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Optimization of the Power Conversion System for a Pulsed Fusion Power Plant with Multiple Heat Sources using a Dynamic Process Model

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ABSTRACT

The optimization of the power conversion system, responsible for thermal-to-electrical energy conversion, for a pulsed fusion power plant is presented. A spherical tokamak is modelled as three heat sources, all pulsed, with different stream temperatures and available amounts of heat. A thermal energy storage system is considered in the design to compensate for the lack of thermal power during a dwell. Thermal storage enables continued power generation during a dwell and can avoid thermal transients in sensitive components like turbomachines. Multiple lower grade heat sources are integrated into the process through parallel preheating trains. The evaluation of a dynamic model of the power conversion system is used to define an objective function with multiple criteria. A bi-objective optimization problem is defined to investigate the trade-off between the size of the thermal energy storage system and the variability in turbine power output during a dwell. The set of non-dominated designs demonstrates the trade-off, with designs covering the range from steady state turbine power output to a design that reduces the turbine power output by 46.3% during a dwell. The dynamics of three non-dominated designs demonstrate the power conversion system can maintain relatively stable conditions at the turbine inlet under different operating conditions, but molten salt temperature control is an issue.

Keywords: Optimization, Dynamic Modelling, Energy Conversion, Energy Storage, Fusion Power, Modelica

INTRODUCTION

The United Kingdom Atomic Energy Authority (UKAEA) is leading the Spherical Tokamak for Energy Production (STEP) programme to design and build a fusion power plant that demonstrates net electricity generation [1,9]. Fusion is an appealing prospect for clean and abundant energy but faces several engineering challenges. Two of these challenges are addressed here:

- Pulsed tokamak operation - the steady state nature of early fusion power demonstrators, notably tokamaks, will be challenging due to operational uncertainty and, as for conventional tokamaks, pulsed operation may be required. Rapid dynamics of the plasma compound this issue
- Multiple heat sources - generated thermal power is distributed to multiple tokamak components, and will be extracted via multiple coolant streams at different temperatures and flow rates

A power conversion system design for a pulsed fusion tokamak is presented, featuring a thermal energy storage system, using molten salts as is common in solar thermal power plants, and two parallel feed water trains to integrate multiple lower grade heat sources.

The pulsed heat generation requires the use of dynamic models to evaluate the performance of the power conversion system. The dynamic models are used within an optimization framework such that each objective

