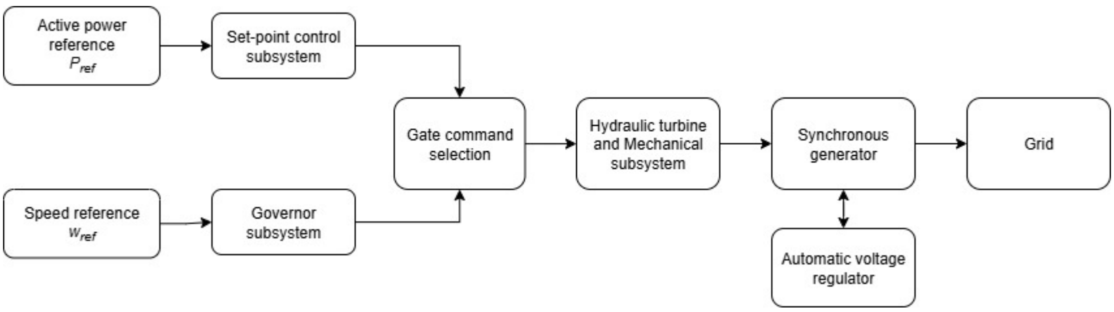

Figure 2. Block diagram representation of the developed system

The main inputs to the model are, active power reference signal (P_{ref}) and rotor speed reference signal (w_{ref}). The model outputs include active power output, reactive power output, terminal voltage, stator current and rotor speed.

The final FS-PHS model consisted of four major subsystems:

- Set-point control subsystem
- Governor subsystem
- Mechanical subsystem
- Electrical subsystem

3.2.1. Set-point control subsystem

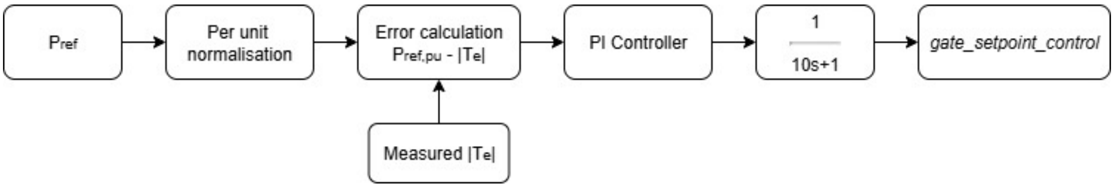

Figure 3. Block diagram representation of set-point control subsystem

The setpoint control subsystem (Figure 3) is responsible for generating the turbine gate position reference required to achieve the desired operating power level of the pumped hydro storage system. The subsystem processes the active power reference signal and compares it with the measured electromagnetic torque of the synchronous machine. The primary objective of this subsystem is to regulate the turbine gate opening such that the generated electrical power follows the desired reference value. The subsystem provides an additional layer of supervisory control before the governor subsystem acts on the speed error signal.

The setpoint control subsystem receives two input signals:

- Active power reference (P_{ref})
- Rotor speed reference (w_{ref})

The reference power signal (P_{ref}) represents the desired operating power level of the pumped hydro storage unit. The active power reference is normalised using the machine rated power base. The model uses a gain block represented by the reciprocal of $FS\_PSH.Sn$, where $FS\_PSH.Sn$ represents the rated apparent power of the synchronous machine.

The measured electromagnetic torque signal (T_e) from the electrical subsystem is converted into its absolute value and compared with the power reference signal. The error signal is then passed through a proportional-integral controller. The PI controller reduces steady-state error and improves transient response. The controller output is subsequently passed through a first-order transfer function represented by the reciprocal of $10s + 1$. This transfer function introduces a dynamic lag into the control system and represents the physical response limitations associated with turbine gate actuation mechanisms. The final output of the subsystem is the gate position reference signal, $gate\_setpoint\_control$, which is sent to the mechanical subsystem.

During operation, the active power reference signal determines the desired machine operating point. The measured electromagnetic torque from the synchronous machine acts as a feedback signal representing the actual electrical loading condition of the machine. If the electrical power output deviates from the desired reference value, an error signal is generated. The PI controller processes this error and modifies the turbine gate opening command accordingly. An increase in gate opening allows greater water flow through the hydraulic turbine, resulting in increased mechanical torque and electrical power output. Conversely, a reduction in gate opening decreases the mechanical power supplied to the synchronous machine. The setpoint control subsystem therefore acts as the supervisory active power regulation mechanism within the system.

3.2.2. Governor subsystem

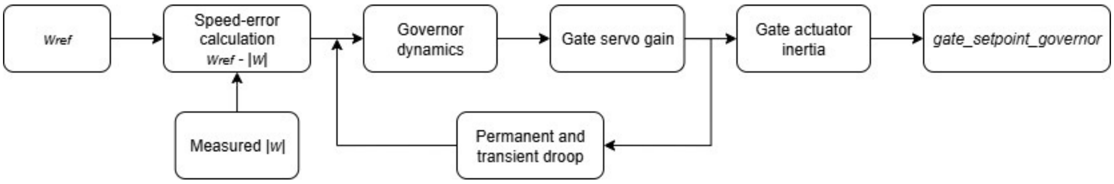

Figure 4. Block diagram representation of governor subsystem

The governor subsystem regulates turbine gate position based on rotor speed deviation (see Figure 4). The governor plays an important role in maintaining machine speed stability and ensuring proper frequency response during disturbances. The governor continuously compares the machine rotor speed with the reference speed value and adjusts the turbine gate position to minimise speed deviation. The governor subsystem receives two input signals:

- Rotor speed reference (w_{ref})
- Measured rotor speed (w)

The measured rotor speed signal is first processed using an absolute value block, $|w|$. This allows the governor to operate correctly under both generating mode and pumping mode. The measured speed is continuously compared with the reference synchronous speed, w_{ref} , which is normally maintained at 1.0 pu for nominal synchronous operation. The first stage of the governor computes the speed deviation signal. The speed error is passed through the governor dynamic transfer function which is the reciprocal of $FS\_PSH.T_p s + 1$. This block represents the dynamic response of the hydraulic pilot valve and governor control mechanism. The parameter $FS\_PSH.T_p$, is the governor time constant that models actuator inertia, pilot valve delay, and mechanical governor dynamics. The governor model includes permanent droop feedback represented by the gain, $FS\_PSH.R_p$. The droop mechanism establishes the steady-state relationship between frequency deviation and active power output. Permanent droop prevents multiple generators from competing aggressively for frequency regulation. With droop control, load changes are shared proportionally among generators, and stable power sharing is achieved. The implemented governor also includes transient droop compensation using $FS\_PSH.R_t$ and $FS\_PSH.T_r$. The transient droop loop temporarily modifies governor sensitivity during fast system disturbances.

