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Dynamic Modelling and Prototype Operator Training Simulation of a 5 MW Geothermal Wellhead Power Plant at Olkaria Using MATLAB/Simulink

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ABSTRACT

Kenya's Olkaria field deploys modular ~5 MW geothermal wellhead plants that monetize steam early but face variable steam supply, frequent load changes, and distribution-level grid disturbances. This paper develops and validates a lumped-parameter dynamic model of a representative 5 MW Olkaria wellhead unit, from production well through separator, steam line, governor/control valves, steam turbine, and synchronous generator, implemented in MATLAB/Simulink with thermophysical properties from CoolProp. Model parameters are identified from plant P&IDs and manuals, commissioning sheets, and historian/SCADA logs (Aug–Nov 2022). The model is verified at steady state and validated against two start-ups and load-step tests using bias, RMSE, and settling-time criteria agreed with plant experts. Within the operating range of interest, turbine inlet pressure and electrical power trajectories remain within acceptance bands, providing "training-grade" fidelity. A simple prototype OTS interface built in MATLAB App Designer allows users to set power targets and visualize the resulting pressure and power trajectories, demonstrating interactive use of the model for start-up and load-change scenarios. The work concludes that the validated model and prototype OTS provide a foundation for richer training tools, including the future integration of SOP prompts, alarm rationalization, and digital twin applications.

1 INTRODUCTION

1.1 Background of the Study

Kenya's Olkaria geothermal field hosts multiple single-flash steam stations alongside 21 modular wellhead power plants totaling approximately 83.5 MW. Unlike centralized plants with extensive steam-gathering networks and large substations, wellhead units sit close to single production wells and historically interfaced with lower-voltage networks; they therefore experience more direct effects from well flow variability and grid disturbances than conventional installations. Operator training for these units is also constrained: control is PLC-based (without built-in training modules typical of DCS platforms), operators are distributed across eight locations, and trip/restart frequency can be higher (Kenya Electricity Generating Company PLC, n.d.) (DiPippo, 2015) (Kabeyi & Olanrewaju, 2021).

Dynamic modelling is thus pivotal for:

1. Commissioning and tuning support,
2. Incident forensics,
3. Building Operator Training Simulators (OTS) tailored to local realities.

1.2 Problem Statement

Wellhead plants in Olkaria are directly exposed to upstream steam fluctuations and, for some units, to distribution-level grid perturbations. With operators spread across multiple sites and PLC-based controls lacking advanced training packages, consistent start-up, shutdown, and upset handling are challenging. A validated dynamic model specific to about 5 MW wellhead units is needed to underpin an OTS and harmonize procedures.

1.3 Purpose of the Study

To design, implement, and validate a dynamic model of a 5 MW geothermal wellhead power plant and demonstrate its application in an Operator Training Simulator (OTS).

1.4 Objectives

- Develop a mathematical model of the major systems of a 5 MW geothermal wellhead plant.
- Perform verification and validation of the model using design and operational data.
- Illustrate practical uses of the model, including development of an OTS.

2 RESEARCH DESIGN AND LOCALE

2.1 Research Design

This study follows a model-based engineering approach. A plant-wide dynamic model of the 5 MW wellhead unit was implemented in MATLAB/Simulink, combining first-principles control-volume balances with semi-empirical component relations (valve characteristics, turbine maps, and loss coefficients). Continuous states are integrated using a variable-step stiff solver, while controllers run at 50–100 ms sample times with rate limits and simple lag blocks for actuators and measurements. The modelling workflow comprised four main steps: first, defining system boundaries and causal subsystems from the production well to the generator and grid proxy; second, parameterizing each block using datasheets, plant manuals, and commissioning records; third, calibrating key parameters against plant historian data; and finally, validating the model on held-out start-ups and load-change transients.

2.2 Locale / Case Context

Single-flash 5 MW condensing wellhead unit in the Olkaria field (Kenya), sited adjacent to its production well. Steam quality and ambient conditions reflect East African operation. NCG extraction (ejectors) maintains the condenser vacuum. The unit is representative of KenGen wellhead configurations.

2.3 SOP linkage (to OTS)

Startup, load change, and alarm-handling SOPs from the plant manual are used to shape the scenarios and the interface design of the OTS prototype. In the current MATLAB App Designer interface, users enter load set-points and run simulations while following the existing SOPs alongside the simulator, using the plotted pressure and power trajectories as feedback. In future versions, these same SOPs will be embedded more directly as on-screen prompts and checklists so that disturbances (e.g., a +0.2 MW step or a 49.5 Hz dip) are explicitly coupled to operator actions (valve checks, permissives, alarm acknowledgements) within the OTS environment.

