Economic assessment of different operational reactor cycle structures in a pulsed DEMO-like power plant.

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Economic assessment of different operational reactor cycle structures in a pulsed DEMO-like power plant.

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Abstract

The operative cycle of a pulsed fusion power plant is composed by a sequence of phases whose duration cannot be arbitrarily chosen due to both technical and physical constraints. A pulsed DEMO-like power plant is modeled with the FRESCO code and the optimization of the operative cycle structure is carried out with a genetic algorithm in order to find the economic optimal solution. Specifically, the duration of each cycle phase (current ramp up and ramp down, plasma heating, burn, central solenoid recharge) is changed randomly in order to identify the set of phase durations that minimizes the cost of electricity. The results show that the solution region is populated by local minima. The absolute minimum is achieved when the phases composing the dwell time are minimized. It also emerges that the power plant under study generates cheaper electricity when operating in hybrid mode. Moreover the optimum flat top duration is a function of the heating and current drive costs.

Keywords: Fusion economics, FRESCO code, DEMO, Pulsed operation, Cost of Electricity, Genetic algorithm.

1. Introduction

The cost of the electricity (COE) from fusion is a key driver for the future energy market deployment. The uncertainties on the operative and economic aspects of a fusion power plant (FPP) make the use of stochastic analyses useful for COE estimates [1]. In case of a pulsed FPP, besides the uncertainties on investment an O&M costs, the duty cycle affects the COE as well. Therefore this paper tries to answer to the following questions: a) “How much sensitive is the COE to the cycle structure for a given pulsed power plant?” b) “Which cycle structure minimize the COE for given investment and O&M costs?”.

The investigation is carried out on a pulsed DEMO-like power plant [2] modelled with the FRESCO code [3]. Different operational cycle structures are studied under both physical and technological constraints. Investment and O&M costs are set at their average values for all PP components, but those whose size is affected by the duration of each phase of the cycle. A genetic algorithm [4] coupled with the FRESCO code [3] provides the optimal cycle structure, i.e. that minimizing the COE.

2. Model of a pulsed DEMO-like power plant

The FRESCO code is used to generate the model of a pulsed fusion power plant whose features are taken from the DEMO 1 model proposed by EUROfusion [2]. Table 1 shows the main input parameters together with relevant output.

<table>
<thead>
<tr>
<th>Table 1: Relevant parameters for the DEMO-like pulsed power plant modeling in FRESCO</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input to FRESCO code</strong></td>
</tr>
<tr>
<td>Fusion power (MW)</td>
</tr>
<tr>
<td>2035</td>
</tr>
<tr>
<td><strong>FRESCO code output</strong></td>
</tr>
<tr>
<td>a (m)</td>
</tr>
<tr>
<td>2.9</td>
</tr>
</tbody>
</table>

*Assuming the following blanket and divertor lifetime and time for replacement: blanket (5y, 4m), divertor (3y, 8m). Unexpected unavailability is neglected.

3. Operative cycle phases and constraints

The FRESCO code is conceived for economic assessments of simplified models of FFPs. The approach used for modeling the operative cycle is described in the following referring to Figure 1. The thermal energy generated by fusion reactions during the burn phase is partly converted into electricity and partly stored in a thermal energy storage, operating with solar salt (60% NaNo3, 40% KNO3) [3],[5].

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The FPP lifetime is set at the maximum between 60 y and the number of years needed to perform 2x10^5 cycles. The upper limit to the number of cycles to failure is relaxed to 2x10^5 in order to explore a wider range of possible solutions, also in consideration of possible future technological improvements.

3.1. Plasma current ramp up and ramp down

The resistive component of the flux consumption, which is indeed a function of the current ramp up time, in FRESCO is constrained according to Eq. 1:

$$\int_{t_0}^{t_{RU}} R_p \left[ T(t) \right] i_p dt \geq C_{Ejima} H_p R I_p$$

(1)

where $R_p$ is plasma resistance, that is a function of the plasma temperature $T$, $t_{RU} - t_0 = t_{RU}$ is the current ramp up time, $C_{Ejima}$ is the Ejima coefficient, set to 0.45, $i_p$ is the plasma current and $I_p$ its value at flat top. Eq. 1 asserts that the resistive Volt per second consumptions must be greater than or equal to the minimum flux consumption derived from the Ejima formulation [3].