The governor output is multiplied by $FS\_PSH.Q$, which represents the gate servo gain or flow gain. The resulting signal passes through gate limits, integrator and additional saturation blocks. The saturation blocks enforce physical operating constraints on wicket gate motion, preventing excessive gate opening, negative gate positions or unrealistic water flow rates. The integrator block converts gate velocity into gate position. This represents the physical movement of the hydraulic gate actuator over time. The integrator ensures that gate movement occurs continuously rather than instantaneously, catering to accurate modelling of real hydro-mechanical gate systems.

The final gate signal passes through another first-order transfer function which is the reciprocal of $FS\_PSH.T_g s + 1$. This block represents, gate actuator inertia and mechanical gate movement dynamics. The parameter $FS\_PSH.T_g$, defines the gate actuator time constant. This delay is introduced because hydro wicket gates require finite time to move.

The final output of the subsystem is z ($gate\_setpoint\_governor$). This signal determines wicket gate opening, hydraulic water flow, turbine torque and mechanical power production. The gate position directly influences the amount of water entering the turbine.

The governor continuously monitors machine rotor speed during simulation. When electrical loading increases suddenly, the synchronous machine rotor speed tends to decrease due to increased electromagnetic torque demand. The governor detects this speed reduction and increases turbine gate opening. The increased gate opening allows greater water flow into the turbine, increasing mechanical power production and restoring rotor speed toward its reference value. Similarly, if the rotor speed rises above the reference value, the governor reduces turbine gate opening to decrease mechanical power input. The governor therefore acts as the primary frequency stabilisation mechanism within the fixed-speed pumped hydro storage system.

3.2.3. Mechanical subsystem

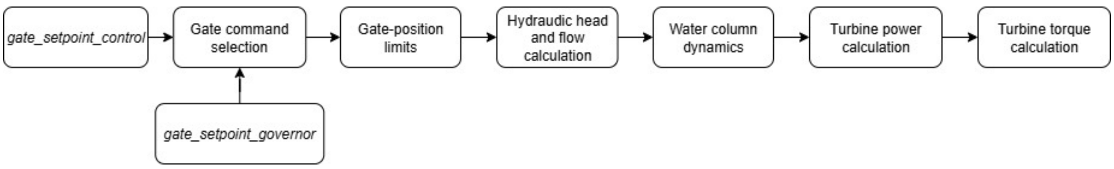

Figure 5. Block diagram representation of mechanical subsystem

The mechanical subsystem of the FS-PHS model represents the hydraulic and mechanical energy conversion process occurring between the governor system and the synchronous generator (see Figure 5). The purpose of this subsystem is to convert hydraulic energy into mechanical torque, model hydraulic turbine dynamics, represent water inertia effects, calculate turbine mechanical power and provide shaft torque to the synchronous machine. The subsystem receives gate opening commands from the setpoint controller and governor controller, and converts them into hydraulic flow, turbine head, mechanical power, and shaft torque. This subsystem therefore forms the electromechanical coupling between hydraulic control and electrical power generation.

The subsystem receives two gate position commands:
- Gate position from setpoint control ($gate\_setpoint\_control$)
- Gate position from governor ($gate\_setpoint\_governor$)

These signals are combined before being applied to the turbine model. This ensures power control operation and speed regulation operation. The setpoint controller regulates desired active power. The governor regulates rotor speed stability. Both controllers influence the final hydraulic gate position. The resulting gate signal determines water flow entering the turbine. The combined gate signal passes through a saturation block. This block limits the allowable gate opening range. The saturation block prevents unrealistic negative gate positions, excessive gate opening or physically impossible hydraulic conditions. The wicket gate opening is therefore constrained within practical operating limits, $z\_min \leq z \leq z\_max$.

The turbine model receives three input signals:
- Gate position (z)
- Rotor speed (w)

- Reference speed (w_{ref})

The turbine block generates the output, T_mech, which represents turbine mechanical torque. The hydraulic head represents the effective pressure energy available to the turbine. Hydraulic head determines the amount of energy transferred from water to the turbine. One of the most important dynamic characteristics of hydro turbines is water inertia. The model includes this behaviour using integrators, dynamic gain blocks, and feedback loops. The turbine model contains an integrator which represents water column dynamics. Water inside long penstocks possess large inertia. Therefore, water flow cannot change instantaneously, turbine power response becomes slower and oscillatory hydraulic behaviour may occur.

The turbine model compares the actual hydraulic head with the nominal head. The resulting deviation is integrated dynamically to represent pressure transient behaviour, hydraulic energy storage, and flow oscillations. The model includes a no-load flow term, $FS\_PSH.qNL$. This represents the minimum hydraulic flow required to keep the turbine rotating even under very low power conditions. Water flow never becomes exactly zero during operation. The turbine power coefficient, A_t, represents the turbine energy conversion efficiency. This gain converts hydraulic power into mechanical power.

The turbine mechanical power is approximately:

$$P_{mech} \propto A_t \times q \times h \quad (1)$$

where:

q= water flow
h= hydraulic head

The turbine model also includes rotor speed deviation feedback. This speed deviation influences turbine mechanical power production. When rotor speed changes, turbine loading characteristics also change. The model therefore includes damping compensation using a gain. This damping term improves electromechanical stability, oscillation damping and transient response.

The turbine model calculates the mechanical power, P_{mech}, using hydraulic variables and damping compensation. The generated power depends on gate opening, hydraulic flow, water head and rotor speed. The final turbine mechanical torque is calculated as:

$$T_{mech} = \frac{P_{mech}}{w} \quad (2)$$

where:

T_mech= mechanical shaft torque,
P_mech= mechanical power,
w= rotor speed.

The final turbine power output is calculated by multiplying turbine mechanical torque with rotor speed. The subsystem output is, $Turb\_Power$, which represents the total turbine mechanical power supplied to the synchronous generator.

3.2.4. Electrical subsystem

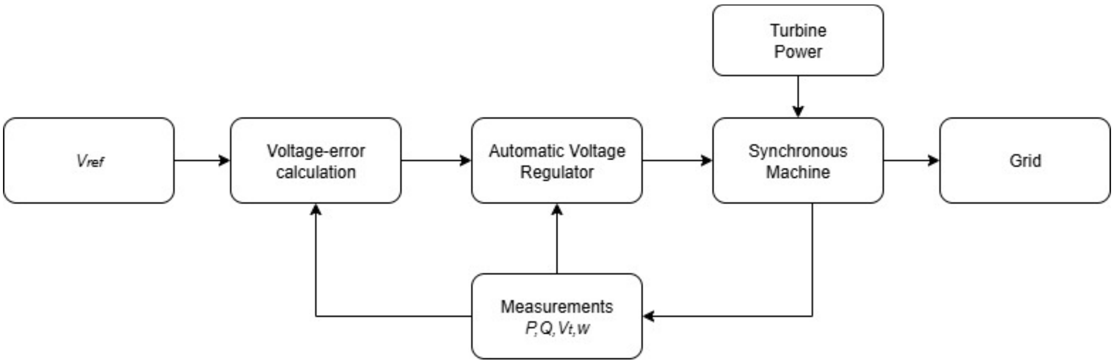

Figure 6. Block diagram representation of electrical subsystem

The electrical subsystem of the fixed-speed pumped hydro storage model represents the electrical energy conversion stage of the system (see Figure 6). This subsystem converts the mechanical power produced by the hydraulic turbine into electrical power supplied to the grid during generating operation or absorbs electrical power during pumping operation. The subsystem also regulates machine terminal voltage and reactive power exchange through excitation control.