3 SAMPLE SIZE, MATERIALS, AND EQUIPMENT

3.1 Scope (sample)

This study focuses on one representative ~5 MW geothermal wellhead unit at Olkaria. The operating envelope includes typical disturbances such as ±5–10% active power set-point changes, steam-supply ramps and drops, and small grid frequency dips. Start-ups and load changes drawn from this envelope are used to exercise and validate the model; frequency dips are considered primarily as target scenarios for future OTS extensions.

3.2 Materials and records

Model structure and parameters are drawn from plant piping and instrumentation diagrams (P&IDs), the operation and startup manuals, valve sizes and nominal Cv information, turbine and generator datasheets, and condenser / non-condensable-gas (NCG) system characteristics. Commissioning test sheets provide additional reference points for rated conditions. Historian/SCADA logs provide time-series data for pressures, temperatures, flows, electrical quantities, and valve positions. For this case unit, vendor documentation consulted includes the OLK10/C50 startup and SOPs manual, the Turbine Inlet Valves manual, and the Steam Turbine Generator (STG) manual.

3.3 Software and tools

The dynamic model is implemented and simulated in MATLAB/Simulink. MATLAB scripts are used for data import and cleaning, analysis using the validation metrics defined in Section 4.4, and generation of the figures presented in the Results section.

4 DATA COLLECTION AND ANALYSIS INSTRUMENTS

4.1 Tag set

The tag set used for modelling and validation includes pressure (wellhead, separator, condenser), temperature (flash, exhaust, and cooling circuit), flow (steam and condensate), electrical variables (active power in MW and grid frequency), and actuator positions for the governor and control valves. Key operational events, such as breaker closures and load set-point changes, are also tagged to support event-based alignment and analysis.

4.2 Acquisition window

Historian and PLC logs spanning 12 August 2022 to 6 November 2022 were extracted at a nominal sampling interval of one minute, yielding more than 490,000 data points across the selected parameters. Within this window, two emergency shutdowns (20 October and 2 November 2022) followed by subsequent restarts provide rich start-up transients that are used as primary validation cases.

4.3 Pre-processing

Raw logs were exported as CSV files, ingested into the analysis environment, and then timestamp-aligned, outlier-removed using a Hampel filter, and resampled to match the model time step. Units were normalized where necessary (e.g., bar(a) vs kPa, MW vs kW), and event markers such as breaker close and set-point changes were aligned across signals to enable consistent comparison between measured and simulated trajectories.

4.4 Validation metrics and acceptance thresholds

Validation focuses on separator pressure and active power. The primary metrics are root-mean-square error (RMSE) and mean absolute error (MAE), steady-state error (targeted within ±1–2%), settling-time difference (within ±10–15%), and overshoot difference (within ±10% absolute). In addition, the Fraction of Variance Unexplained (FVU) can be used as a compact measure of aggregate fit quality across each transient. Acceptance thresholds for these metrics were defined together with plant experts to reflect what is adequate for training-grade fidelity.

5 MODEL DEVELOPMENT

5.1 Architecture & Assumptions

Subsystems. The plant model is organized as a series of subsystems, starting from the production well, through the flash separator with level control, the steam pipeline, the governor control valve, and the steam turbine, and ending with a synchronous generator/grid proxy, a condenser with NCG extraction, and the instrumentation and PI-controller layer. The overall model architecture is shown in Figures 1 and 2, highlighting the main process blocks and the governor/OTS control loop.