Then, the assumption of L to H mode transition at the end of the ramp up holds. RF systems are supposed to provide the threshold power calculated with the Martin scaling [6].

The ramp up time depends on the central solenoid (CS) size and performances as well as on requirements for plasma shape control. While the CS technical features and dimensions are not changed in this analysis (height = 18m, average diameter = 3 m, number of turns = 3944), an upper limit for the current ramp up rate is fixed at 0.1 MA/sec, in order to ensure plasma stability, in line with [7]. Similarly, the plasma current ramp down rate cannot be lower than -80 kA/sec which is the limit to ensure plasma shape control [7].

As a consequence in the optimization the following constraints are set on $t_{RU}$ and on the current ramp down time, $t_{RD}$: $200 \text{s} \leq t_{RU} \leq 600 \text{s}; \ 260 \text{s} \leq t_{RD} \leq 900 \text{s}$.

3.2. Plasma current flat top

The flat top phase includes the heating phase ($t_{HF} = t_2 - t_1$) where the plasma is brought to the fusion conditions and the burning phase ($t_{burn} = t_2 - t_3$) where the fusion reactions take place. Thus the flat top time is $t_{FT} = t_{HF} + t_{burn}$.

During the heating phase, H&CD systems deliver power ($P_{HCD}$) to heat the plasma and sustain the plasma current, if required. During the heating phase, additional power ($AP \geq 0$) could be necessary to raise the plasma temperature and thus increase the plasma energy ($\Delta W$) to the operative conditions:

$$\Delta P = 2 \left( \frac{\Delta W}{t_{HF}} - P_{HCD} \right)$$

(2)

Furthermore we assume that additional heating systems provide 50 MW thermal power to plasma during the whole flat top, whatever the operative mode (hybrid i.e. with current drive, or inductive).

3.3. Time for the vacuum vessel pump down

The time for the vacuum vessel (VV) pump-down $t_{pump}$ extends from the end of the current ramp down phase ($t_d$) until the next plasma initiation ($t_i$). In this analysis $t_{pump} = t_d - t_0$ is maintained at a fixed value and derived from the following equation:

$$p(t) = K \left( \frac{e^{at}}{a^t} \right) + \frac{1}{V} K_1 \int_{t_0}^{t} t e^{at} dt$$

where $V = 2213 \text{ m}^3$ is the vessel volume, $p = 0.5 \text{ mPa}$ is the pressure required at $t_d$, $S = 195 \text{ m}^2/\text{sec}$ is the pumping speed, $a = S/V, K_1 = 9 \text{ Pa m}^3/\text{s}$ is the outgassing rate and $n = -0.73$ is the decay index, according to [7,8]. The resulting $t_{pump}$ is 502 sec.

3.4. Time for Central Solenoid recharge

The time allowed for CS recharge, $t_{CS}$ is inversely proportional to the power from the electric grid ($P_{grid}$): through the energy stored in the solenoid ($E_{CS}$): $P_{grid} = E_{CS}/t_{CS}$. Whenever $P_{grid}$ exceeds 500 MW, an inductive storage system is added to the PP model. The costs of the CS power supply (PS) and the inductive storage (IS) are estimated as follows:

$$PS = k_1 \cdot P_{grid}^{2/3}$$

$$IS = k_2 \cdot (E_{CS}/0.9)^{0.47}$$

where $k_1$ and $k_2$ are unit costs, according to [10].

3.5. Dwell time

The dwell time ($t_{dwell}$) extends from the end of the burn until the beginning of the next heating phase. It therefore includes all the cycle phases, but flat top.

Since the CS is charged while the VV is pumped down, the two phases can partially or fully overlap. Thus the dwell time is recovered as:

$$t_{dwell} = t_{RU} + \max \left( t_{CS}, t_{pump} \right) + t_{RD}$$

(3)

Being $t_{dwell}$ a linear combination of optimization variables, further constrains are not set on this parameter.

4. Genetic algorithm

Genetic Algorithms (GAs) are numerical search tools able to efficiently find the global optimum of a real
objective function, whose natural applications are the multi-parametric optimization problems. A GA generates a set of possible solutions (the duration of the phases of the cycle, in the present work). Each candidate is then supplied to FRESCO to compute the corresponding COE. Only candidates that result in a low cost of energy are allowed to participate to the generation of the next set of test vectors, going through a mutation/crossover process. For the present optimization we select the Differential Evolution (DE) scheme [11] because it performs well for multidimensional real-valued functions and does not use gradients technique to look for the best solution: DE is a good choice for very noisy problem, as in the present case.

