Scenario optimisation for ITER

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Introduction Automatic design and tracking of close-to-optimal control signals is of high interest for present tokamak operation and most certainly crucial for ITER. As opposed to presently operated tokamaks, ITER does not allow the discovery of an operating optimum by trial and error because of the high risk of damage to the tokamak and its surrounding systems in the discovery process. ITER operation thus requires design of control strategies which allow close-to-optimal operation while avoiding possibly harmful disruptions. Although close-to-optimal performance means, in the vast majority of cases, operation near mechanical or stability limits and thus risk increase, ITER must explore this operation space in order to reach its design purpose, i.e. demonstrate the feasibility of fusion as an economically viable energy provider.

Optimal control often consists of an open-loop control strategy in which the optimal actuator trajectories are computed before performing the plasma pulse and implemented as pre-programmed signals during the pulse itself. This is well-suited for processes that do not require strong feedback such as plasma heating [1], but this may lead to poor results when applied to plasma equilibrium control due to the intrinsic instabilities of plasma equilibria and possibly significant modelling errors. It is thus necessary to develop optimal control strategies that will allow close-to-optimal operation while minimising the risk of disruption. In this paper, we present our latest development of such strategies, namely the optimisation of *scenario* trajectories, as opposed to *actuator* trajectories. We expose the fact that this approach, although not a feedback strategy, allows automated close-to-optimal operation while avoiding loss of plasma equilibrium control. Feedback optimal control strategies are also discussed as possible future work, especially Necessary Conditions of Optimality (NCO) tracking strategies.

The DINA-CH full tokamak simulator [2] provides an ideal framework to test this class of control strategies. DINA-CH was therefore used as a validation step before possible implementation on a real tokamak.

Problem statement In a plasma pulse, the ramp-up phase is extremely demanding on several plant systems. Regarding plasma equilibrium evolution, the most critical limitations are those of finite PF coil power supply voltages and the maximum currents flowing in the PF coils. For that reason, it is of interest to try and maximise the plant systems distance to their respective limits, while maintaining the desired plasma shape and current.

In the case of ITER, plasma shape is defined by 6 *gaps* distributed around a poloidal cross-section of the tokamak. They consist of 6 distances between the limiting surfaces and the last closed flux surface with respect to 6 reference points and lines of sight. On the other hand, ITER possesses 11 distinct PF coil main converter power supplies. Therefore, optimising the distribution of PF coil currents while maintaining the 6 gaps and plasma current close to their respective references may be envisaged, since the system is under constrained.

This problem may be stated in the standard optimal control format:

$$\min_u J(u) = \int_{t_0}^{t_f} \left[q_u u^2 + q_x x^2 + q_{ref} (x - x_{ref})^2 \right] dt ,$$

with the definitions

$$x = \begin{bmatrix} I_{CS3U} & \cdots & I_{PF6} & I_P & gap_1 & \cdots & gap_6 \end{bmatrix}^T$$

$$u = \begin{bmatrix} V_{CS3U} & \cdots & V_{PF6} \end{bmatrix}^T$$

$$x_{ref} = \begin{bmatrix} I_{CS3U_{ref}} & \cdots & I_{PF6_{ref}} & I_{P_{ref}} & gap_{1_{ref}} & \cdots & gap_{6_{ref}} \end{bmatrix}^T$$

$$q_x = \begin{bmatrix} q_{I_{CS3U}} & \cdots & q_{I_{PF6}} & 0 & 0 & \cdots & 0 \end{bmatrix}$$

$$q_{ref} = \begin{bmatrix} 0 & \cdots & 0 & q_{I_P} & q_{gap_1} & \cdots & q_{gap_6} \end{bmatrix}$$

$$q_u = \begin{bmatrix} q_{V_{CS3U}} & \cdots & q_{V_{PF6}} \end{bmatrix} .$$

The autonomous state evolution is given by

$$\dot{x} = f(x, u) \qquad \text{such that} \qquad x(t_0) = x_0 ,$$

and the following constraints

$$I_{PF_i} \le I_{PF_i\ max} \qquad u_L \le u \le u_U \qquad gaps(t_f) = gaps_f \qquad I_P(t_f) = I_{P_f} .$$

The weightings q are arbitrary. They embodied the quantitative aspect of the cost function. q_u and q_x encapsulate the requirement to maximise the distance of the PF coil currents and voltages to their limits. q_{ref} enforces the following requirements: (a) we demand high fidelity in the reference gap tracking, (b) we require lesser fidelity in the reference plasma current tracking, and (c) we do not require reference PF coil currents tracking. We penalise the proximity to the PF coil current limits and PF coil power supply voltages limits with the same order of magnitude.

