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INTRA-SHOT TOOLS FOR PLASMA SCENARIO OPTIMIZATION AND MAGNETIC CONTROL

M. MATTEI[1,2], L.E. DI GRAZIA[2] and D. FRATTOLILLO[1,2]
[1]Università di Napoli Federico II, Napoli, Italy
[2]Consorzio CREATE, Napoli, Italy
Email: massimiliano.mattei@unina.it

Abstract

Scenario design tools will be very important in view of the start-up and operation of future large tokamaks like ITER. An efficient design procedure can reduce costs and risks, and a well designed ramp-up can have a positive influence on the quality of the entire pulse. The success of a ramp-up is strongly dependent on magnetic control, and in particular on the design of current and voltage waveforms. Model based intra-shot optimization tools have been proved to be useful for the magnetic design of plasma initiation and early ramp-up scenarios with experiments on TCV and MAST-U by the authors of this paper. The possibility to extend such procedures to design an entire ramp-up has been more recently tested on MAST-U. The proposed algorithm is based on iterative learning control concepts. After a first model-based design obtained with classical tools, the scenario is corrected step by step solving a linearly constrained quadratic optimization problem which makes use of the results of previous experiments. Up to now the procedure was used without considering closed loop control action controlling plasma current and shape but the vertical stabilization controller. This paper describes how the algorithm was modified to account for the beneficial contribution of closed loop control which may help to reduce the number of iterations to converge to an optimal scenario. Examples on the design of a ramp-up for JT-60SA and ITER tokamak are presented.

1. INTRODUCTION

The definition and optimization of plasma scenarios is a key element for the success of tokamak research and operations. Scenarios are defined in term of events determining plasma current ramp-up, flat top and ramp-down of the plasma current. The way the actuators (not only magnetic) are used to implement the desired sequence of plasma conditions is the objective of scenario design which has been the subject of many scientific papers [1, 2]. Scientists and operators try to achieve the desired sequence of plasma states using knobs at their disposition including auxiliary heating, active circuit currents, fuelling, etc.

Besides the scenario definition, the capability of controlling the plasma along the optimized target sequence of dynamic equilibria is of paramount importance. For the control of plants whose desired behaviour is known in advance, the adoption of a feedback plus feed-forward control strategy is common, where the feed-forward action is optimized using a mathematical model of the plant, and the feedback part of the control action compensates for the effects of errors and uncertainties in modelling, and for the presence of possible external disturbances. If the controlled plant is asymptotically stable, iterative procedures such as the so-called ILC (Iterative Learning Control) can improve performance, provided that control tasks are performed repetitively [3]. In particular, one can consider previous experimental data to correct the system behaviour over (almost repetitive) disturbances and uncertainties (see the workflow represented in Fig. 1).

For plasma scenario optimization, if the correction process takes short time compared to the duration of the interval between two consecutive pulses, the iterative approach can be used to set-up a so called intra-shot optimization procedure. ILC for intra-shot procedures have been proposed for TCV [4] and MAST-U [5] for the breakdown and early ramp-up phases. Both are based on the results described in [6]. The user can decide the desired breakdown location, the time evolution of some magnetic quantities including the magnetic field map in the vacuum chamber, and the target evolution of the electric field, based on inductive loop voltage, at the plasma Breakdown (BD) location. The design problem is formulated and solved as a Quadratic Programming (QP) problem with linear constraints assuming some simplifying hypotheses. Constraints include coil currents and power supply voltage limits.

The ILC approach was more recently applied to the entire MAST-U ramp-up: this extension has been done under RT04 campaign in 2024 and required a methodological revision to take into account elongated plasma shapes. For larger tokamaks with superconducting coils like ITER, the problem becomes more complex because of the more important effect of the passive structures slowing down the field penetration time for active control. The authors already proved the possibility of applying a shot to shot procedure for start-up optimization for this class of tokamaks in [7].

The novelty of the present paper with respect to the previous ones by the same co-authors is to take into account feedback action in the intra-shot design procedure and to present numerical results on large tokamaks like JT-60SA and ITER.

