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Overview of Modelling Activities for Plasma Control Upgrade in JET

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ABSTRACT

The JET enhancement project PCU (Plasma Control Upgrade) aimed at increasing the capabilities of the plasma Vertical Stabilization (VS) system. One of the activities of this project was devoted to the development of simple but sufficiently accurate models of the VS system so as to address the main design choices, use the simulation tools as reliable test-beds, and provide an adequate support to the engineering design and commissioning of the new Enhanced Radial Field Amplifier (ERFA). This paper illustrates some of the main achievements of the modelling activity, which gave rise to a closed loop model of the VS system, including plasma, PF coils and passive structures.

In particular the paper deals with the selection of the set of turns to be used in the control coils and with the estimation of the eddy current effects on the VS system. The latter analysis addressed an upgrade of the converter units of ERFA, which was successfully implemented during its commissioning on plasma in August 2009.

1. INTRODUCTION

Phase 2 of the JET enhancement project PCU (Plasma Control Upgrade) [1] aimed at increasing the capabilities of the plasma Vertical Stabilization (VS) system to recover from large (2MJ) edge localised modes. The modelling activity was focused to the optimization of the simulation tools, in order to tune the VS system so as to provide its best performance after the 2009-10 shut down.. It also intended to provide an adequate support from modelling and control groups to the engineering design and commissioning of the new Enhanced 12kV-5kA Radial Field Amplifier (ERFA) [2], supposed to replace the previous one (FRFA). The main achievements include:

- the development of a closed loop model of the VS system, including ERFA as well as the coupling between VS and the plasma Shape Control (SC), which in some cases may yield undesired oscillations [1];
- the choice of the turns to be used in the control coils, taking into account the parameters of ERFA.

The model includes a sufficiently detailed treatment of the passive metallic structures surrounding the plasma. The eddy currents induced during transient phases of the PF system may produce undesired effects on the performance of the machine, which deserve careful assessment. In particular the following effects were analyzed:

- on the magnetic sensors, in view of the installation of the ITER-like wall [3], which modifies the local geometry and electrical conductivity of the material; this effect led to the choice of a new controlled variable that does not make use of the sensors expected to be the most shielded by the structure;
- on the voltage drop of the ERFA dc converter, to address its upgrading [4] by estimating the charging capability needed for JET operation;
- on the breakdown, so as to ease plasma initiation with different sets of turns [5].

2. CLOSED LOOP MODEL OF THE VS SYSTEM AND MITIGATION OF VERTICAL OSCILLATIONS

As reported in [1], an open loop model of the plasma response to the poloidal field circuits had been developed and successfully validated, taking into account the eddy currents induced in JET passive structures. Afterwards, a detailed description of the VS controller and FRFA power supply had been prepared and compared with the experimental data, so as to be able to test the closed loop behavior, even in the presence of the shape controller action.

This allowed to understand the mechanisms behind the undesirable plasma vertical low frequency (5-10Hz) oscillations as well as predicting their amplitude and frequency [1]. These oscillations were mainly due to an oscillating made generated by a coupling between the shape control loop and the VS control loop. This mode, usually not excited by the standard control commands, in some situations can be excited by a number of different factors, such as low frequency oscillations generated by the relay characteristics used to command the vertical stabilization power supply, or swarms of ELMs occurring in the presence of H-mode plasmas. Using the closed loop model it was found that, acting on the current gain in the VS control laws, the amplitude and the frequency of these oscillations can be modified. Theoretical predictions, validated by experimental tests showed that these oscillations could be reduced by increasing the value of the current gain.

3. BENCHMARK CRITERIA AND COIL TURN OPTIMIZATION

Benchmark conditions for a simulation have been defined in terms of largest unstable displacement that can be tolerated without exceeding current limits or yielding plasma-wall contact. Kick and recovery tests have also been proposed for an experimental benchmark in well established conditions. The figure of merit was then the amplification factor G of the maximum tolerable disturbance d_{max} (in terms of initial displacement or ELM size) when passing from standard to alternative options.

In case of kick and recovery tests, the figure of merit for a given plasma configuration is simply related to the maximum vertical velocity obtained at the end of a kick (a rectangular ERFA voltage pulse with the VS controller switched off) that can be stabilized in the recovery phase. The 2D models were also capable to predict the maximum duration tk of a kick, given by the a simple relationship, i.e. $\exp(\gamma t_k)<2$, if there is no ERFA current saturation. The simplified first order model that confirms this relationship can also effectively be used to have an on-line measurement of the growth rate, based on the ratio between recovery time and kick duration.