The electrical subsystem consists primarily of:

- Synchronous machine
- Automatic voltage regulator (AC1A type excitation system)
- Measurement interfaces

The subsystem receives mechanical turbine power and electrical feedback signals, and generates terminal voltage, active power, reactive power, stator currents, and field excitation voltage.

The synchronous machine was rated at:

- Rated Power: 125 MVA
- Active Power Rating: 100 MW
- Terminal Voltage: 11 kV
- Frequency: 50 Hz
- Rotor Type: Salient pole
- Number of Poles: 2

The synchronous machine receives:

- Mechanical power input (P_m) from turbine
- Excitation voltage (V_f) from AC1A excitation system

The synchronous machine converts turbine mechanical power into electrical power while simultaneously providing reactive power support through excitation control. The turbine provides shaft torque, while the excitation system controls electromagnetic field strength. Inside the synchronous machine, the rotor magnetic field rotates at synchronous speed, stator windings generate three-phase AC voltage and electromagnetic torque is developed.

The AVR continuously monitors terminal voltage and adjusts field excitation voltage accordingly. The excitation system used in this model is the IEEE Type AC1A excitation system. The excitation system dynamically controls the field voltage (E_{fd}) applied to the synchronous generator rotor winding. The excitation system receives three inputs, reference voltage (V_{ref}), terminal voltage (V_t) and field current (I_{fd}). The AVR computes the voltage regulation error. If terminal voltage drops ($V_t < V_{ref}$), excitation increases, rotor magnetic field strengthens, reactive power injection increases and terminal voltage recovers. If terminal voltage rises, excitation reduces, reactive power output decreases.

The core AVR regulator is represented by the transfer function:

$$\frac{K_a}{T_a s + 1} \tag{3}$$

where:

K_a= AVR gain,
T_a= AVR time constant.

The regulator output passes through saturation limits. These limits represent physical exciter constraints representing its inability to produce infinite field voltage. The exciter dynamics transfer function block represented by the reciprocal of $T_e s$, models exciter magnetic dynamics, field winding response and exciter delay. The output is the internal exciter voltage, V_e. The excitation system includes a magnetic saturation block which models nonlinear magnetic behaviour. The subsequent rectifier block converts exciter AC voltage into DC field voltage. The rectifier output is F_{ex}, which contributes to field excitation voltage generation. The final excitation voltage is E_{fd}. This voltage is applied to the synchronous machine rotor winding.

The AVR therefore enables the synchronous machine to support grid voltage stability. This behaviour forms the basis of reactive power support capability in the fixed-speed pumped hydro storage system.

3.3. Model validation

3.3.1. Reactive power capability assessment

Following model development, a simplified test network was constructed to evaluate the reactive power support capability of the FS-PHS system.

The test network consisted of (see Figure 7, and the supplementary material):

- FS-PHS unit
- 11/220 kV transformer
- Variable load
- Infinite bus (represented using a three-phase AC voltage source operating at 220 kV)

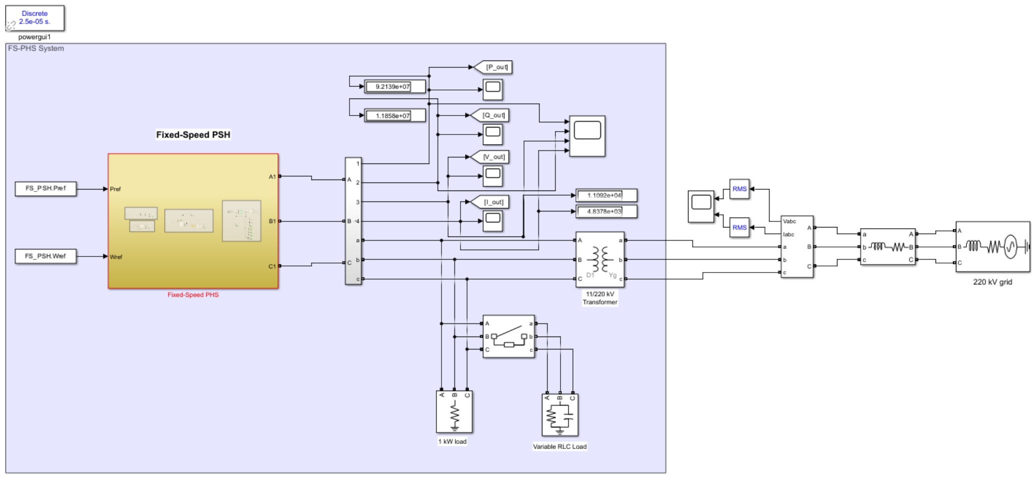

Figure 7. Simulink implementation of FS-PHS in the test network used for capability assessment

The purpose of this investigation was to determine the reactive power operating limits of the FS-PHS system and evaluate its response under different loading conditions. A constant active power load of 300 MW was connected to the system. The reactive power demand of the load was then varied systematically by changing inductive and capacitive reactive power components. The load was connected at (t = 60) seconds and removed at (t = 120) seconds within a total simulation period of 180 seconds.

For each simulation case, the following quantities were recorded:

- Active power output
- Reactive power output
- Terminal voltage
- Stator current

Sensitivity analysis was performed by varying reactive load demand and observing the resulting reactive power output of the synchronous generator. The results were then compared against the theoretical generator capability limits.

3.3.2. Modified IEEE 9-bus system development

Following validation of the standalone FS-PHS model, the system was integrated into a modified IEEE 9-bus transmission network (see Figure 8, and the supplementary material). The IEEE 9-bus system was selected due to its simplicity, widespread acceptance within power system research and suitability for evaluating power system dynamic behaviour (Anwar et al., 2020). Several modifications were made to the original IEEE 9-bus configuration to better represent Aotearoa New Zealand operating conditions:

- System frequency changed to 50 Hz
- Generator bus voltages changed to 11 kV
- Transmission voltage levels changed to 220 kV
- Transformer ratings adjusted accordingly