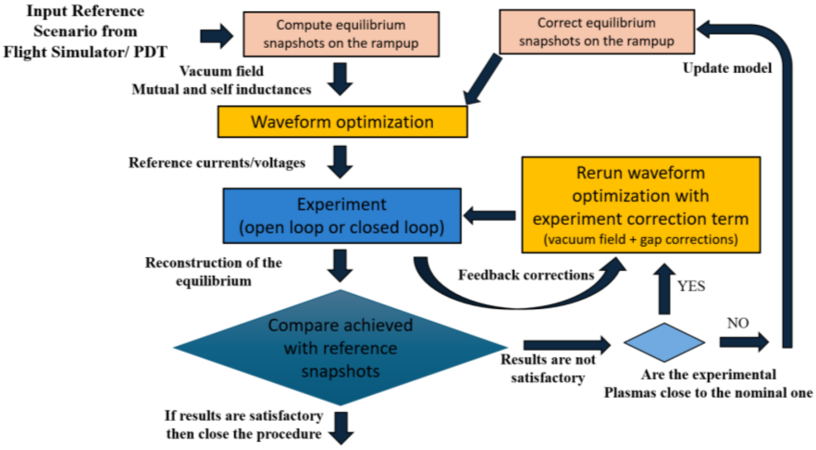

FIG. 1. Workflow of the ILC intra-shot procedure.

2. THE SCENARIO DESIGN PROBLEM

Magnetic control in tokamaks often consists of a nominal pre-designed control action (also called feedforward control action), and a feedback control action calculated in real-time. The design of the nominal feedforward control action consists in calculating currents in the active control circuits to drive plasma evolution through a desired sequence of plasma equilibria whereas feedback provides corrections to counteract uncertainties and possible disturbances or unpredictable events. The currents requested by both feedforward and feedback actions are then tracked by a current controller driving voltages on the coils power supplies. The objective of this paper is to describe a technique to compute active coil currents, based on a simple model of the plant, aimed at achieving a plasma scenario. Then the design is corrected, shot after shot, on the basis of the experimental results mitigating the effects of possible modelling errors and uncertainties. The experiments are done with closed loop control and the feedback control action is taken into account in the step by step procedure.

The starting point is the characterization of a reference scenario in terms of time histories of plasma current, shape and main plasma parameters. Then, as shown in the workflow depicted in Fig. 1, a significant number of equilibrium snapshots are computed. This allows to compute the vacuum magnetic field evolution for the given snapshots, and a Linear Time Varying (LTV) model for conductors and plasma dynamics. The LTV model also links the value of the active, passive, and plasma currents to the vacuum magnetic field map and to the plasma shape descriptors of interest (e.g. plasma wall distances at given locations, namely gaps).

Then a model based optimization problem to compute scenario active current and voltage waveforms is solved. Experiment is done and, if the control performance is satisfactory, the procedure is ended, otherwise, if plasma misalignments with respect to the nominal expected plasma are moderate, the experimental data are used to re-run a modified optimization procedure and the current and voltage waveforms are updated. If instead plasma evolution is significantly different from the expected one, an update of the equilibrium snapshots and corresponding models is needed. In this case a new set of equilibrium snapshots has to be computed.

3. SIMPLIFIED MODEL OF THE PLASMA-CIRCUIT INTERACTION

The following equations describe the dynamic behaviour of both passive and active currents and their impact on the flux and field distributions in the vacuum chamber:

$$L_{aa}\dot{I}_a(t) + L_{au}\dot{I}_u(t) + L_{ap}(t)\dot{I}_p(t) + \big(R_a + R_{SN}(t)\big)I_a(t) = V_a(t) \qquad (1a)$$
$$L_{ua}\dot{I}_a(t) + L_{uu}\dot{I}_u(t) + L_{up}(t)\dot{I}_p(t) + L_{uu}I_u(t) = 0 \qquad (1b)$$