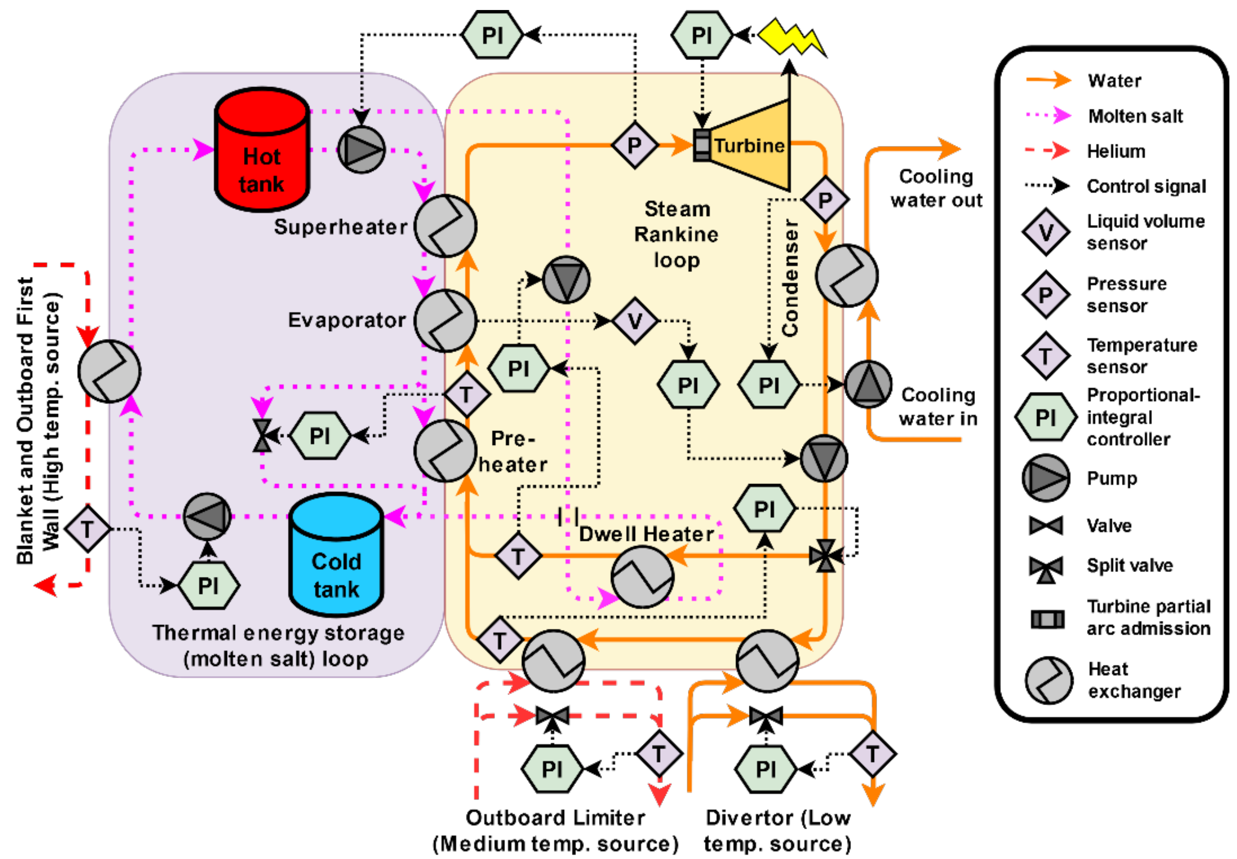

Figure 1: Power conversion system layout for a fusion tokamak with three pulsed sources. The high temperature source is used to heat and store molten salt for use during a dwell. The other two sources are used to heat feed water during a pulse. Their heat duty is replaced by a dwell heater, fed by molten salt, during a dwell. Note that all heat exchangers are counter current.

function evaluation involves a dynamic simulation of the designs identified by the optimization procedure.

DYNAMIC POWER CONVERSION SYSTEM MODEL

Figure 1 shows the proposed power conversion system layout. There are three heat sources available from the fusion tokamak, with pulse and dwell values summarized in Table 1. While the tokamak outlet temperatures are fixed as the model boundary conditions, the temperature of the coolant returning to the tokamak is not fixed. Each source follows a C^1-continuous pulsed profile with an initial 2 h pulse period, a 5 min ramp down, a 15 min dwell period followed by a 5 min ramp up back to pulse.

The high temperature source exchanges heat with the molten salt in the thermal energy storage loop (left side of the process diagram in Figure 1) via the high temperature heat exchanger. The hot molten salt is stored in an insulated tank, at a target temperature of 550°C, where it can be pumped on demand to provide heat to the steam Rankine cycle (the right side of the process diagram in Figure 1). The cooled molten salt is stored in another insulated tank, at a target temperature of 350°C, for pumping and reheating by the high temperature heat source.

Table 1: Parameters of the available heat sources from the tokamak during a pulse, with values during a dwell given in brackets. These are early estimate values.

Source grade	Coolant	Outlet temperature (°C)	Target return temperature (°C)	Thermal power (MWth)
High	Helium	600 (450)	450 (450)	1,350 (0)
Medium	Helium	450 (225)	225 (225)	215 (0)
Low	Water	300 (275)	275 (275)	270 (0)

A steam Rankine cycle is used to generate electrical power. Feed water is pumped through two parallel heating trains: the low and medium temperature heat exchangers that heat the feed water from their respective heat sources during a pulse; and a dwell heater that heats the feed water using molten salt from the hot tank. The feed water then passes through a preheater, an evaporator and a superheater, with heat provided by the hot molten salt in counter current exchanges. The water exits as superheated steam. The steam then drives a turbine to generate electrical power before being condensed back to the liquid phase by the condenser, exchanging heat with cooling water, closing the loop for the steam cycle.