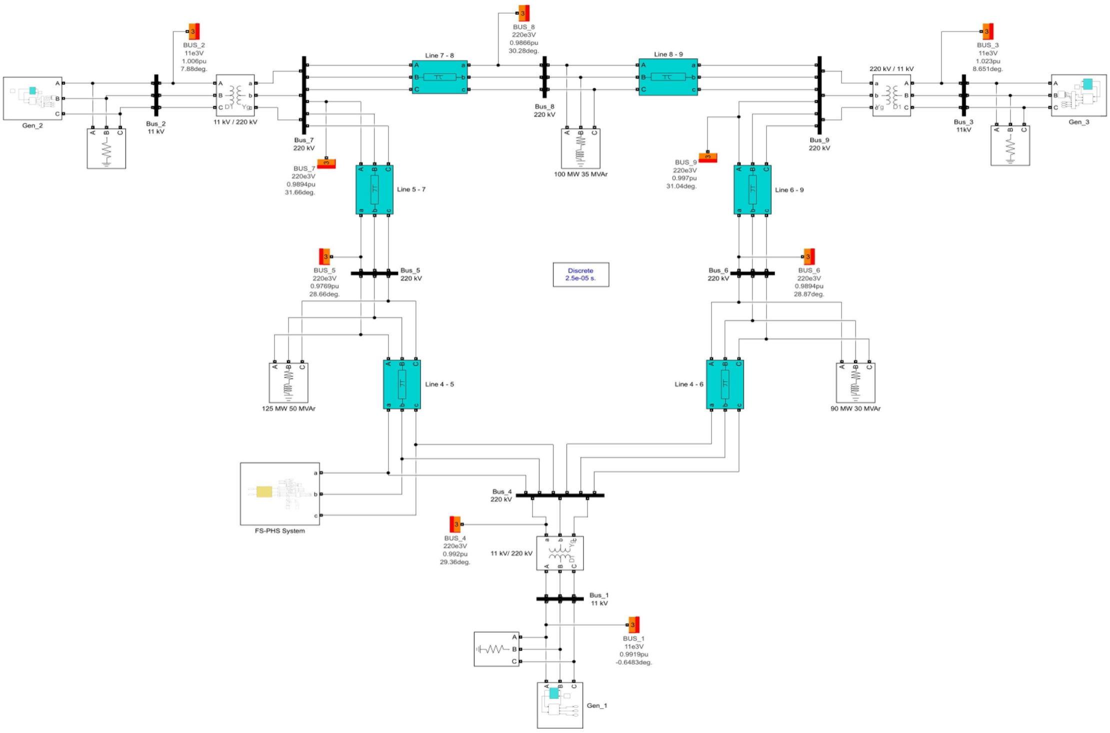

Figure 8. Simulink implementation of modified IEEE 9 bus network with FS-PHS connected at bus 4

To evaluate system-level performance, the FS-PHS unit was connected at Bus 4 of the modified IEEE 9-bus network. When the FS-PHS unit was connected, Generator 1 was removed from service and replaced by the pumped hydro unit. This approach allowed the contribution of the FS-PHS system to be directly assessed while maintaining overall system structure. Bus 4 was selected because it provided a suitable location for evaluating voltage support and reactive power exchange between the FS-PHS unit and the wider transmission network. Bus 5 was selected as the primary study bus because its reactive loading could be varied to create voltage regulation challenges, allowing the effectiveness of the FS-PHS unit to be assessed.

3.3.3. Load flow and electromagnetic transient studies

Load flow analysis was conducted to determine the steady-state operating conditions of the modified IEEE 9-bus network.

Load flow simulations were performed for:

- Base case (without FS-PHS)
- FS-PHS connected case

The calculated bus voltages, active power flows and reactive power flows were used to assess the impact of FS-PHS integration on overall network performance.

Electromagnetic transient (EMT) simulations were performed using MATLAB/Simulink to investigate the dynamic behaviour of the modified IEEE 9-bus system following changes in network reactive power demand. The FS-PHS unit was connected at Bus 4, while Generator 1 was removed from service to facilitate direct assessment of the pumped hydro unit. Reactive power demand at Bus 5 was systematically varied while maintaining constant active power loading. This approach enabled evaluation of the ability of the FS-PHS system to respond to changing reactive power requirements and maintain acceptable voltage levels within the network.

The following quantities were monitored during each simulation:

- Bus voltages
- Active power output of the FS-PHS unit
- Reactive power output of the FS-PHS unit
- Generator terminal voltages

Simulation results obtained from the base case and FS-PHS-connected case were subsequently compared to assess the effectiveness of the pumped hydro system in supporting voltage regulation and reactive power management under varying loading conditions.

4. Results and discussion

This section presents the results obtained from the standalone FS-PHS capability assessment and the modified IEEE 9-bus integration study. The results are first used to evaluate the active-power, reactive-power, voltage and current responses of the developed model. The effects of FS-PHS integration and increasing reactive demand are then examined and discussed.

4.1. Reactive power capability assessment of the FS-PHS system

Following the development of the fixed-speed pumped hydro storage model, a series of simulations were conducted to evaluate its reactive power support capability. The objective of these studies was to determine the operational reactive power limits of the synchronous generator and assess its response under varying reactive loading conditions.

Under normal operating conditions, the synchronous generator operated at approximately 100 MW active power output while maintaining terminal voltage close to its rated value of 11 kV. The infinite bus supplied the remaining active-power requirement and network losses. Prior to the application of additional reactive loading, the generator produced approximately 12.61 MVAr of reactive power. This operating point served as the reference condition for subsequent sensitivity studies. The observed operating characteristics confirmed that the governor system successfully maintained active power output while the excitation system regulated terminal voltage through reactive power control.

The first set of simulations investigated the response of the FS-PHS system under increasing capacitive loading conditions (see Figure 9 and 10). Capacitive reactive loads reduce the reactive power demand imposed on the synchronous generator and may require the machine to absorb reactive power to maintain voltage regulation. As the capacitive component of the connected load increased, the reactive power output of the synchronous generator progressively decreased and became negative. The simulation results showed that the generator was capable of absorbing approximately 75 MVAr of reactive power before reaching its operational limit. The minimum reactive power observed during the study was approximately -75.14 MVAr. This behaviour is consistent with the theoretical capability of a 125 MVA synchronous generator operating at approximately 100 MW active power output.