$$\left(L_{pa}(t)\dot{I}_a(t) + L_{pu}(t)\dot{I}_u(t)\right) \cdot 1(t - t_{BD}) + L_{pp}(t)\dot{I}_p(t) + R_p(t)I_p(t) = 0 \quad (1c)$$
$$y = C_a I_a + C_u I_u + C_p I_p \quad (1d)$$
$$y_v = C_{av} I_a + C_{uv} I_u \quad (1e)$$
$$I_a(t_0) = I_{a0},\ I_u(t_0) = 0,\ I_p(t_0) = 0 \quad (1f)$$

where I_a is the vector of currents in the active PF (Poloidal Field) circuits, I_u is the vector of eddy currents in the passive structures, I_p is the plasma current, *L*(*t*) and *R(t)* are possibly time varying mutual inductance and resistance matrices ($R_{SN}(t)$ is the resistance matrix of the Switching Networks Resistors used at the start of the discharge and during the early phase of the ramp up to increase the loop voltage on the plasma), *C* are the matrices linking the active currents to outputs. 1(*t*) is the Heaviside function which is used to activate plasma current dynamics at the BD time t_{BD}. y_v is a vector of magnetic vacuum fields and/or fluxes in points of interest, named Control Points (CPs), where the value of the magnetic field and of the electric field is optimized/constrained. For the early ramp-up phase [3], the plasma is modelled as a circular rigid conductor with a given resistance, a fixed position and volume, and a prescribed current distribution. At higher plasma currents, information on the reference scenario plasma equilibrium current distribution is used. Filaments are placed in the plasma region to carry plasma current and the electromagnetic interaction between filaments and conductors (mutual inductance matrices in equations (1)) and their effect on magnetic fields and fluxes in the vacuum chamber is modelled using Green functions. Model (1) can be rewritten in the state space assuming as state vector $x = [I_a^T\ I_u^T\ I_p]$, and $u = V$ as input vector. Moving to a sampled data system, with varying sampling time, the following discrete-time state space representation can be obtained:

$$x(t_{k+1}) = A(t_k)x(t_k) + B(t_k)u(t_k),\quad x(t_0) = x_0 \quad (2a)$$
$$y_v(t_k) = C_v x(t_k)\ . \quad (2b)$$

Sampled data systems imply a piecewise constant input function to the continuous time system. Assuming $\dot{u} = w$, and including u in the state vector $z = [x^T u^T]^T$, equations (2) are rewritten as:

$$z(t_{k+1}) = \tilde{A}(t_k)z(t_k) + \tilde{B}(t_k)w(t_k) \quad (3a)$$
$$y_v(t_k) = \tilde{C}_v z(t_k) \quad (3b)$$
$$\dot{y}_v(t_k) = \hat{C}_v z(t_k) + \hat{D}_v w(t_k) \quad (3c)$$
$$z(t_0) = z_0 \quad (3d)$$

where voltage is now piecewise linear and also the time derivatives $\dot{y}_v$ are included among the outputs of interest. The implicit discrete time representation (3) can be readily converted into an explicit one in the form as typically done to implement model based predictive controllers [8]

$$Y = \Phi_Y z_0 + H_Y W(t_k) \quad (4a)$$
$$W = [w(t_0)^T w(t_1)^T w(t_2)^T \ldots w(t_k)^T]^T \quad (4b)$$
$$Y(t_k) = [y_V(t_0)^T \ldots y_V(t_k)^T]^T \quad (4c)$$

4. THE DESIGN PROBLEM

Given the discrete-time plasma tokamak dynamics (3), the scenario design problem considered in this paper is to find initial values of initial conditions $z(t_0)$ corresponding to active circuit currents and active voltages, and a piece-wise constant discrete time function $w(t_k)$ (implying a piece-wise linear voltage function $u(t_k)$), in the time interval [t_0, t_f] guaranteeing: maximum initial flux in the CPs, to maximize the duration of the discharge; a desired value of electric field in the CPs at the BD time; a reference map of the stray field at BD in a sufficiently large region to ensure the required connection length; a reference (time-varying) equilibrium vacuum field in the CPs and a reference I_p evolution for $t_f \geq t > t_{BD}$.