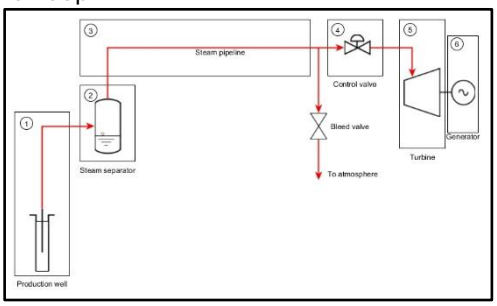


Figure 1: Components Selected from the Power Plant for Modelling

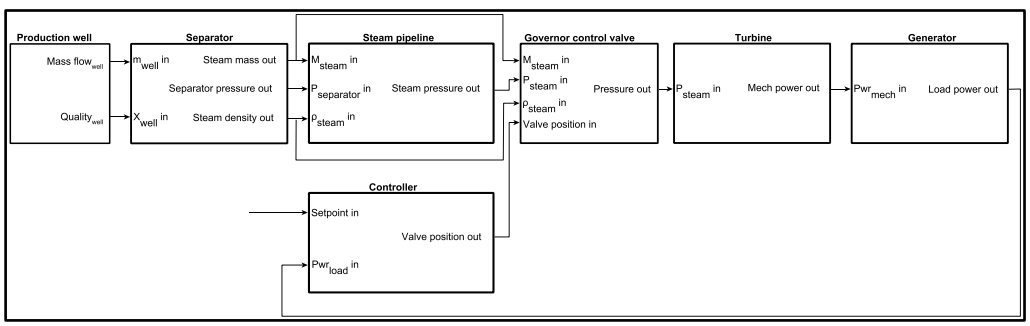


Figure 2: Input/Output Relationship of Overall Architecture Model in Simulink

Assumptions: single-pressure flash; saturated steam at separator outlet; constant turbine efficiency in a narrow band; lumped condenser; linearized actuator dynamics with rate limits; first-order measurement lags (Sanchez, Torres, Guillen, & Larrazabal, 2013) (Yu, et al., 2020).

5.2 Governing Relations & Plant-Specific Parameters

5.2.1 Mass/Energy/Momentum balances

Each element in Figure 1 is modelled as a control volume obeying the standard conservation equations for a fixed region in space. For a single-phase or two-phase fluid of density ρ and velocity vector V, the general forms are:

$$\frac{d}{dt}\int_V \rho\, dV = \sum_i\left(\int_S \rho\, V_n dS\right)_i - \sum_o\left(\int_S \rho\, V_n dS\right)_o \tag{1}$$

$$\frac{d}{dt}\int_V e\rho\, dV = \dot{Q} + \dot{W} + \sum_i\left(\int_S e\rho\, V_n dS\right)_i - \sum_o\left(\int_S e\rho\, V_n dS\right)_o \tag{2}$$

$$V\frac{d(\rho u)_s}{dt} = \dot{m}_{s,i}\dot{u}_{s,i} - \dot{m}_{s,o}\dot{u}_{s,o} + \left(p_{s,i} - p_{s,o}\right)A + F_s \tag{3}$$

Here ρ is fluid density, V is the velocity vector with normal component V_n on the control surface S, e is specific total energy, $\dot{Q}$ and $\dot{W}$ are net heat and shaft-work rates, u_s is the streamwise velocity in the steam line, V is the control-volume size, A is the cross-sectional area, and F_s represents net body and friction forces.

Under the usual lumped-parameter assumption that properties are uniform within each control volume, Equations (1) to (3) reduce to ordinary differential equations in time; the component models below (production well, separator, pipeline, valves, and turbine) are obtained by specializing these balances to the geometry and flow paths in Figure 1.

5.2.2 Production well

The production well is represented as a boundary condition supplying two-phase fluid to the separator rather than a fully distributed reservoir-wellbore model. For the validation dataset, the total well mass flow was approximately $\dot{m}_{well} \approx 18.1\ kg/s$ with steam quality $X \approx 0.65$, as inferred from site data. In the model, this is implemented as a commanded well flow that follows a step input filtered by a first-order lag with time constant $\tau \approx 100$ s, which captures the observed sluggishness of well opening and surface facilities. A saturation block prevents negative flows and caps the maximum admissible $\dot{m}_{well}$ to remain within the measured range. This representation is sufficient for the present study, where the focus is on separator, valve, and turbine dynamics at the surface; more detailed reservoir or wellbore dynamics can be added in future work if long-term resource behaviour becomes a modelling objective.

5.2.3 Separator

The flash separator is modelled as a horizontal vessel with internal length of approximately 1.0 m and cross-sectional area of about 2.9 m^2, giving a total internal volume of roughly 2.9 m^3. For a normal brine level of 0.41 m, this defines both the liquid inventory and the vapour-space volume in which the steam mass Ms resides. A dynamic mass balance on the steam region gives:

$$\frac{d\,M_S}{dt} = \dot{m}_w X_w - \dot{m}_s \tag{4}$$

where $\dot{m}_w$ is the total well mass flow, X_w is the steam quality at separator conditions, and $\dot{m}_s$ is the steam flow leaving the separator towards the turbine. In the full dynamic model this state equation allows short-term inventory swings during start-up and transients. For the steady-state operating points used to initialize and validate the model, the separator is treated as quasi-steady so that $\frac{d\,M_S}{dt} \approx 0$ and the relation reduces to:

$$\dot{m}_s \approx \dot{m}_w X_w \tag{5}$$

i.e. the steam outflow equals the steam fraction of the well inflow. Steam density ρ_s is obtained from the vapour-space volume and mass, and the separator pressure is then taken from the saturation curve using a property library with thermophysical properties evaluated via CoolProp (Bell, Wronski, Quoilin, & Lemort, 2014).