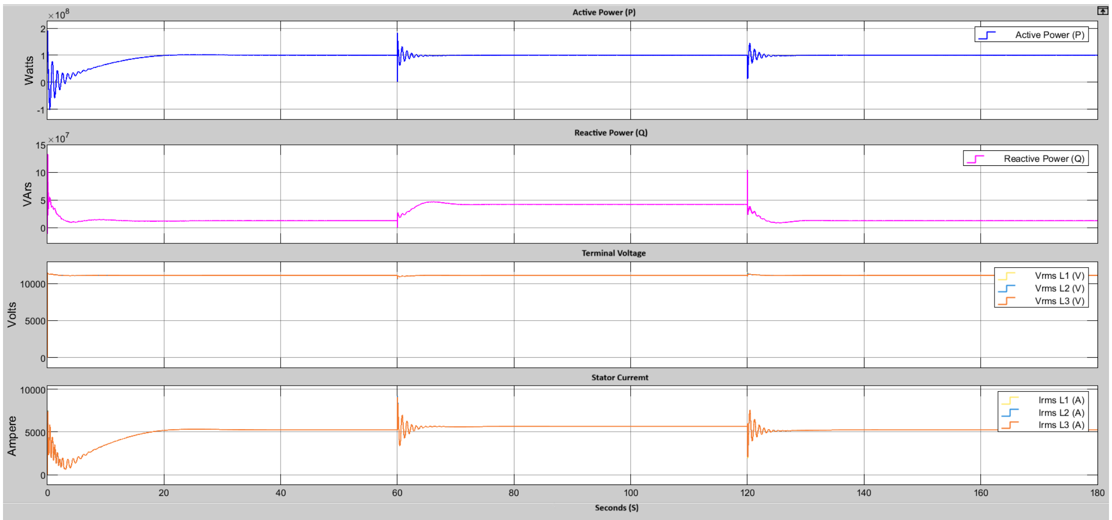

Figure 9. FS-PHS dynamic response under 300 MW network load

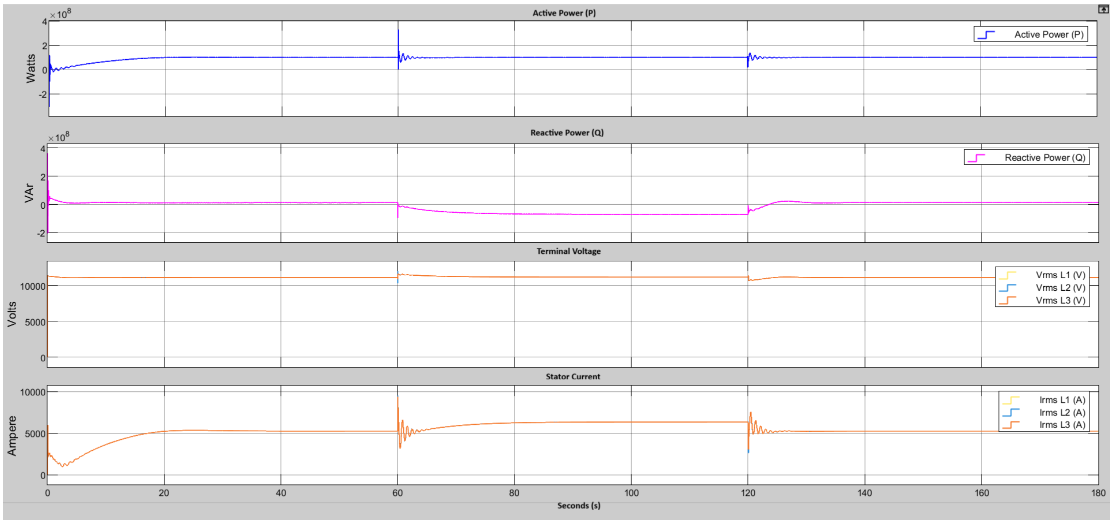

Figure 10. FS-PHS dynamic response under 300 MW, 125 MVAr capacitive loading

The second set of simulations investigated the response of the FS-PHS system under increasing inductive loading conditions (see Figure 11). Inductive loads require reactive power support from the generator to maintain acceptable voltage levels. Consequently, the excitation system increased field excitation to supply additional reactive power to the network. The simulation results demonstrated that the FS-PHS unit could supply approximately 75 MVAr of reactive power under heavily inductive loading conditions. The maximum observed reactive power output was approximately 75.12 MVAr. As reactive power demand increased, terminal current also increased, reflecting the additional reactive current supplied by the generator. Despite the increased loading, terminal voltage remained within acceptable operating limits, demonstrating effective excitation system operation.

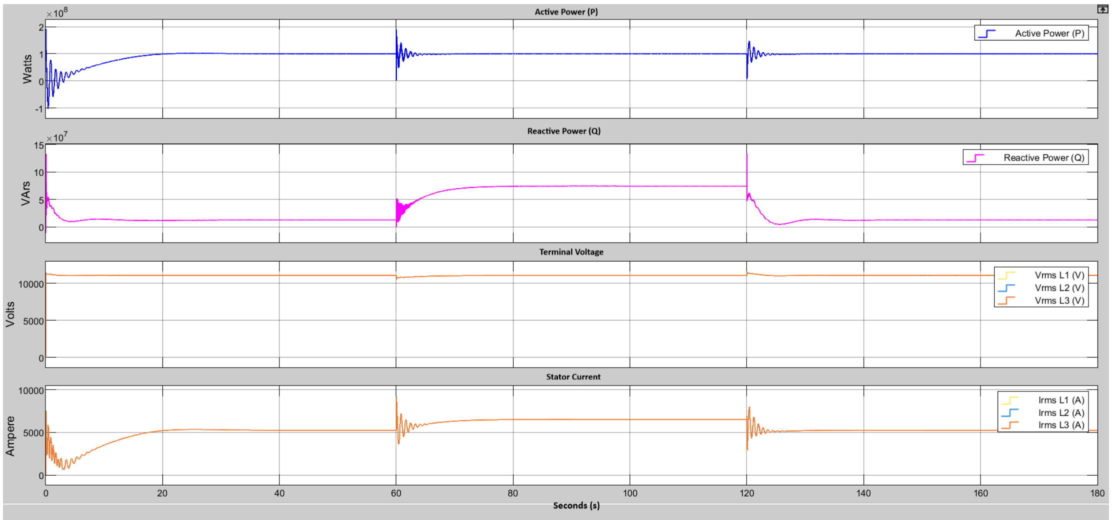

Figure 11. FS-PHS dynamic response under 300 MW, 35 MVAr inductive loading

The theoretical reactive power capability of the generator can be estimated from the apparent power relationship:

$$S^2 = P^2 + Q^2 \tag{4}$$

For a machine rated at 125 MVA operating at 100 MW, Q_max = 75 MVAr and Q_min = -75 MVAr.

The sensitivity analysis demonstrated that the simulated reactive power limits closely matched the theoretical capability limit. The maximum reactive power supplied was approximately +75.12 MVAr, while the maximum reactive power absorbed was approximately -75.14 MVAr.

4.2. Integration of the FS-PHS system into the IEEE 9-bus network

Following validation of the FS-PHS model, the system was integrated into a modified IEEE 9-bus network operating at 50 Hz with 220 kV transmission voltage levels and 11 kV generator buses. Initial load flow analysis was performed on the base network to identify potential voltage support requirements (see Figure 12). The load flow results indicated that Bus 5 exhibited the lowest voltage magnitude within the system at approximately 0.97 $p.u.$, making it the weakest bus in the network. This suggested that Bus 5 would be an appropriate location for investigating voltage support requirements and reactive power compensation.