These design requirements can be translated into the cost function of an optimization problem. The region in which the plasma is expected to be born, i.e. the BD region is the place where a massive circular conductor simulating the plasma for the early ramp-up phase is located. At BD, the requested poloidal field map is prescribed to be a quadrupolar field. Before the BD, a purely vertical field that fades linearly over time, is superimposed to the quadrupolar field to avoid undesired BDs. The reference field in the presence of plasma is first obtained by superimposing the Shafranov field to the quadrupolar field (early phase of the ramp-up); then, as the plasma elongation increases, the Shafranov field gradually leaves space to a target vacuum magnetic equilibrium field that is computed by an equilibrium code like CREATE-NL+ [9]. The connection from the circular plasma equilibrium field to the sequence of new equilibrium references is obtained using an alpha-blending in which $\alpha(t)$ is a sigmoidal function of time. The switching time interval amplitude is a parameter chosen to ensure smooth transitions in the reference signals. Control points for the vacuum fields corresponding to elongated plasmas cover a large region in the vacuum chamber.

Design constraints can be also taken into account and in particular: maximum/minimum current in the active circuits; maximum/minimum active voltage and voltage derivative in power supplies; the electric field at the expected plasma centre must be more than a minimum value.

The ramp-up design problem can be readily translated into a quadratic cost optimization problem with linear constraints:

$$\min_{W,z_0}(Y_{ct} - Y_{ctd})^T Q_w (Y_{ct} - Y_{ctd}) + W^T R_w W + z_0^T R_{z_0} z_0 \quad (5a)$$
$$Y_{csm} \leq Y_{cs} \leq Y_{csM} \quad (5b)$$
$$W_m \leq W \leq W_M \quad (5c)$$
$$z_{0m} \leq z_0 \leq z_{0M} \quad (5d)$$
$$I_u(0) = 0, I_p(0) = 0 \quad (5e)$$

where Y_{ct} and Y_{cs} are vectors of controlled and constrained outputs respectively, Y_{ctd} is the vector of desired controlled outputs, Q_w, R_w and R_{z0} are suitable weighting matrices. The problem can be solved via a QP solver, providing optimal W and z_0.

The above scenario design algorithm is affected by unavoidable discrepancies between the real tokamak behaviour and the mathematical model prediction. Some of the uncertainties are related to the circuit dynamics, the surrounding toroidally continuous conducting structures in which passive currents are induced, and their mutual coupling with plasma current dynamics. ILC gradually compensates for the modelling errors estimated during the experiments by solving a modified optimization problem. Given the target value of the controlled quantities Y_{ctd}, the value Y_{ct} predicted by the model, and the value $\hat{Y}_{ct}$ estimated during, or just after, the experiment, the tracking error is defined as $\Delta Y_{ct} = \hat{Y}_{ct} - Y_{ctd}$ which is due to a combined effect of the tracking error resulting from the (imperfect) solution of the off-line optimization problem, namely $\Delta_1 Y_{ct} = Y_{ct} - Y_{ctd}$ and the modelling error, namely $\Delta_2 Y_{ct} = \hat{Y}_{ct} - Y_{ct}$.

The main goal of the ramp-up design procedure is to minimize $\Delta Y_{ct} = \Delta_1 Y_{ct} + \Delta_2 Y_{ct}$ whereas in the off-line design problem (5) only $\Delta_1 Y_{ct}$ is taken into account, under the hypothesis that the real experiment behaves as the model. The following ILC current/voltage waveform correction requires a sequence of consecutive shots.

Step 1. j = 0. Solve the Problem (5). Denote as W^j the obtained optimal waveform and z_0^j the optimal initial condition.

Step 2. j = j+1. Run the experiment (shot *j*). If $\|\Delta Y_{ct}\| \leq \epsilon_F$ (where ϵ_F is a specified tolerance) then end the procedure, else go to Step 3.