5. Results and Discussion

The genetic algorithm is coupled to FRESCO in order to identify the set of phase lengths ($\tau_{\text{CV}}$, $\tau_{\text{RU}}$, $\tau_{\text{H}}$, $\tau_{\text{H&CD}}$, $\tau_{\text{thermal}}$, $\tau_{\text{ru}}$) that minimizes the cost of electricity. The COE (Eurocent/kWh) is calculated with the levelized cost method [12] and discounted to year 1990.

Three cases are studied with different assumption on unit costs (low - medium - high) of cycle sensitive PP components, i.e. those components whose size depends on the cycle phase duration, namely H&CD system, CS power supply, thermal storage, magnet structure. As for the costs of the remaining components, they are fixed at the average values listed in [3].

The optimization demonstrates that the best set of phase durations indeed depends on the costs of the cycle sensitive components (Table 1). For example the optimal $\tau_{\text{ru}}$ decreases as the unit cost of those components (especially H&CD) increases.

In the following the relation between the cycle phase durations and the COE is discussed with reference to the “medium cost” case.

Table 1: Results from optimization.

<table>
<thead>
<tr>
<th>Optimisation variables</th>
<th>Low cost</th>
<th>Medium cost</th>
<th>High cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_{\text{CV}}$ (s)</td>
<td>502</td>
<td>502</td>
<td>502</td>
</tr>
<tr>
<td>$\tau_{\text{RU}}$ (s)</td>
<td>200</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>$\tau_{\text{H}}$ (s)</td>
<td>7</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>$\tau_{\text{H&amp;CD}}$ (s)</td>
<td>10692</td>
<td>7721</td>
<td>5690</td>
</tr>
<tr>
<td>$\tau_{\text{thermal}}$ (s)</td>
<td>260</td>
<td>260</td>
<td>260</td>
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</table>

<table>
<thead>
<tr>
<th>Relevant parameters</th>
<th>Low cost</th>
<th>Medium cost</th>
<th>High cost</th>
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<tr>
<td>Total cycle time</td>
<td>3h 15'</td>
<td>2h 25'</td>
<td>1h 51'</td>
</tr>
<tr>
<td>$\tau_{\text{FT}}$ (s)</td>
<td>10699</td>
<td>7729</td>
<td>5700</td>
</tr>
<tr>
<td>$\tau_{\text{ru}}$ (s)</td>
<td>962</td>
<td>962</td>
<td>962</td>
</tr>
<tr>
<td>Duty cycle</td>
<td>0.91</td>
<td>0.89</td>
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</tr>
<tr>
<td>PP lifetime (y)</td>
<td>49</td>
<td>44</td>
<td>34</td>
</tr>
<tr>
<td>$P_{\text{C}}$ [MWe]</td>
<td>168</td>
<td>145</td>
<td>117</td>
</tr>
<tr>
<td>$P_{\text{E}}$ [MWe]</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Auxiliary power (MWe)</td>
<td>419</td>
<td>364</td>
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<tr>
<td>$\tau_{\text{s}}$ (s)</td>
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<tr>
<td>$\Delta P$ (MW)</td>
<td>12</td>
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<tr>
<td>Net electric power (MW)</td>
<td>375</td>
<td>390</td>
<td>290</td>
</tr>
<tr>
<td>COE (Eurocent/kWh)</td>
<td>73</td>
<td>84</td>
<td>102</td>
</tr>
</tbody>
</table>

Figure 2: COE contour plot as a function of $\tau_{\text{RU}}$ and $\tau_{\text{H&CD}}$. (*) is the best case.

Figure 3: COE contour plot as a function of $\tau_{\text{ru}}$ and $\tau_{\text{FT}}$. (*) is the best case.

Figure 4: Plot of $\tau_{\text{ru}}$ vs $\tau_{\text{FT}}$. $\Delta P$ is the additional power possibly required to raise the plasma temperature to burn conditions.

5.1. Minimum time for current ramp up and ramp down

In Figure 2 COE is plotted as a function of $\tau_{\text{RU}}$ and $\tau_{\text{H&CD}}$; the minimum values allowed for $\tau_{\text{ru}}$ and $\tau_{\text{FT}}$ (see section 3.1) provide the optimal solution.