	Block name	Block type	Bus type	Bus ID	Vbase (kV)	Vref (pu)	Vangle (deg)	P (MW)	Q (Mvar)	Qmin (Mvar)	Qmax (Mvar)	V_LF (pu)	Vangle_LF (deg)	P_LF (MW)	Q_LF (MVA)
1	SM 3/M3 100 MVA 11 kV	SM	PQ	BUS_3	11.0000	1.0000	0	85.0000	20.0000	-Inf	Inf	1.0104	6.3005	85.0000	20.0000
2	Three-Phase Parallel RLC Load2	RLC load	Z	BUS_3	11.0000	1.0000	0	0.0100	0	-Inf	Inf	1.0104	6.3005	0.0102	0
3	Gen_2/M2 200 MVA 11 kV	SM	PQ	BUS_2	11.0000	1.0000	0	163.0000	30.0000	-Inf	Inf	0.9967	5.4629	163.0000	30.0000
4	Three-Phase Parallel RLC Load1	RLC load	Z	BUS_2	11.0000	1.0000	0	0.0100	0	-Inf	Inf	0.9967	5.4629	0.0099	0
5	Gen_1/M1 200 MVA 11 kV	SM	swing	BUS_1	11.0000	1.0000	0	0	0	-Inf	Inf	1.0000	0	69.4247	27.9534
6	Three-Phase Parallel RLC Load	RLC load	Z	BUS_1	11.0000	1.0000	0	0.0100	0	-Inf	Inf	1.0000	0	0.0100	0
7	Load Flow Bus3	Bus	-	BUS_4	220.0000	1.0000	0	0	0	0	0	0.9780	26.7864	0	0
8	125 MW 50 MVAr	RLC load	PQ	BUS_5	220.0000	1.0000	0	125.0000	50.0000	-Inf	Inf	0.9693	26.0592	125.0000	50.0000
9	Load Flow Bus6	Bus	-	BUS_7	220.0000	1.0000	0	0	0	0	0	0.9796	29.1158	0	0
10	100 MW 35 MVAr	RLC load	PQ	BUS_8	220.0000	1.0000	0	100.0000	35.0000	-Inf	Inf	0.9758	27.7130	100.0000	35.0000
11	Load Flow Bus8	Bus	-	BUS_9	220.0000	1.0000	0	0	0	0	0	0.9847	28.5003	0	0
12	90 MW 30 MVAr	RLC load	PQ	BUS_6	220.0000	1.0000	0	90.0000	30.0000	-Inf	Inf	0.9758	26.2810	90.0000	30.0000

Figure 12. Base case load flow results for modified IEEE 9-bus system

To assess the impact of pumped hydro integration, Generator 1 was removed from service and replaced with the FS-PHS unit connected at Bus 4 (see Figure 13). Generator 2 and Generator 3 were operated as PQ generators supplying 163 MW / 30 MVAr and 85 MW / 20 MVAr respectively. Subsequent load flow analysis indicated that the FS-PHS unit was required to provide approximately 71.32 MW of active power and 21.39 MVAr of reactive power to satisfy network requirements.

	Block name	Block t...	Bus type	Bus ID	Vbase (...	Vref (pu)	Vangle (de...	P (MW)	Q (Mvar)	Qmin (Mvar)	Qmax (Mvar)	V_LF (pu)	Vangle_LF (deg)	P_LF (MW)	Q_LF (MVA)
1	SM 3/M3 100 MVA 11 kV	SM	PQ	BUS_3	11.0000	1.0000	0	85.0000	20.0000	-Inf	Inf	1.0304	8.4947	85.0000	20.0000
2	Three-Phase Parallel RLC...	RLC load	Z	BUS_3	11.0000	1.0000	0	0.0100	0	-Inf	Inf	1.0304	8.4947	0.0106	0
3	Gen_2/M2 200 MVA 11 kV	SM	PQ	BUS_2	11.0000	1.0000	0	163.0000	30.0000	-Inf	Inf	1.0169	7.6839	163.0000	30.0000
4	Three-Phase Parallel RLC...	RLC load	Z	BUS_2	11.0000	1.0000	0	0.0100	0	-Inf	Inf	1.0169	7.6839	0.0103	0
5	Three-Phase Parallel RLC...	RLC load	Z	BUS_1	11.0000	1.0000	0	0.0100	0	-Inf	Inf	0.9964	-0.6516	0.0099	0
6	Load Flow Bus3	Bus	-	BUS_4	220.0000	1.0000	0	0	0	0	0	0.9965	29.3578	0	0
7	125 MW 50 MVAr	RLC load	PQ	BUS_5	220.0000	1.0000	0	125.0000	50.0000	-Inf	Inf	0.9887	28.6568	125.0000	50.0000
8	Load Flow Bus6	Bus	-	BUS_7	220.0000	1.0000	0	0	0	0	0	0.9999	31.5902	0	0
9	100 MW 35 MVAr	RLC load	PQ	BUS_8	220.0000	1.0000	0	100.0000	35.0000	-Inf	Inf	0.9962	30.2441	100.0000	35.0000
10	Load Flow Bus8	Bus	-	BUS_9	220.0000	1.0000	0	0	0	0	0	1.0048	31.0003	0	0
11	90 MW 30 MVAr	RLC load	PQ	BUS_6	220.0000	1.0000	0	90.0000	30.0000	-Inf	Inf	0.9951	28.8699	90.0000	30.0000
12	FS-PHS System/Fixed-Sp...	SM	swing	*1*	11.0000	1.0000	0	100.0000	0	-75.0000	75.0000	1.0000	0	71.3179	21.3893
13	FS-PHS System/Three-Ph...	RLC load	Z	*1*	11.0000	1.0000	0	0.0100	0	-Inf	Inf	1.0000	0	0.0100	0

Figure 13. Load flow results after FS-PHS integration at bus 4

A 120 second electromagnetic transient simulation was performed without introducing any disturbance into the network. The simulation results showed that the FS-PHS unit stabilised at approximately 100 MW active power output and approximately 63 MVAr reactive power output. Although the load flow analysis predicted lower power requirements, the dynamic simulation demonstrated that the FS-PHS unit contributed substantially more reactive power support to maintain network voltage conditions (see Figure 14.

This difference highlights the limitations of steady-state load flow analysis when evaluating dynamic reactive power behaviour and demonstrates the importance of EMT simulations for studying excitation system response.

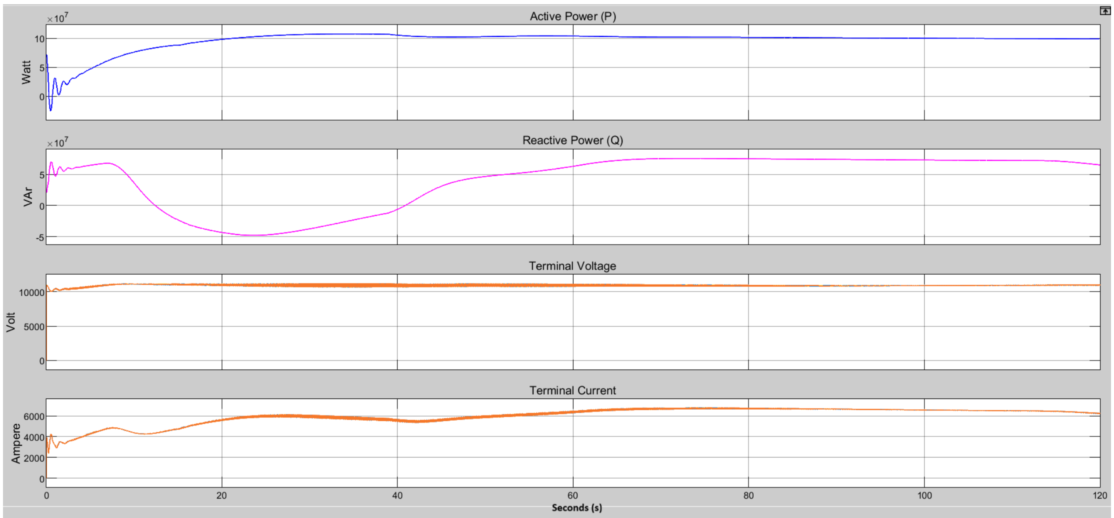

Figure 14. Dynamic response of FS-PHS following integration into IEEE 9-bus network