Step 3. Find new waveforms and initial conditions W^{j+1} and z_0^{j+1}, by solving an optimization problem, which is a modified version of problem (5) with the addition of a $\Delta_2 Y_{ct}^j$ term representing the error due to the model-reality mismatch, the addition of a term weighing the difference between waveforms and initial conditions at step *j* and *j*+1.

$$\min_{W^{j+1}, z_0^{j+1}} \left(Y_{ct} - Y_{ctd}^j - \Delta_2^j Y_{ct}\right)^T Q_w \left(Y_{ct} - Y_{ctd}^j - \Delta_2^j Y_{ct}\right) + {W^{j+1}}^T R_w W^{j+1} + {z_0^{j+1}}^T R_{z_0} z_0^{j+1} + (W^{j+1} - W^j)^T P_w (W^{j+1} - W^j) + (z_0^{j+1} - z_0^j)^T R_{z_0} (z_0^{j+1} - z_0^j) \quad (6)$$

where Q_w, R_w, R_{z_0}, P_w, and P_{z0} are suitable weighting matrices.

Step 4 Go to Step 2.

Although converging to the reference vacuum fields ($\|\Delta Y_{ct}\| < \epsilon_F$) corresponding to the nominal sequence of equilibria, the real evolution of the plasma may behave differently from the desired one. Then, even a perfect tracking of the desired evolution of the vacuum field does not guarantee the desired sequence of plasma shapes.

The mismatch between expected and real plasma is due to plasma internal kinetic and current diffusion dynamics leading to an evolution of the current density distribution which is difficult to predict with high accuracy.

Therefore, the procedure is enhanced with the possibility to add a compensation term based on the plasma shape displacement, evaluated as the difference between reference values on selected gaps, and gap values estimated during the experiment for a given number of snapshots, i.e. a subset of sampling times when plasma is well formed and gaps are well defined. In the neighbourhood of a given plasma equilibrium, relationships between small variations of the active currents and gaps γ can be modelled with a linear approximation. The same can be done for relationships between vacuum fields and currents. This means that correction to the shape can be easily be translated in corrections to the vacuum fields.

The application of the proposed procedure, which has been proved to work in MAST-U from the pre-charge conditions to the flat top, may imply risks for large tokamaks especially during the burning phase of the scenario, where iterations may cause, more than once, plasma-wall contacts until modelling error are compensated. An important improvement to the ILC design procedure tested in simulation on JT-60SA and ITER is to make experiments in closed loop activating not only the Vertical Stabilization (VS) control but also shape and I_p control.

The presence of feedback however adds a corrective action in the experiment j, say δW_{CL}^{j} which in principle moves the plasma toward the desired trajectory. Hence $(W^{j+1} - W^{j})$ must be replaced by $\left(W^{j+1} - W^{j} - \delta W_{CL}^{j}\right)$ including the feedback action in the optimal waveforms optimized at step j. The addition of the contribution δW_{CL}^{j} implies a corresponding additional contribution δY_{ctCL} to the prediction that has to be taken into account in the expression of $\Delta_2 Y_{ct} = \hat{Y}_{ct} - (Y_{ct} + \delta Y_{ctCL})$.

5. NUMERICAL RESULTS

Two numerical examples are presented to demonstrate the validity of the proposed approach also in the presence of feedback control. The first example, on JT-60SA puts in evidence how the intra-shot optimization procedure works for large superconducting coils tokamaks and the benefits deriving from the use of shape and *Ip* feedback corrections. The second is an application to an ITER early operation scenario demonstrating that the proposed approach can be beneficial for early tokamak operations to reduce times to reach the desired conditions which are rapidly changing during the commissioning phases.

5.1. JT-60SA 4.6MA Ramp-up Scenario

The JT-60SA ramp-up scenario considered in the following simulations is a variant of the 4.6 MA in Deuterium scenario whose profile parameters have been computed using METIS [10]. Relevant quantities are reported in Fig. 2. Red dots in this figure show the time instants where the equilibrium snapshots have been computed using CREATE-NL+ and were both filamentary models in the form (1) and linearized models to make corrections based on shape are updated. Plasma shape descriptors (gaps) used in the procedure are also shown in Fig. 2. The focus of the numerical experiment is on the time interval $[0.5 \leq t \leq 20]$.
The design procedure is first carried out in open loop without the action of feedback control. Results are shown in the first column of Fig. 3. Iteration 1 has the main effect of compensating plasma current errors but the plasma touches the wall in the Low Field Side (LFS) region before or during the L to H transition. The application of a shape correction term in the cost function starting from iteration 2, allows to reach the flat-top in a diverted shape without plasma wall contact, in 5 iterations of the ILC algorithm. Plasma current and position and shapes at given time instants compared to target shapes are shown in Fig.2.