There are ten proportional-integral controllers in Figure 1. Two controllers regulate the feed water temperature at the outlet of the parallel heating trains by controlling the flow rate of molten salt to the dwell heater and the split fraction of feed water between the two trains. This allows the plant control to switch between the two heating modes when the tokamak switches between pulse and dwell.

The condenser pressure is regulated by a controller manipulating the flow of cooling water. A controller manipulates the mass flow rate of feed water in the Rankine cycle to ensure the evaporator doesn't flood or dry out due to a lack or excess of evaporation respectively. The turbine power output and inlet pressure are regulated by two controllers manipulating the turbine's partial arc admission and the mass flow rate of hot molten salt to the superheater respectively.

There is a bypass for the molten salt around the preheater, where the bypass valve opening is manipulated by a controller regulating the temperature of feed water leaving the preheater. This is to avoid the feed water boiling before the evaporator. Each of the heat sources has a controller regulating the temperature of coolant returning to the tokamak.

For the high temperature source, the mass flow rate of cold molten salt is manipulated. For the other two sources, the openings of bypass valves for the coolants are manipulated. The controllers are all hand tuned by repeated simulations here to reduce the dimension of the optimization problem. Previous work has looked at the controller parameters as decision variables [10].

The model has been implemented in the Modelica language [6] and solved numerically using OpenModelica [8]. Full descriptions of the dynamic models will be published in a future paper that is currently under review.

OPTIMIZATION OF THE POWER CONVERSION SYSTEM FOR REDUCED DWELL POWER

Based on industry experience with thermal energy storage for solar thermal power plants, thermal energy storage systems are a significant fraction of total investment. For a 50MWel concentrating solar power plant, a cost of 33M€ was predicted [7]. With STEP expected to be generating ~500MWel (before parasitic loads like the tokamak itself), significant thermal storage would be required to generate a steady amount of power for fusion tokamaks [1]. The size of the storage system could be reduced by reducing the power generation during a dwell; stopping power generation entirely is infeasible due to the thermal stresses this would place on the components.

To investigate this, we propose an optimization problem to find the trade-off between the size of the thermal storage system, quantified as the volume of each tank V_{tank} and the dwell power fraction φ, the fraction by which the turbine power setpoint is reduced during dwell relative to pulse. The bi-objective optimization problem is stated as:

$$\begin{aligned} \min_{x} & \begin{bmatrix} V_{tank} \\ -\varphi \end{bmatrix} \\ s.t.\ & \boldsymbol{g}(\boldsymbol{x}) \leq \boldsymbol{0} \\ & \boldsymbol{h}(\boldsymbol{x}) = \boldsymbol{0} \end{aligned} \tag{1}$$

where the decision vector $\boldsymbol{x} = [V_{tank}, \varphi, P_{pulse}]^T$ includes the turbine power setpoint during a pulse P_{pulse}. This is necessary as designs that reduce the power generated during a dwell will necessarily generate more power during the pulse to satisfy energy balances in the overall process over time. Between a pulse and dwell periods, the setpoint smoothly transitions between P_{pulse} and φP_{pulse} by following a sinusoidal curve. The equality constraints $\boldsymbol{h}(\boldsymbol{x})$ represent the dynamic model. The inequality constraints $\boldsymbol{g}(\boldsymbol{x})$ include requirements for long term operability of the plant. For a simulation to be completed, the volume of molten salt in either tank V_{MS} must stay in the range $0.05 \leq V_{MS}/V_{tank} \leq 0.95$ for the $T_{sim} = 15900s$ of simulated time. The simulated time covers an initial pulse period $T_{pulse} = 7200s$, a dwell period $T_{dwell} = 900s$ and another pulse period, with a ramp down and ramp up between them of $T_{ramp} = 300s$. These are estimated from the DEMO pre-concept design [2]. The simulation covers the period of interest, namely the ramp-dwell-ramp dynamics. The bounds on the decision variables are $2000m^3 \leq V_{tank} \leq 8000m^3$, $0.25 \leq \varphi \leq 1$ and $500MW \leq P_{pulse} \leq 750MW$.