Small changes in $\tau_{\text{RU}}$ (+10%) turn into relevant COE increase (+25% in the worst case) due to the linear relation between $\tau_{\text{ru}}$ and magnetic flux consumption [3]. In fact, modest flux availability during the flat top corresponds to great and costly H&C&CD power. On the other hand, even large increase of $\tau_{\text{H&CD}}$ (+80%) have a small impact on COE (+15% in the best case) since it effects $\tau_{\text{ru}}$ only.
5.2. Overlap of CS recharge and VV pump-down phases

As for $\tau_{CS}$, the region explored ranges from 200 to 900 s. However the optimal $\tau_{CS}$ is as long as $\tau_{pump}$. Thus, in the optimal solution the two operations perfectly overlap. In the optimal case, 60 MW are required to recharge the CS. Shorter $\tau_{CS}$ would increase the cost of the power supply and, in the worst case, would require an additional inductive storage. On the other and, if $\tau_{CS}$ exceeds $\tau_{pump}$, COE increases because of a longer $\tau_{dwell}$.

5.3. The dwell time is minimized

Being the optimal $\tau_{dwell}$ and $\tau_{RD}$ the minimum values allowed (see 5.1) and $\tau_{CS} = \tau_{pump}$ (see 5.2), the optimal $\tau_{dwell}$ (eq. 2) is the minimum allowed as well. Nevertheless room exists for an extension of $\tau_{dwell}$ (+30%) with small COE increase (+10%) as showed by the COE contour plot in Figure 3. However, the flexibility on $\tau_{dwell}$ in the neighborhood of the optimal value is actually limited to $\tau_{RD}$ (see 5.1).

5.4. Flat top duration

Figure 3 maps the values of COE as a function of $\tau_{dwell}$ and $\tau_{FT}$. It shows that the optimal solution ($\tau_{FT} = 7729$ s and $\tau_{dwell} = 962$ s) is the absolute minimum with the given constraints and that several local minima do exist. As $\tau_{FT}$ is reduced, the number of operative cycles per year increases, then, due to the constraint on the maximum allowable cycles to failure, a too short $\tau_{FT}$ shortens the PP lifetime and thus increases COE (see [3]). On the other hand, longer $\tau_{FT}$ would turn into greater requirements for H&CD power to sustain a larger non-inductive plasma current component. However, in this case of study, even large increases of $\tau_{FT}$ (up to by a factor of 5) turns into a COE rise not exceeding 30%.

5.5. Heating phase duration

In Figure 4 the dotted line contains all the possible solutions with $\Delta P = 0$. As shown in the same figure the optimal solution lies on this line, i.e. $\tau_{H}$ and $\tau_{PT}$ are such that $P_{HCD} = AW/\tau_{H}$. As $\Delta P$ increases, the COE raises as expected.

6. Conclusions

The optimization performed with the genetic algorithm demonstrates that an absolute optimal solution does exist. In particular, the optimal cycle duration decreases (from 3h 15' to 1h 51') as unit costs of cycle sensitive PP components increase.

The COE contours plotted as a function of the duration of the cycle phases clearly show that numerous local minima also exist.

For all the three cost cases considered the minimum COE is achieved at the minimum allowed $\tau_{dwell}$. Further $\tau_{dwell}$ reduction could be hardly achieved by shortening $\tau_{dwell}$ and $\tau_{SP}$, whose minimum length is determined by physical constraints (plasma shape control); $\tau_{pump}$ could be lowered, by improving material and cryopump system performances. However, in order to affect $\tau_{dwell}$, $\tau_{pump}$ reduction should be accompanied by shorter $\tau_{CS}$, which in turn claims for more costly CS power supply. The optimal $\tau_{PT}$ is a function of the cost of the H&CD power system. In fact, more optimistic assumptions on the cost of additional power systems lead to longer operative cycle and reduced COE for the PP model under study.

The uncertainties on the costs and reliability of components along with uncertainties on financial issues would definitely further enlarge the range of the COE estimations. Stochastic analyses coupled to optimisation algorithms would be therefore advisable to deepen the relation between the operative cycle structure and the economics of a pulsed FPP.

Acknowledgments

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References