Then the ILC iterations are repeated taking into account the feedback action. Results are shown in the second column of Fig.3. Already from the first simulated experiment (iteration #0), feedback compensates modelling errors guaranteeing better performance with respect to the previous case. Then a new ILC step is made both without including the feedback action terms in the ILC procedure (iteration #1a) and with the inclusion of these terms (iteration #1b). It is evident that the inclusion of feedback terms in the optimization procedure improves the quality of the desired plasma current and shape time history tracking.

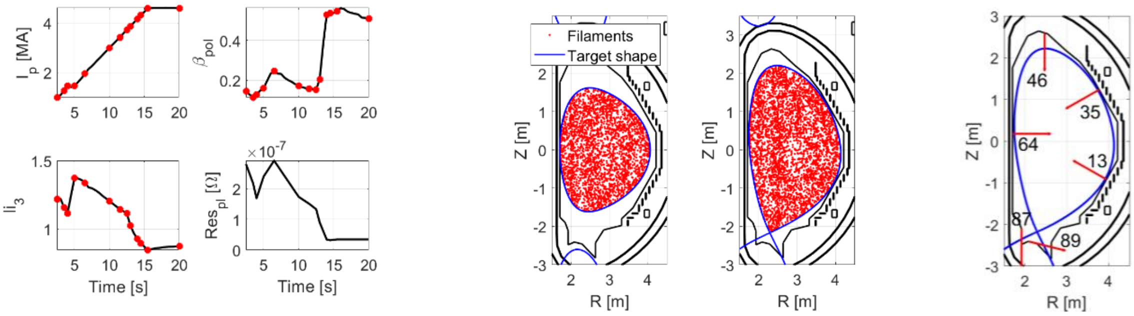

FIG. 2. From left: ramp-up main quantities, distribution of current filaments for two snapshots; plasma wall gaps adopted in the design procedure (4.6 MA in Deuterium ramp-up scenario in JT-60SA).