To evaluate the inequality constraints, a simulation must be performed using the dynamic model of the power conversion system presented in section 2. A multi-objective plant propagation optimization algorithm, as implemented by the Fresa.jl package [5], is used to solve the optimization problem. Fresa is a black-box optimization algorithm that does not require gradients which would be computationally costly to estimate using finite differences. Fresa is also population-based, allowing for many simulations to be run in parallel, making effective use of multi-core desktop computers. The OMJulia.jl

Table 2: Parameters used for the *solve* function of Fresa. For more detailed explanations, please refer to the documentation at ucl.ac.uk/~ucecesf/fresa.html.

Description	Parameter	Value
Number of objective evaluations before stopping	$nfmax$	100
Number of solutions to propagate each generation	np	$(20,40)$
Parameter for similarity function	ϵ	0.01
Multi-objective solutions ranked based on [2]	$fitnesstype$	$:nondominated$
Solutions are compared based on their values of $\boldsymbol{x}$	$issimilar$	$Fresa.similarx$
The non-dominated solutions are automatically included in the next generation	$elite$	$true$
Any pruned non-dominated solutions are added back to the population at the end of the run	$archiveelite$	$true$

Table 3: Infeasibility g of different simulation outcomes, favoring designs that are expected to be closer to being feasible. $t_{failure}$ is the internal simulation time at the failure. ΔV_{MS} is the change in stored hot molten salt at the end of the simulation relative to one full cycle earlier in the simulation.

Simulation Outcome	Reasoning	$\boldsymbol{g}$
Simulation takes longer than $1{,}800s$	Undesirable behaviour, like oscillations, are slowing the simulation	$1e6$
Simulation fails before initialization	Unknown error	$1e3$
Simulation fails after initialization	Molten salt is being greatly over/under-utilized in the design, so P_{pulse} needs to be adjusted	$1+(1-\frac{t_{failure}}{T_{sim}})$
Simulation completes successfully	Designs that underutilize molten salt will be feasible but outcompeted by propagated designs that balance molten salt better and have smaller tanks – useful to keep in the population	$-\frac{\Delta V_{MS}}{V_{tank}}-0.01$

package is used to run the Modelica model within Julia. The Fresa parameters used are presented in Table 2. With these parameters, 126 calls of Fresa.solve are made, each one being initialized with the final population of the previous run. This is necessary to clear simulation processes from memory periodically.

The simulation based objective function assigns an infeasibility value, g, to every design. Designs with g≤0 are considered feasible and other values indicate infeasible designs. This indication of feasible and infeasible is used by Fresa in the selection of solutions to propagate during the search. To help the algorithm search, different simulation outcomes are identified for calculating g, shown in Table 3.

NON-DOMINATED DESIGNS OF THE POWER CONVERSION SYSTEM

The set of non-dominated designs found by the optimization algorithm is presented in Figure 2. The flexibility in turbine operation during a dwell can allow for the volume of the molten salt tanks to be reduced by up to 40.5% at the cost of a 46.3% reduction in the dwell turbine power output relative to pulse values.