To further investigate voltage support capability, the reactive power demand at Bus 5 was increased from 50 MVAr to 75 MVAr. Load flow analysis was repeated, and a 120 second EMT simulation was conducted. The results showed that the FS-PHS unit supplied approximately 99.6 MW active power and 72.74 MVAr reactive power. Despite the increase in reactive demand, the generator remained within its reactive power capability limits (see Figure 15).

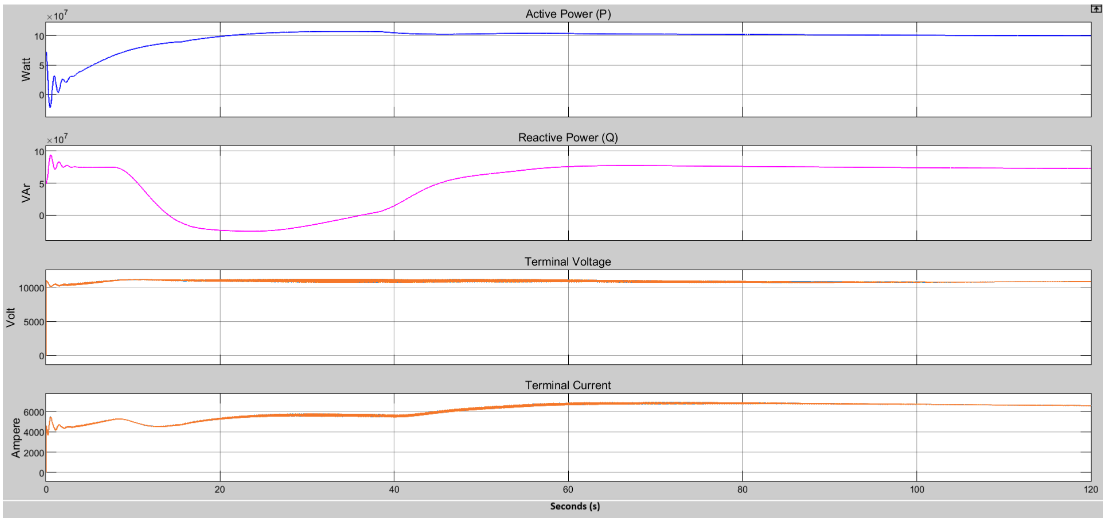

Figure 15. FS-PHS response following increase of bus 5 reactive load to 75 MVAr

A final scenario was investigated by increasing the Bus 5 load to 125 MW and 100 MVAr. This scenario was intended to determine whether the generator would exceed its rated reactive power capability. Simulation results showed that the FS-PHS unit supplied approximately 99.8 MW active power and 72.85 MVAr reactive power. Importantly, the reactive power output remained below the theoretical limit of approximately 75 MVAr, confirming that the excitation system and capability limits successfully constrained generator operation (see Figure 16).

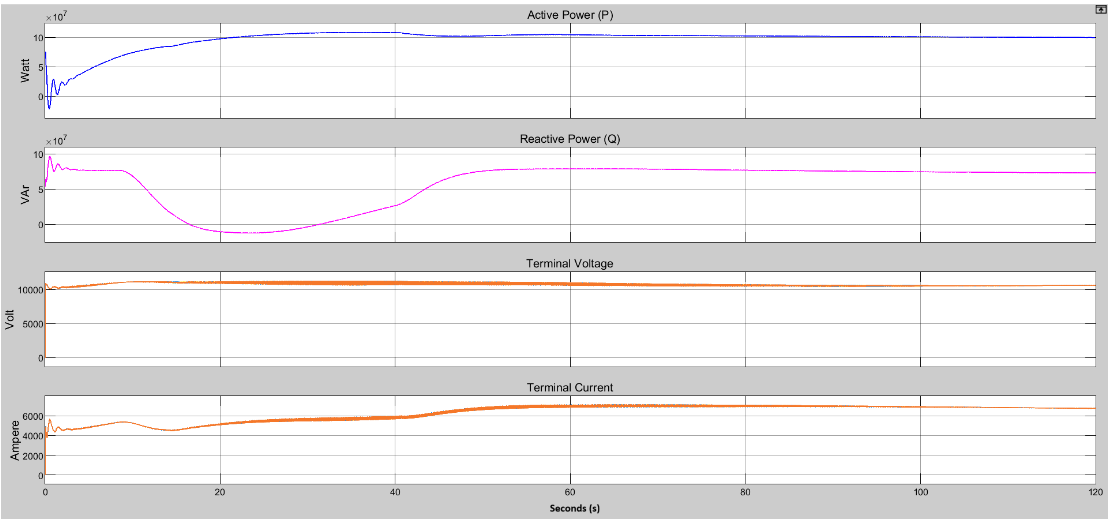

Figure 16. FS-PHS response following increase of bus 5 reactive load to 100 MVAr

4.3. Discussion

The results obtained from the sensitivity analysis demonstrate that the developed fixed-speed pumped hydro storage (FS-PHS) model possesses significant reactive power support capability. By systematically varying the reactive power requirements of the connected load while maintaining an active power output of approximately 100 MW, the operating limits of the synchronous generator were assessed. The simulation results showed that the generator could supply approximately +75 MVAr and absorbing approximately -75 MVAr of reactive power while maintaining stable active power output and acceptable terminal voltage regulation. These values closely matched the theoretical capability limit of a 125 MVA synchronous generator operating at 100 MW, yielding a theoretical reactive power capability of approximately ±75 MVAr.

The close agreement between theoretical and simulated values show that the developed model accurately represents the electrical behaviour of a practical fixed-speed pumped hydro storage plant. Furthermore, the results demonstrate that the excitation system and automatic voltage regulator successfully controlled generator terminal voltage through the adjustment of field excitation, allowing the machine to respond appropriately to changing reactive power requirements. The ability of the generator to both supply and absorb reactive power is particularly important from a power system operation perspective. Unlike many renewable energy sources that depend on power electronic converters for voltage support, synchronous generators possess inherent reactive power capability and can respond naturally to changing system conditions through excitation control. This characteristic makes synchronous-machine-based technologies particularly valuable for maintaining voltage stability in modern power systems.