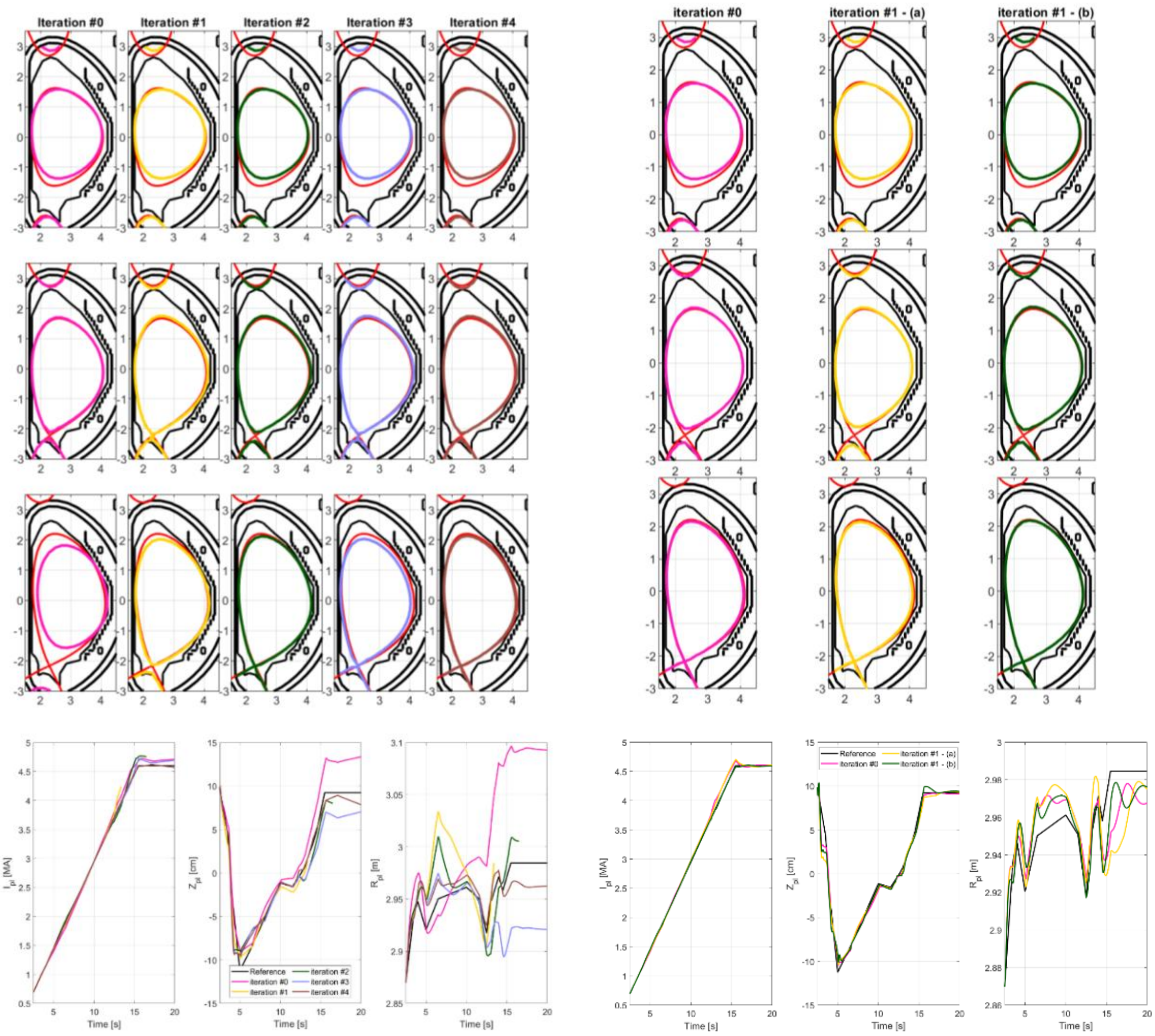

FIG. 3. Sequence of plasma currents, positions and shapes obtained without using feedback (column1) and with using feedback (column 2). Time slices at t=2.5, 5 and 15s (4.6 MA in Deuterium ramp-up scenario in JT-60SA)

5.2. 2MA ITER Ramp-up Scenario

The reference scenario chosen for ITER is a 2MA scenario at 2.65T, whose relevant quantities during ramp-up are reported in Fig. 4. This Figure also puts in evidence, with red dots, the time instants where the filamentary and linearized plasma models to apply the ILC algorithm are computed. The active magnetic controller includes a VS control with in-vessel coils VS3, a plasma current controller, and a plasma centroid radial and vertical position control. Switching Networks Resistors are also used to increase loop voltage at BD and during the early phase of the ramp-up.

The first simulation has been carried out using nominal currents and voltages from ITER database, computed with DINA code. Due to model discrepancies, when simulating with CREATE-NL+ notable differences between the expected and actual plasma evolutions are observed (iteration #0).

The application of the CREATE- ILC code allows already at the iteration #1 to correct the plasma current evolution as reported in Fig.4. PF active currents modifications are significant for the first iteration. Successive iterations provide smaller corrections with shape and position parameters rapidly converging to the target time behaviours.