5.2.4 Steam pipeline

The steam line between the separator and the governor valve is represented as a rigid, one-dimensional pipe of length L and internal diameter D. Applying the momentum balance in Equation. (3) to this control volume and neglecting elevation changes leads to the familiar Darcy–Weisbach form for pressure drop:

$$\Delta P_{friction} = \frac{1}{2}\rho v^2 f \frac{L}{D} \tag{6}$$

where v is the bulk steam velocity, ρ is the steam density, and f is the friction factor. For turbulent flow in rough pipe, f is obtained from the Colebrook–White relation:

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{\varepsilon}{3.7D} + \frac{2.51}{Re\sqrt{f}}\right) \tag{7}$$

$$Re = {Vd}/{\nu} \tag{8}$$

with ε the effective roughness (including corrosion and scaling) and ν the kinematic viscosity. In the present model the pipeline between separator and valve is characterized by L≈35 m and D≈0.3556 (14-inch line, from P&IDs), with $\varepsilon \approx 1\times10^{-3}$ m as a representative roughness for scaled geothermal piping.

5.2.5 Governor control valve

The governor control valve (GCV) is implemented as a pneumatic-actuated, fail-close control valve (site configuration) that throttles steam between the separator outlet and the turbine inlet. In the model, the valve opening $v \in [0,1]$ is driven by the controller output through a rate-limited actuator, so that both finite stroking speed and travel saturation are captured. The intrinsic valve characteristic is taken as equal-percentage, with an effective flow coefficient Cv(v) that maps stem travel to hydraulic area over a rangeability of approximately 50–100. This is represented by a standard equal-percentage law:

$$Cv(v) = Cv_{max} R^{(v-1)}, \quad 0 \le v \le 1, \tag{9}$$

here Cv_{max} is the fully open coefficient and is the rangeability. To connect this to the momentum balance, Cv(v) is converted to a valve loss coefficient $K_\ell(v)$ referenced to a mid-stroke point v_{ref}=0.5:

$$K_l(v) = K_{l,ref}\left(\frac{Cv_{ref}}{Cv(v)}\right)^2, \tag{10}$$

with $K_{\ell,ref}$ chosen from rated conditions so that the model reproduces the measured inlet-pressure drop at nominal load. The instantaneous pressure loss across the valve is then given by

$$\Delta P_{valve}(v) = \frac{1}{2}\rho V^2 K_l(v), \tag{11}$$

which feeds directly into the steam-line momentum equation. Steam compressibility is retained by using the local density ρ and velocity V at the valve inlet, and actuator rate/position limits are preserved. The governor control valve body is a 6-inch valve, while the associated emergency/stop valves are 8-inch units; exact make/model and the vendor Cv(v) curve will be inserted once the nameplate data are retrieved (Pondini, Colla, & Signorini, 2017).

5.2.6 Steam turbine

The steam turbine is modelled using a Stodola/Chaibakhsh–Ghaffari type formulation that links mass flow to the pressure ratio across the machine. For an upstream pressure p_{in} and downstream pressure p_{out}, the steam mass flow is given by:

$$\dot{m}_{in} = \frac{K}{\sqrt{T_{in}}}\sqrt{P_{in}^2 - P_{out}^2} \tag{12}$$

where K is a fitted constant, T_{in} is the turbine inlet temperature, and P_{in} and P_{out} are the inlet and outlet pressures. For the present 5 MW unit, the calibrated value is K≈195.85, which reproduces the nominal flow at rated inlet and exhaust conditions. The expansion is treated as adiabatic, with the outlet state obtained from steam tables and the power computed from the enthalpy drop. The turbine work rate is

$$W = \eta\dot{m}(h_{in} - h_{out}) = \eta C_p \dot{m}(T_{in} - T_{out}) \tag{13}$$

where η is a lumped mechanical efficiency, C_p is an effective specific heat in the operating range, and h_{in}, h_{out} (or T_{in}, T_{out} are the inlet and outlet states. A first-order lag with time constant $\tau \approx 10$ s is introduced on the mechanical power channel to capture the observed inertia and fill-up dynamics during transients. Within the operating band of interest, the fitted efficiency is approximately $\eta \approx 98.5\%$ (Cooke, 1985) (Chaibakhsh & Ghaffari, 2008) so off-design behaviour is primarily driven by changes in mass flow and pressure ratio.