Following validation of the standalone model, the FS-PHS unit was integrated into a modified IEEE 9-bus network operating at 50 Hz and 220 kV transmission voltage levels. The objective of this study was to evaluate the behaviour of the pumped hydro system when connected to a more realistic transmission network. Load flow analysis of the base network indicated that Bus 5 represented the weakest location within the system, exhibiting a voltage magnitude of approximately 0.969 $p.u$. This observation provided a suitable basis for investigating voltage support and reactive power compensation requirements. As a result, Bus 5 was selected as the primary study location for subsequent reactive loading investigations.

When the FS-PHS unit replaced Generator 1 and was connected at Bus 4, the network remained stable and the pumped hydro unit successfully contributed both active and reactive power to the system. The load flow analysis indicated that the FS-PHS system supplied approximately 71 MW of active power and 21 MVAr of reactive power under normal operating conditions. However, dynamic EMT simulations revealed significantly higher reactive power contributions, with the machine supplying approximately 63 MVAr while maintaining active power output close to 100 MW. This difference highlights an important distinction between steady-state and dynamic studies. Conventional load flow analysis provides a static representation of operating conditions and does not fully capture excitation system dynamics. In contrast, EMT simulations account for the dynamic behaviour of the automatic voltage regulator, generator excitation system, and machine electromechanical interactions. Consequently, the dynamic simulations provide a more realistic representation of the reactive power support that can be delivered by the FS-PHS system during operation.

Further investigations were conducted by increasing the reactive power demand at bus 5. As reactive loading increased from 50 MVAr to 75 MVAr and subsequently to 100 MVAr, the FS-PHS system automatically increased its reactive power output. The machine supplied approximately 72.74 MVAr and 72.85 MVAr respectively under these conditions. Although the reactive loading of the network continued to increase, the reactive power output of the generator remained below its theoretical capability limit. This behaviour demonstrates that the excitation system successfully regulated generator operation while considering machine capability constraints. The results therefore confirm that the developed FS-PHS model can provide substantial reactive power support without exceeding operational limits.

The findings obtained from this study are particularly relevant when considered within the context of future New Zealand electricity networks. New Zealand is experiencing increasing levels of renewable energy development, with significant growth in wind and solar generation expected over the coming decades. While these technologies contribute to national decarbonisation objectives, they also alter the electrical characteristics of the power system due to their reliance on inverter-based interfaces. Northland represents one region where these challenges may become increasingly important. The region is supplied through relatively long transmission corridors extending north from Auckland and has been identified by Transpower as an area with substantial renewable energy development potential. Recent Renewable Energy Zone investigations indicate that renewable generation proposals within Northland exceed the current transmission capability of the region, creating a need for network reinforcement and additional system support services. The electrical characteristics of Northland make voltage regulation particularly important. The region contains geographically dispersed loads connected through long transmission lines, conditions that can increase voltage sensitivity and reactive power requirements. Furthermore, future increases in inverter-based renewable generation may reduce the contribution of conventional synchronous generation, potentially decreasing the availability of inertia, fault current and reactive power support. Although the modified IEEE 9-bus network used in this study does not directly represent the Northland transmission system, it exhibits several characteristics that make it a useful analogue for investigating voltage support applications. These include transmission distances, connected loads, weak bus locations, varying reactive power requirements and dependence on remote generation sources. The identification of bus 5 as the weakest bus within the network and the subsequent improvement in system support provided by the FS-PHS unit illustrate the type of voltage support function that may be required in electrically weak regions. Under such conditions, a FS-PHS facility could provide multiple benefits beyond energy storage. In addition to storing and generating electrical energy, the synchronous generator associated with the FS-PHS plant can contribute reactive power support, voltage regulation, fault current contribution and rotational inertia. These services become increasingly valuable as the proportion of inverter-based generation increases.

The results obtained in this study suggest that a 100 MW fixed-speed pumped hydro storage facility could provide approximately ±75 MVAr of reactive power capability while simultaneously delivering active power to the network. Such a capability would represent a valuable ancillary service resource capable of supporting voltage management objectives within future renewable-dominated power systems. Potential connection locations for future pumped hydro developments in Northland would likely be associated with major transmission nodes such as Marsden Point, Bream Bay, Maungatapere or Kaikohe, where proximity to transmission infrastructure and renewable energy developments could maximise system benefits. While identification of a specific site is beyond the scope of this study, the results demonstrate that fixed-speed pumped hydro storage technology possesses the technical characteristics necessary to contribute meaningfully to voltage regulation and reactive power management within regions exhibiting characteristics like Northland.

5. Conclusions

This research investigated the reactive power support capability of a fixed-speed pumped hydro storage (FS-PHS) system and evaluated its potential contribution to voltage regulation in power systems with increasing penetration of inverter-based renewable energy resources. A detailed FS-PHS model was developed in MATLAB/Simulink based on a Sandia National Laboratories reference model and adapted to Aotearoa New Zealand operating conditions by modifying the system frequency to 50 Hz and generator voltage to 11 kV.

A sensitivity analysis conducted using a simplified test network demonstrated that the FS-PHS system possesses significant bidirectional reactive power capability. The synchronous generator could supply approximately +75 MVAr and absorbing approximately -75 MVAr while maintaining stable operation at an active power output of approximately 100 MW. These results closely matched the theoretical capability limits of the generator, validating the developed model.

The FS-PHS system was subsequently integrated into a modified IEEE 9-bus network to assess its performance in a transmission system environment. The results showed that the system responded effectively to increasing reactive power demand by automatically adjusting excitation and providing additional reactive power support while maintaining acceptable voltage levels. The study demonstrated that FS-PHS can contribute not only as an energy storage technology but also as a valuable source of voltage regulation and ancillary services.

5.1. Limitations of the study

Several limitations should be acknowledged when interpreting the results presented in this work. Firstly, the modified IEEE 9-bus system represents a simplified transmission network and does not capture the full complexity of the Aotearoa New Zealand power system. Consequently, the results should be interpreted as demonstrating the technical capability of the FS-PHS system rather than predicting the exact behaviour of a specific transmission network. Secondly, the study focused primarily on reactive power support and voltage regulation under steady operating conditions. Other aspects of pumped hydro operation, including frequency response, transient stability support, fault ride-through capability and black-start performance, were not investigated. Finally, site-specific geographical, environmental and economic considerations associated with pumped hydro deployment were beyond the scope of this work. Future studies could extend the present research by integrating detailed Northland transmission network models and evaluating the performance of FS-PHS systems under a wider range of operating scenarios.

5.2. Recommendations

Future work should investigate the performance of the FS-PHS system using a detailed Aotearoa New Zealand transmission network model, particularly for regions such as Northland where voltage support requirements may become increasingly important. Additional studies should also evaluate frequency response, transient stability, fault ride-through capability, and interactions between FS-PHS and inverter-based renewable generation. Furthermore, site-specific assessments incorporating geographical, environmental, and economic factors would provide valuable insight into the practical deployment of pumped hydro storage systems within the New Zealand electricity network.

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