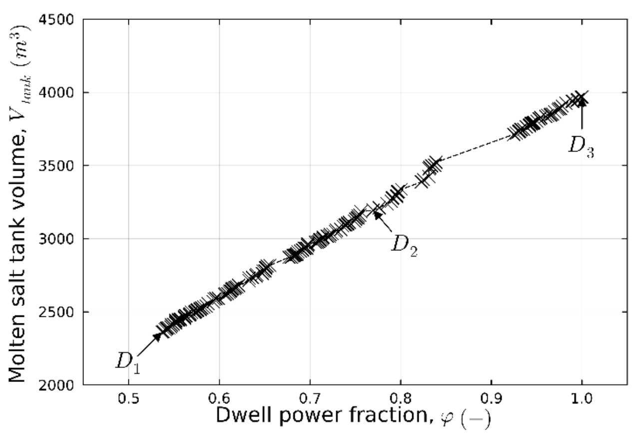

Figure 2: Non-dominated designs showing the trade-off between the size of the thermal energy storage and the fraction of pulse turbine power produced during dwells. Three designs D_1, D_2, D_3 are selected for later discussion.

To investigate the effectiveness of the power conversion system designs, three designs are selected evenly across the range of φ to show their different dynamics. These are shown in Figure 2, and their decision variables are given in Table 4. The dynamics at the turbine are presented in Figure 3, as it is identified as being one of the most sensitive components to large transients.

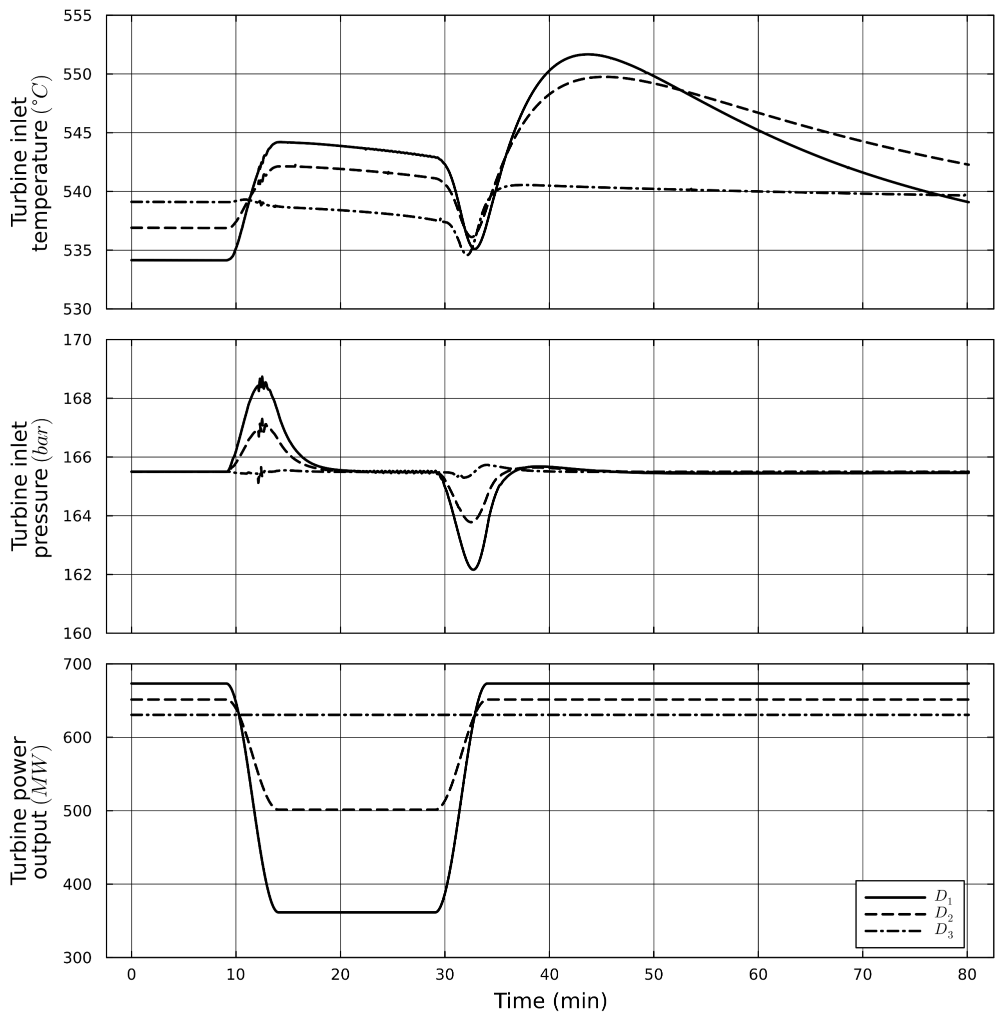

Figure 3: Dynamics of the turbine inlet temperature, inlet pressure and power output of three non-dominated designs from the final population. The time covers a dwell period and part of a subsequent pulse period, when process transients are most significant. Note that the turbine inlet temperature is not directly controlled by a proportional-integral controller, unlike the other two variables.