5.2.7 Synchronous generator

The synchronous generator is represented by a reduced power–angle relation rather than a full multi-state machine model. Electrical power output is approximated by:

$$P_e = \left(\frac{U \times V}{X_d}\right) \times sin\delta \tag{14}$$

where U is the internal excitation voltage, V is the terminal line-to-line voltage, X_d is the direct-axis synchronous reactance, and δ is the power angle. For the present study, these parameters are held constant at representative values ($U \approx 110$ V, $V \approx 11$ kV, $Xd \approx 1.1$ pu, $\delta \approx 30°$) so that the generator primarily acts as a static mapping between mechanical power P_m and electrical power P_e. To avoid unrealistically fast responses, a first-order lag with time constant $\tau \approx 10$ s is applied between the turbine power and the electrical output, which effectively lumps rotor, shaft, and network dynamics into a single time constant. This reduced-order representation is sufficient for operator-training scenarios focused on load-following and frequency response; more detailed electromagnetic and shaft-torsion models can be introduced in future work if needed for protection studies or stability analysis.

5.2.8 Controller

The wellhead unit is assumed to operate against a stiff grid, so active power is controlled via a single-loop governor that adjusts the governor control valve opening. The controller tracks an operator-specified active power set-point P_{ref} and rejects steam-supply and process disturbances. The measured electrical power P_e from the generator block is fed back and compared to the reference to form the error $e(t) = P_{ref} - P_e$. A proportional–integral (PI) controller generates a commanded valve signal u(t) according to:

$$u(t) = P + I = K_p e(t) + \frac{K_p}{T_i} \int e(t)\, dt \tag{15}$$

where K_p is the proportional gain, and T_i is the integral time. In the frequency domain, this is equivalent to a PI transfer function $G_c(s) = K_p + K_i/s$ with $K_i = K_p/T_i$. The gains are tuned to achieve acceptable overshoot and settling time under the OTS acceptance thresholds. Anti-windup is implemented so that the integral term is frozen or back-calculated whenever the actuator saturates, preventing large offsets after significant set-point changes or disturbances(Ogata, 2010).

The controller output u(t) does not instantaneously move the valve; instead, it passes through a dynamic actuator model that captures a finite stroking speed and small mechanical lags. This is represented as a second-order system with natural frequency ω_n and damping ratio ζ whose output is the effective valve opening v(t). In the time domain, v(t) is further subject to rate limits and position saturation $0 \leq v \leq 1$, consistent with the pneumatic actuator and valve travel observed on site. This structure allows the OTS to reproduce realistic sluggishness and overshoot when the controller gains are poorly tuned, so operators can see the effects of both conservative and aggressive tuning settings during start-ups, load changes, and disturbance recovery.

5.3 Operator Training Simulator concept

On top of the validated dynamic model, a simple Operator Training Simulator (OTS) prototype was implemented using MATLAB App Designer. The current interface exposes an active-power set-point entry field and a “Simulate” button on the left pane and displays time histories of steam (turbine inlet) pressure and power output on two plots in the right pane. When a set-point is entered and a simulation is triggered, the model is run and the resulting trajectories are plotted, allowing operators and engineers to see how the wellhead unit responds to different load targets and controller settings in a safe, off-line environment.

Although minimal, this prototype demonstrates how the model can be wrapped in a graphical interface and used interactively. Future extensions will add scenario presets (start-up, load ramps, disturbance injections), training-oriented KPIs, and SOP/alarm prompts; these are outlined as future work rather than being fully implemented in the present WGC version. A screenshot of the current App Designer interface is shown in Figure 3.

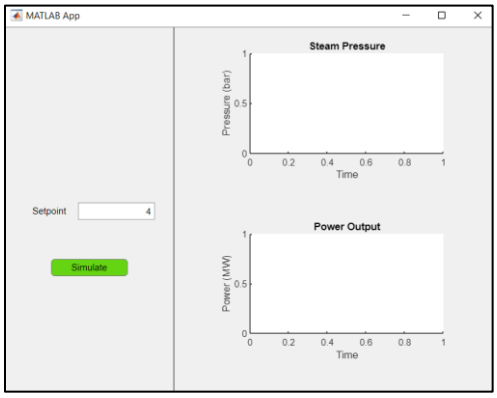


Figure 3: Prototype OTS Interface Implemented in MATLAB App Designer, Showing Set-Point Input and Simulation Plots for Steam Pressure and Power Output

5.4 Calibration

Steady-state reconciliation against commissioning data and GUI readings; loop-by-loop tuning (pressure, speed, level). Scenario-specific micro-tuning constrained within engineering plausibility.