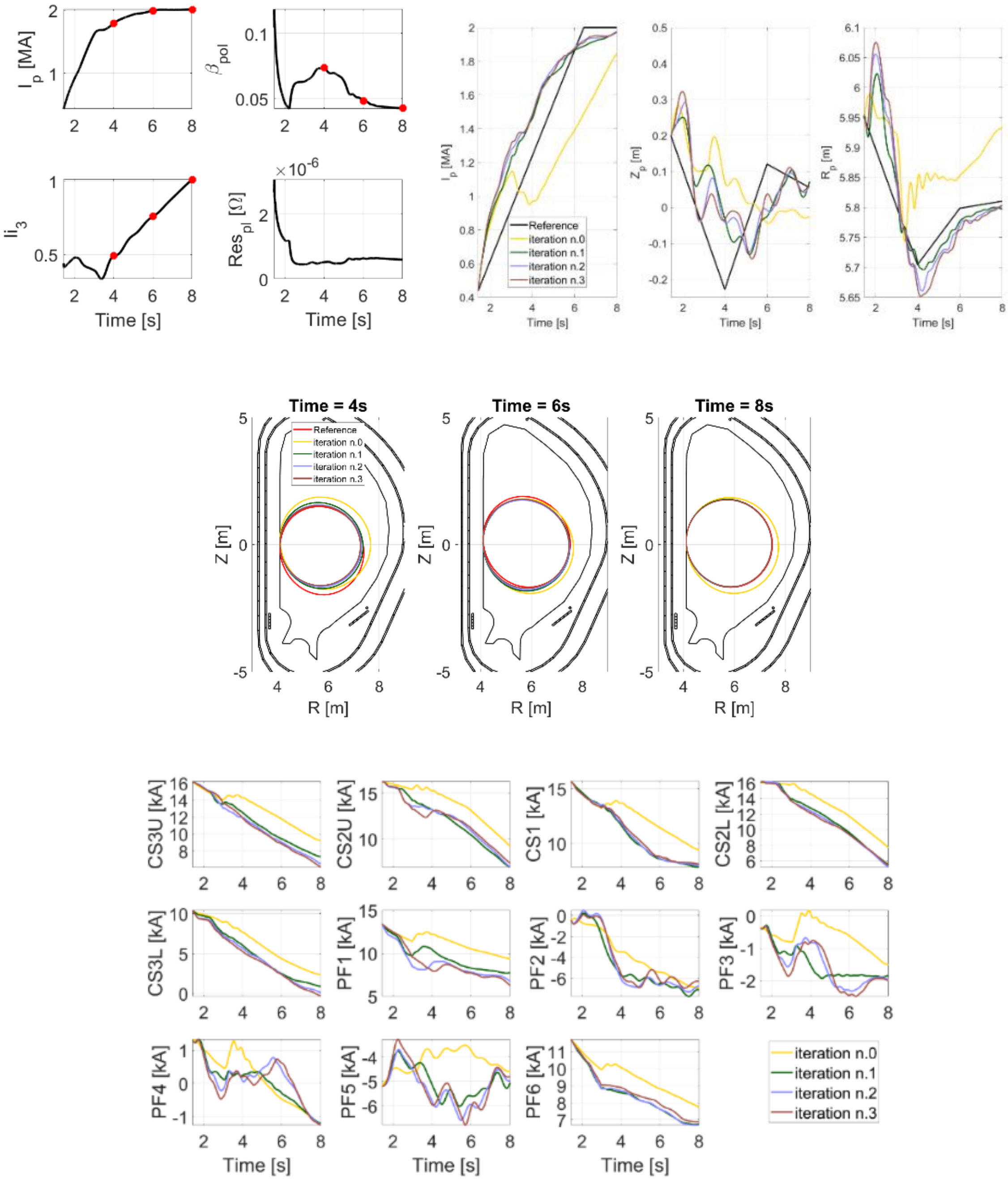

FIG. 4. Plasma current, position, shape, active currents time evolution for the ITER 2MA ramp-up scenario

6. CONCLUSIONS

An improvement of the ILC technique implemented for TCV [4] and MAST-U [5] has been presented in this paper and applied in simulation to large superconducting coils tokamaks like JT-60SA and ITER. The new algorithm takes into account the contribution of plasma current, shape, and position feedback during the experiments. It is shown by comparison that there is an improvement of the speed of convergence to the optimal scenario. Future work will be to test experimentally the procedure in the presence of significant amounts of auxiliary heating power which increases the level of uncertainty on plasma models.

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