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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 1: Relevant parameters for the DEMO-like pulsed power plant modeling in FRESCO

Input to FRESCO code	
Fusion power (MW)	2035
Te (keV)	13
n (10^{19} m^{-3})	0.79
Pedestal	yes
A	3
k	1.59
δ	0.33
q	3
Z_{eff}	2.58
Bootstrap fraction (%)	34.8
H&CD efficiency (%)	40
FRESCO code output	
a (m)	2.9
R (m)	9
Wall loading (MW/m^2)	1.14
Plasma current (MA)	20
AF (%) *	80

*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:

$$\int_{t_0}^{t_1} R_p\,[T(t)]i_p dt \ \geq C_{Ejima}\mu_0 R I_p \qquad (1)$$

where R_p is plasma resistance, that is a function of the plasma temperature T, t_1-t_0 = τ_{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 τ_{RU} and on the current ramp down time, τ_{RD}: $200\,s \leq \tau_{RU} \leq 600\,s$; $260\,s \leq \tau_{RU} \leq 900\,s$.

3.2. Plasma current flat top

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

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 ($\Delta P \geq 0$) could be necessary to raise the plasma temperature and thus increase the plasma energy (ΔW) to the operative conditions:

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

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).

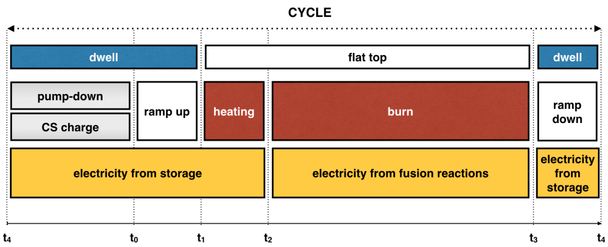

Figure 1: Operative cycle structure in a pulsed fusion power plant.

The constraints are set on τ_H and τ_{FT}: $5\,s \leq \tau_H \leq 300\,s$; $1800\,s \leq \tau_{FT} \leq 30000\,s$.

3.3. Time for the vacuum vessel pump down

The time for the vacuum vessel (VV) pump-down τ_{pump} extends from the end of the current ramp down phase (t_4) until the next plasma initiation (t_0). In this analysis $\tau_{pump} = t_4 - t_0$ is maintained at a fixed value and derived from the following equation:

$$p(t) = \frac{K_1}{S}\left(\frac{e^a}{e^{at}}\right) + \frac{1}{e^{at}}\frac{K_1}{V}\int_{t_4}^{t_0} t^n e^{at}\,dt$$

where V= 2213 m^3 is the vessel volume, p = 0.5 mPa is the pressure required at t_4, S = 195 m^3/sec is the pumping speed, $a = S/V$, K_1 = 9 Pa m^3/s is the outgassing rate and n = -0.73 is the decay index, according to [7,8]. The resulting τ_{pump} is 502 sec.

3.4. Time for Central Solenoid recharge

The time allowed for CS recharge, τ_{CS} is inversely proportional to the power from the electric grid (P_{grid}): through the energy stored in the solenoid (E_{CS}): $P_{grid} = E_{CS}/\tau_{CS}$. 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]. The constraints on τ_{CS} are: $540\,s \leq \tau_{CS} \leq 900\,s$.

3.5. Dwell time

The dwell time (τ_{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:

$$\tau_{dwell} = \tau_{RU} + max(\tau_{CS}, \tau_{pump}) + \tau_{RD} \qquad (3)$$

Being τ_{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 (τ_{CS}, τ_{RU}, τ_{H}, τ_{burn}, τ_{RD}) 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 τ_{burn} 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.

	Low cost	Medium cost	High cost
Optimisation variables			
τ_{CS} (s)	502	502	502
τ_{RU} (s)	200	200	200
τ_{H} (s)	7	8	10
τ_{burn} (s)	10692	7721	5690
τ_{RD} (s)	260	260	260
Relevant parameters			
Total cycle time	3h 15'	2h 25'	1h 51'
τ_{FT} (s)	10699	7729	5700
τ_{dwell} (s)	962	962	962
Duty cycle	0.91	0.89	0.85
PP lifetime (y)	59	44	34
P_{CD} [MWth]	168	145	117
P_{H} [MWth]	0	0	0
Auxiliary power (MWe)	419	364	292
τ_{e} (s)	2.9	3.1	3.3
Q	12	14	17
Net electric power (MW)	375	390	290
COE ($_{1990}$EURcent/kWh)	73	84	102

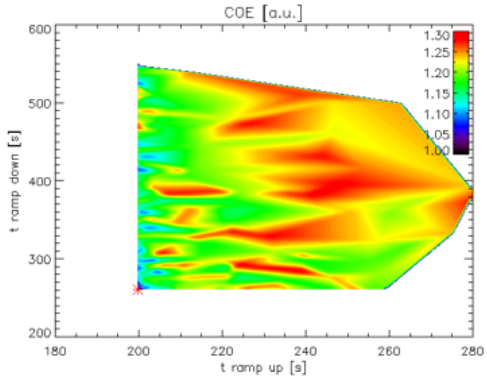

Figure 2: COE contour plot as a function of τ_{RU} and τ_{RD}. (∗) is the best case.