5.5 Validation Scenarios (S1–S3)

S1 load step; S2 steam-supply ramp/drop; S3 grid frequency dip. For each scenario, the validation focuses on overshoot, settling time, steady-state error, and RMSE versus the target set-point, as defined in Section 4.4, together with qualitative comparison of measured and simulated traces.

6 RESULTS

6.1 Verification (steady state)

A MATLAB script implementing the governing equations was first used to verify steady-state behaviour. For the operating point of interest, the separator pressure converged to ≈13.5 bar(a), consistent with the plant GUI, and the simulated electrical power was ≈5.4 MW, close to typical operation (≈5.18 MW). This confirms that the lumped-parameter model can represent a realistic steady operating point for the 5 MW wellhead unit.

6.2 Validation (start-ups and transients)

Historian data from two representative start-ups (20 Oct 2022 and 2 Nov 2022) were exported, filtered, and time-aligned to construct turbine inlet pressure and active power traces. The same initial conditions and ramp sequences were then applied to the model. Validation focuses on the separator /turbine inlet pressure and active power, using the bias, RMSE, settling time, and overshoot notions defined in Section 4.4 as acceptance criteria rather than as exhaustive numerical results.

Across both start-ups, the model reproduces the qualitative dynamic shape of turbine inlet pressure and MW during ramp-up and early load stabilization. Visual inspection and spot checks indicate slight steady-state bias and differences in settling time that are well within the agreed tolerance bands for training-grade use. Measured and simulated traces are shown in Figures 4 and 5, illustrating the agreement between the plant and the model for the main variables of interest.