Table 4: Decision variables of the three highlighted designs in Figure 2.

	V_{tank} (m^3)	φ (-)	P_{pulse} (MW)
D_1	2,363	0.5369	673.2
D_2	3,195	0.7697	651.4
D_3	3,969	1	630.6

Turbine inlet temperature is not directly controlled by any of the controllers and is largely driven by the temperature of molten salt in the hot tank and the flow rate of hot molten salt and steam through the superheater. Design D_3 shows the smallest fluctuation in turbine inlet temperature, which is due to the steam mass flow rate being approximately constant to maintain a constant power output in that design. Designs D_1, D_2 show larger fluctuations due to the decreasing mass flow rate of steam during a dwell. The slower decay of the temperature in design D_2 relative to D_1 is attributed to the increased thermal inertia of molten salt in the hot tank due to the larger tank size, and hence larger mass of 'residual' molten salt that will always be present in valid designs due to the constraints on tank levels discussed in section 3. For all three designs, the temperature change is small enough, and over long enough time periods, that thermal stresses should be acceptable [3].

The turbine inlet pressure is controlled by manipulating the mass flow rate of hot molten salt to the superheater, and the ramp periods can be seen to cause a pressure fluctuation in all the designs. As with the inlet temperature, the magnitude of the changes is larger for designs with larger changes in dwell power, with design

D_3 showing the smallest changes. During the ramp down, all three designs show a small period of small, higher frequency oscillations. This could be due to feedback between multiple controllers or poorly tuned controllers. This could be solved by using more advanced control methods, such as model predictive control, or by including key controller parameters as decision variables.

The turbine power output is well controlled by the controller manipulating the partial arc admission of steam to the turbine, with all designs following the set points well. As expected, designs that produce less power during the dwell produce more power during the pulse, as the total energy input to the system is the same for all designs and hence the total energy output will be the same too, neglecting small differences in efficiency.

Molten salt temperatures below freezing point occur at the preheater and dwell heater outlets for lower values of φ. For every design, heat exchangers are currently sized the same. Resizing the dwell heater for each design, based on its dwell power set point, or adjusting the control system to better regulate molten salt temperatures, such as via electric heaters, could address this.

CONCLUSION

The use of a dynamic process model of a power conversion system for a pulsed fusion power plant in an optimization-based design procedure is presented. The process features the integration of multiple pulsed heat sources of different grades into a single power cycle. Simulations demonstrate this configuration is capable of effectively utilizing the lower grade heat, while maintaining stable operation of the steam Rankine cycle. The dynamic model is developed to minimize simulation time and support automated simulations, allowing for its use within an objective function of an optimization problem.

By using the dynamic model in an optimization framework, the flexibility of the power conversion system design to different dwell operating conditions was investigated. A set of non-dominated designs showed that the size of the molten salt tanks could be reduced by 40.5% by reducing the turbine power output during a dwell by 46.3% relative to during pulse. The dynamics of three non-dominated designs are presented, showing good control of the turbine inlet conditions in all three designs, even for designs with large changes in turbine power output. The control system caused small pressure oscillations in all three designs. Future work could be to include control system parameters as decision variables alongside the process variables considered here and to improve molten salt temperature control. Another interesting direction is to consider plant design for load following.

The optimization methodology can easily be extended to any process model developed in OpenModelica, which is a multi-domain simulation environment. Integration with Julia allows complex analysis to be performed with the design simulation results, giving great flexibility in the objective functions.

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