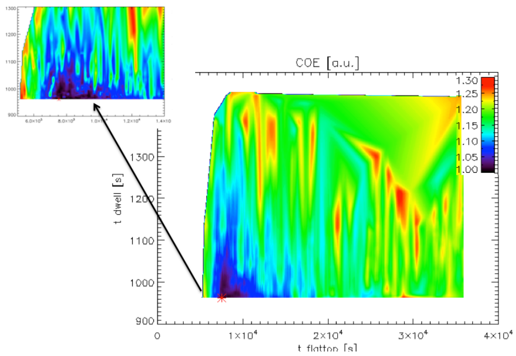

Figure 3: COE contour plot as a function of τ_{dwell} and τ_{FT}. (∗) is the best case.

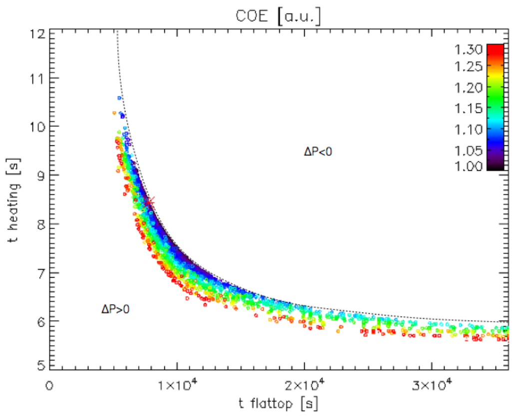

Figure 4: Plot of τ_{H} vs τ_{FT}. ΔP is the additional power possibly required to raise the plasma temperature to burn conditions.

5.1. *Minimum time for current ramp up and ramp down*

In Figure 2 COE is plotted as a function of τ_{RU} and τ_{RD}; the minimum values allowed for τ_{RU} and τ_{RD} (see section 3.1) provide the optimal solution.

Small changes in τ_{RU} (+10%) turn into relevant COE increase (+25% in the worst case) due to the linear relation between τ_{RU} and magnetic flux consumption [3]. In fact, modest flux availability during the flat top corresponds to great and costly H&CD power. On the other hand, even large increase of τ_{RD} (+80%) have a small impact on COE (+15% in the best case) since it effects τ_{dwell} only.

5.2. *Overlap of CS recharge and VV pump-down phases*

As for τ_{CS}, the region explored ranges from 200 to 900 s. However the optimal τ_{CS} is as long as τ_{pump}. Thus, in the optimal solution the two operations perfectly overlap. In the optimal case, 60 MW are required to recharge the CS. Shorter τ_{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 τ_{CS} exceeds τ_{pump}, COE increases because of a longer τ_{dwell}.

5.3. *The dwell time is minimized*

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

5.4. *Flat top duration*

Figure 3 maps the values of COE as a function of τ_{dwell} and τ_{FT}. It shows that the optimal solution (τ_{FT} =7729 s and τ_{dwell}=962 s) is the absolute minimum with the given constraints and that several local minima do exist. As τ_{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 τ_{FT} shortens the PP lifetime and thus increases COE (see [3]). On the other hand, longer τ_{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 τ_{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 lays on this line, i.e. τ_{H} and τ_{FT} are such that $P_{\mathrm{HCD}} = \Delta W / \tau_{\mathrm{H}}$. As ΔP 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 τ_{dwell}. Further τ_{dwell} reduction could be hardly achieved by shortening τ_{RU} and τ_{RD}, whose minimum length is determined by physical constraints (plasma shape control); τ_{pump} could be lowered, by improving material and cryopump system performances. However, in order to affect τ_{dwell}, τ_{pump} reduction should be accompanied by shorter τ_{CS}, which in turn claims for more costly CS power supply. The optimal τ_{FT} 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

[1] Bustreo, C. et al., The Monte Carlo approach to the economics of a DEMO-like power plant, Fusion Engineering and Design 98–99 (2015) 2108–2111
[2] DEMO1 – pulsed power plant with conservative technology, PROCESS 382 : Run on Thu Apr 16 16:10:11 BST 2015 by Richard Kemp Reactor concept design: Pulsed tokamak model, (c) CCFE; Available on: http://www.ccfe.ac.uk/powerplants.aspx
[3] Bustreo, C. et al., FRESCO, a simplified code for cost analysis of fusion power plants, Fusion Engineering and Design 88 (2013) 3141–3151
[4] Sattin, F. et al., Difficulties and solutions for estimating transport by perturbative experiments, Plas. Phys. Contr. Fusion 56 (2014) 114008
[5] Bubelis, E. et al., Final Report on Deliverable Conceptual Design Definition for an Intermediate Cooling Loop Configuration and Coolant, 2014, EFDA_D_2HDVN9
[6] Martin, Y. R., et al., Power requirement for accessing the H-mode in ITER. In: *Journal of Physics: Conference Series*. IOP Publishing, 2008. p. 012033.
[7] Vincenzi, P. et al., EU DEMO transient phases: main constraints and heating mix studies for ramp-up and ramp-down, 2016, 29th SOFT, P4.19.
[8] Battes, K. et al., Basic considerations on the pump-down time in the dwell phase of a pulsed fusion DEMO, Fusion Engineering and Design 100 (2015) 431-435
[9] Wykes, M. et al., Assessment of the ITER dwell pump-down, in: Proceedings of the 21st Symposium on Fusion Engineering (SOFE 2005), IEEE, New York, 2006
[10] W.R. Spears, The SCAN-2 cost model, EUR-FU/XII-80/86/62, 1986.
[11] R. Storn, K. Price, Differential Evolution – A Simple and Efficient Heuristic for global Optimization over Continuous Spaces, Journal of Global Optimization 11 (1997) 341-359
[12] Projected Costs of Generating Electricity, 2010 Edition, OECD Publications, Paris, 2010.