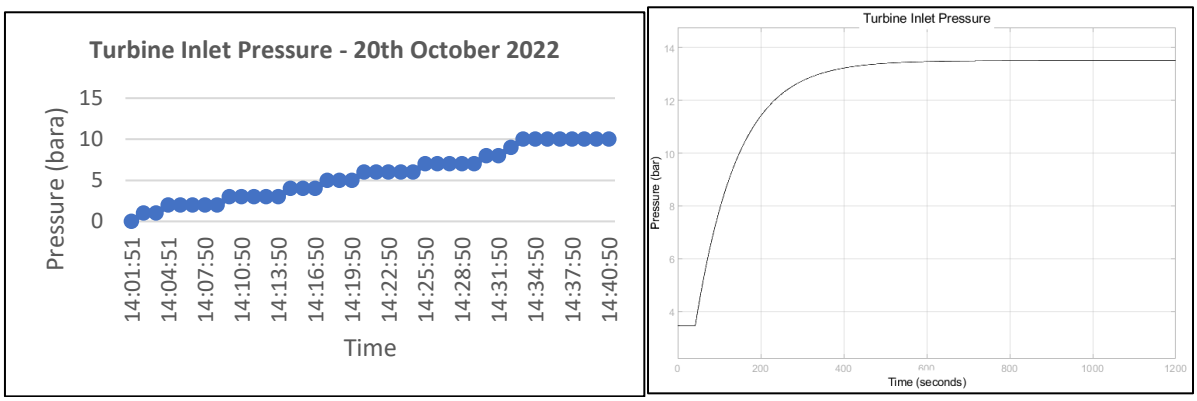


Figure 4: Turbine Inlet Pressure during start-up: (a) measured; (b) simulated

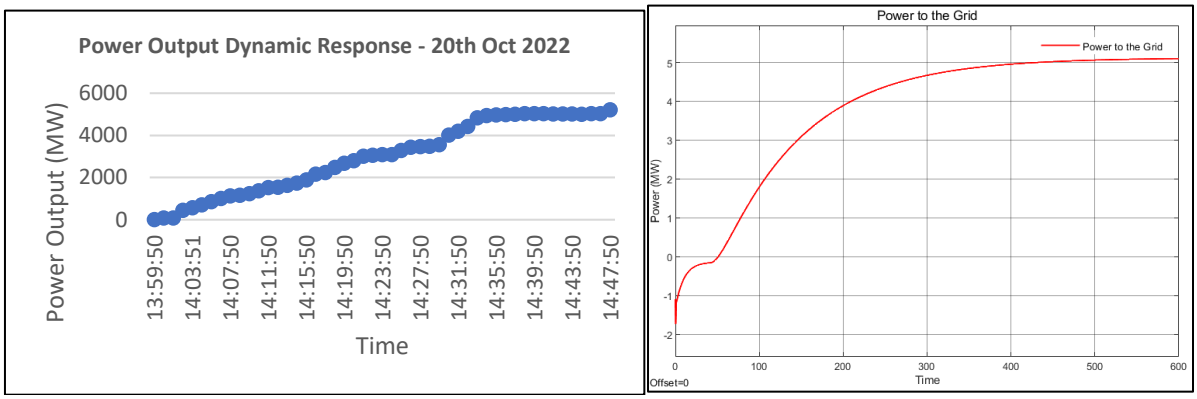


Figure 5: Power Output During Start-up: (a) measured; (b) simulated

6.3 Set-point change experiments

The validated model was then used to study set-point changes around the normal operating region. With the nominal configuration of controller gains and valve parameters, the model settled close to 5.1 MW, consistent with the integrated model and site data. A step from this condition down to 4.0 MW was tracked appropriately, with acceptable overshoot and settling time for training purposes, as shown in Figure 6.

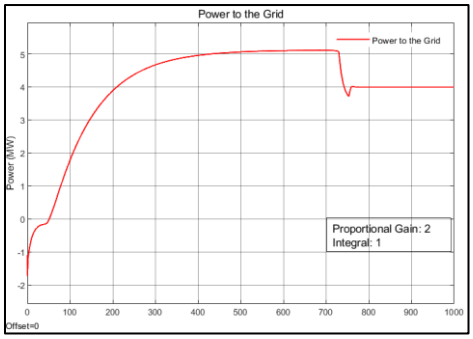


Figure 6: Model's Response to a Set-point Change

However, achieving an intermediate set-point of 4.5 MW required a governor-valve position of approximately 0.52 (per-unit travel), highlighting a limitation of the simplified valve representation and its tuning, as shown in Figure 7.

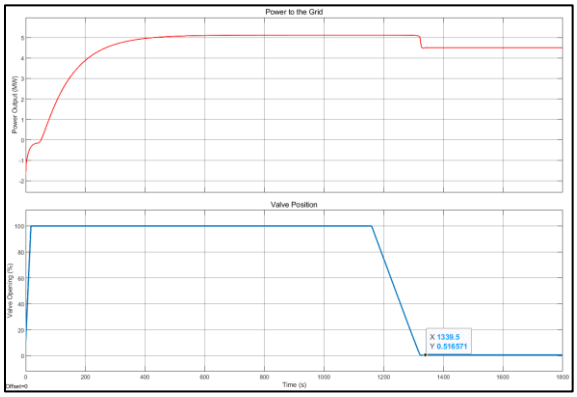


Figure 7: Valve's Response to a Set-point Change

This behaviour motivated a more detailed treatment of the equal-percentage Cv(v) characteristic in the model development section and suggests that a tighter linkage to vendor Cv curves would be beneficial.

6.4 Controller sensitivity

To illustrate the model's training value, a simple controller sensitivity study was performed. Reducing the proportional gain Kp (for example, from 2.0 to 0.2) increased oscillation and lengthened settling time in response to a load-set-point change, while higher values led to faster but more oscillatory responses. The impact of changing Kp is clearly visible in the active-power traces (Figure 8). It is consistent with operator experience of how overly conservative versus overly aggressive tuning affects oscillation and settling behaviour.

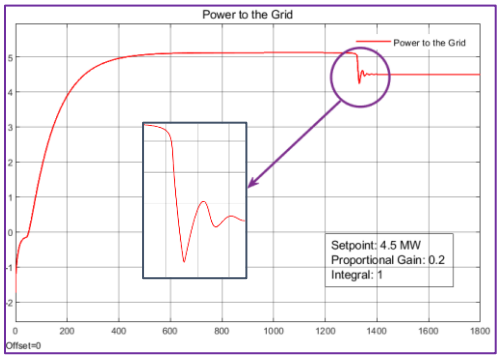


Figure 8: Impact of Changing Proportional Gain on the Power Output

Because the actuator dynamics and valve non-linearities are included, operators can see how tuning choices affect both transient performance and actuator usage, making the model suitable for loop-tuning and "what-if" training scenarios.