Modelling The problem statement expressed earlier requires the definition of an autonomous state evolution function in order to be complete. In other words, modelling of the plant evolution according to given control u and state x is required. This modelling ought to remain as simple as possible, in order to increase the speed and accuracy of the optimum calculation.

With that in mind, we develop a simple nonlinear toy-model of the PF coil current, plasma current and gap evolution according to the PF coil power supply voltages evolution:

$$\begin{bmatrix} \dot{I}_{CS3U} \\ \vdots \\ \dot{I}_{PF6} \\ \dot{I}_{P} \end{bmatrix} = \underline{\underline{M}}^{-1} \left(\begin{bmatrix} V_{CS3U} \\ \vdots \\ V_{PF6} \\ 0 \end{bmatrix} - \underline{\underline{\Omega}} \cdot \begin{bmatrix} I_{CS3U} \\ \vdots \\ I_{PF6} \\ I_{P} \end{bmatrix} \right),$$

where

$$\underline{\underline{M}} = \begin{bmatrix} L_{CS3U} & M_{CS3U-CS2U} & \cdots & M_{CS3U-PF6} & M_{CS3U-plasma} \\ M_{CS3U-CS2U} & L_{CS2U} & & \vdots & \vdots \\ \vdots & & \ddots & & \\ M_{CS3U-PF6} & \cdots & & L_{PF6} & M_{PF6-plasma} \\ M_{CS3U-plasma} & \cdots & & M_{PF6-plasma} & L_{P} \end{bmatrix} \quad \underline{\underline{\Omega}} = \begin{bmatrix} \Omega_{CS3U} & 0 & 0 & 0 \\ 0 & \ddots & 0 & 0 \\ 0 & 0 & \Omega_{PF6} & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix},$$

where L_i is the self-inductance of the i-th PF coil, M_{ij} is the mutual inductance between the i-th and j-th PF coils, Ω_i is the resistance of the i-th PF coil and the plasma is treated as a rigid static coil in the middle of the vacuum vessel. The gap evolution is given by

$$\dot{gap}_i = C(gap_i)\frac{I_P}{2\pi R_{gap_i}} \begin{bmatrix} M_{CS3U-gap_i} & \cdots & M_{PF6-gap_i} & M_{plasma-gap_i} \end{bmatrix} \cdot \underline{\underline{M}}^{-1} \begin{bmatrix} V_{CS3U} \\ \vdots \\ V_{PF6} \\ 0 \end{bmatrix}$$

where $C(gap_i)$ is a gap-dependent constant, which corresponds to the average poloidal magnetic field 'near' gap_i, R_{gapi} is the R-coordinate of the intersection between the gap line of sight and the limiter, and $M_{PFj-gapi}$ is the mutual inductance between the j-th PF coil and a rigid static coil 'near' gap_i.

This modelling of PF coil current, plasma current, and gaps evolution provides adequate results for us to perform the desired optimisation procedure. This model assumes that the action of vertical stabilisation provided by VS1 does not notably affect the flux state or the gaps.

Optimisation procedure and results The optimisation was performed using a direct sequential approach with forward sensitivity analysis to increase the optimiser performance.

The converged value of the cost quickly reaches its minimum value for a low number of stages, namely $n_s = 3$.

This procedure provided a set of proposed optimal PF coil power supply voltages trajectories. However, as opposed to many processes that use optimal control approaches, we cannot directly apply these voltages directly on the simulated tokamak because of the fact that open loop control is not able to reject disturbances, which we know to exist and to be rather large and unexpected during tokamak operation.

We therefore implemented the optimised *scenario* trajectories, namely the PF coil currents, plasma current, and gap trajectories, onto the DINA-CH full tokamak simulator. Thanks to previously developed controllers, these newly defined scenario trajectories are successfully tracked during the simulated plasma pulse.

This scenario trajectory optimisation strategy demonstrated encouraging preliminary results and denoted a clear decrease of the cost function when compared with a nominal scenario.

Conclusion and future work Optimal control strategies have been applied to the problem of plasma equilibrium evolution. However, this requires the development of more advanced strategies than the standard optimal control open loop strategy. An example of such an alternative strategy is optimal scenario trajectories tracking, as performed in this study. This strategy, although demonstrating acceptable behaviour, remains a pre-programmed strategy – which may not be adequate for real tokamak operation.

Future work will therefore include the study of NCO tracking strategies, thus allowing pure feedback optimal control.

References

[1] Federico Felici, '*Optimization, real-time simulation and feedback control of tokamak plasma profiles on TCV*', this conference.

[2] Jo Lister, '*Development of the DINA-CH full tokamak simulator*', and references therein, this conference.

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