7 DISCUSSION

The results show that a relatively compact, lumped-parameter model can provide training-grade fidelity for a 5 MW geothermal wellhead unit. By applying standard mass, energy, and momentum balances to a small number of control volumes (production well, separator, pipeline, valves, turbine, and generator), and by specializing these to the geometry and flow paths in Figure 1, the model captures the dominant dynamics that operators interact with during start-ups and load changes. The steady-state verification and transient validation indicate that turbine inlet pressure and electrical power are reproduced with acceptable bias, RMSE, and settling times for the operating range of interest.

At the same time, the limitations of this approach are clear. Despite the good alignment in the main operating range, several limitations and threats to validity remain. Discrepancies arise from (i) operator-driven multi-step load ramping and manual interventions during some commissioning runs, which are only approximated in the replayed input profiles; (ii) simplified valve dynamics and approximate Cv(v) curves, since vendor-specific characteristics have not yet been inserted and an equal-percentage assumption is used with calibration at nominal load; and (iii) unmodelled cold-end and non-condensable-gas (NCG) effects that influence condenser vacuum and turbine backpressure. In addition, historical data are logged at roughly 1-minute cadence, so fast transients may be undersampled, and some short-lived excursions may not be fully captured in the validation metrics. Degradation mechanisms such as fouling and scaling explain observed pressure drops versus design and can be represented in future iterations via a time-varying degradation factor applied to key loss coefficients. NCGs raise condenser partial pressure (reducing vacuum), increase turbine exhaust pressure, and depress net output; they may also slow transient recovery following upsets (DiPippo, 2015). In the present model, these cold-end and NCG effects are represented implicitly via backpressure disturbances. A future journal version will introduce an explicit NCG partial-pressure state and an NCG-extraction performance map to capture these effects more mechanistically.

From an operational and training perspective, the validated model already supports several practical uses. In guided scenarios, operators can rehearse start-ups using the same broad sequence of actions as on the plant, but with the advantage of seeing how separator level, valve position, and MW trajectories respond to different choices. For load-change scenarios, the simulator highlights the trade-offs between overshoot and settling time, and the consequences of overly aggressive or overly conservative ramping. Alarm rationalization can also be explored: in future versions, by superimposing SOP prompts and alarm messages on the dynamic response, the OTS could be used to test revised alarm groupings and priorities, helping to reduce nuisance alarms and focus operator attention during upsets.

Finally, the present implementation is tuned to a single 5 MW wellhead configuration and is deployed as a MATLAB/Simulink model rather than a fully integrated digital twin. Extending the model to additional plant systems and multiple wells, refining condenser and NCG treatment, and introducing explicit regression/degradation factors will enhance realism, especially for long-term performance studies. Streaming selected live signals into the simulator would open a path towards a digital-twin mode, enabling advanced control experiments and richer training scenarios while maintaining the core lumped-parameter structure. These enhancements are natural next steps and will be pursued in follow-up work and in the planned journal papers.

8 CONCLUSION

This paper has presented a dynamic model of a 5 MW geothermal wellhead unit, calibrated and validated against site data, and structured explicitly to support an Operator Training Simulator. The model combines standard control-volume balances, equal-percentage valve characteristics, and a reduced turbine–generator representation with a practical PI governor and actuator dynamics. Within the operating range of interest, the model reproduces start-up and load-change behaviour with acceptable bias, RMSE, and settling times for turbine inlet pressure and electrical power.

On this foundation, a prototype OTS has been implemented that allows operators and engineers to experiment with load set-points and controller adjustments in a safe environment, using simulated steam pressure and power trajectories as feedback. For utilities operating multiple wellhead units, such a tool offers a low-risk way to standardize procedures, accelerate onboarding, and explore controller settings before applying them on the plant. Future work will extend the model to additional wellhead configurations, refine condenser and non-condensable gas treatment, and progressively integrate SOP prompts, alarm rationalization, and site-specific GUIs and data logging for formal training evaluations.

9 RECOMMENDATIONS

For day-to-day operations, the validated model can be used to define conservative but efficient load ramp presets, embed SOP cues for separator level and valve management, and rationalize alarms to reduce duplication and nuisance. From an engineering and data perspective, we recommend improving historian synchronization and logging rates for key tags, and documenting valve Cv curves and degradation indicators to support future re-tuning. On the modelling side, future work should extend the simulator to additional plant systems and multiple wells, incorporate a regression/degradation factor to capture long-term performance drift, and enable streaming of selected live signals to support a digital-twin mode and advanced control or scenario-generation studies.

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