Since ERFA nominal voltage (12kV) is 20% higher than FRFA whereas ERFA nominal current (5kA) is twice as much as FRFA, coil turn reduction was expected to be advantageous to increase the voltage per turn and the time derivative of the stabilizing field. The price to be paid is the reduction of the Ampere turns, hence the maximum stabilizing field. For this reason, coil turn reduction was suggested for medium-high growth rates. Three different coil options of P2RU-P3RU-P2RL-P3RL turns were then proposed for PCU-ERFA commissioning.

The reduced symmetric option (8, 20, −8, −20) was obtained by reducing the coil turns of P2R, for which the allowed values are 16, 8, 0. For medium-high growth rate plasmas the expected gain G for medium-high values of the growth rate γ ranges from 1 to 1.2. Using using 2.5kA ERFA current offset G>1 also for lower growth rates.

The (16, 20, −8, −2) asymmetric option replaced the (16, 20, 0, 0) initial more advantageous proposal, due to the risks related to the high voltage per turn.

Particular care was devoted to the risk analysis and the measures to be taken whenever needed, so as to carry out ERFA commissioning safely. To avoid the potential risk due to underestimation of the manpower and time needed to change connections, it was proposed to change coil turns during the week-end. Since approximate models used for the optimization, the experimental response was compared to model predictions in dry runs after changing the turns. In case of ERFA current saturations with particular plasma configurations, which however did not occur, the PCU project was ready increase the current gain, or use current offset. Also the possible impact on other subsystem was preventively taken into account. To ease breakdown phase, it was possible to act on the radial field feedback loop. In case of interaction with other circuits and shape control, it was envisaged to avoid the asymmetric option or increase the current gain of the VS system.

The asymmetric option, although successfully tested during the commissioning phase, was eventually discarded because of interference and control problems with no significant benefits with respect to the reduced symmetric option, which was selected after the experimental kick and recovery tests, which confirmed the theoretical predictions [6].

4. EFFECTS OF PASSIVE STRUCTURES ON MAGNETIC SENSORS AND NEW CONTROLLED VARIABLE

A full replacement of JET first wall materials is planned, with beryllium in the main wall and tungsten in the divertor. Major effects are expected in the top region, where the new beryllium tiles will be attached to thick INCONEL dump plates. The electromagnetic time constant of a dump plate with the beryllium tiles has been estimated to be about 7ms, i.e., one order of magnitude longer than the present plates.

The potential impact on the magnetic sensors measuring the tangential field behind the plates used by VS system has been estimated with 2D and 3D analyses and experimental observations. Their step response to radial fields in the presence of the plasma changes sign after some hundreds of microseconds, showing that even the present plates shield the sensors behind. However this step response is scarcely affected by the thickness of the plate, since the vacuum vessel is just behind, and the long time constant mainly shields the normal field.

Although the impact on the VS system was not expected to be dramatic, the PCU project explored the possibility of having a valid alternative to the controlled variable ZPDIP, a linear combination of magnetic measurements, used for several years. The new controlled variable, denoted as OBS05 does not makes use of the magnetic sensors behind the plates. It was successfully tested in JET C27 campaign on a variety of plasma scenarios. The behaviour of OBS05 was better than ZPDIP in the ELMy phases of some pulses, yielding a significant reduction (about 40%) of the excursion of ERFA current [6-7].

5. EFFECTS OF INDUCED CURRENTS DURING BREAKDOWN

A modeling activity has been carried out to analyze the electromagnetic conditions of JET breakdown, also for what concern the possible impact of the new radial field system on plasma breakdown, especially using the asymmetric turn option. The model has been used to make predictions of the static and dynamic vertical and radial field required for breakdown. This work identified for the first time the radial field due to the up-down asymmetric gaps in the iron core and the relative influence on the field null. The reconstructions have been successfully compared with the experimental evolution of the field and passive currents estimations signals being able to follow the dynamics of the first few ms after the electric field is applied to the time when a current carrying plasma column is formed. The flux map simulations are also in good agreement with the new fast visible video camera images [8], showing that it is possible to reliably predict and in principle optimize the region of plasma formation, including a stable field null and extended to the part of the first wall where the magnetic field pushes the plasma against the wall.

6. VOLTAGE DROP OF ERFA DC CONVERTER AND ESTIMATION OF THE CHARGING CAPABILITY

The equivalent scheme in Fig.1, in which the passive structures are represented by a simple first order system coupled to the ERFA circuit, can be used to assess the capability of the charger of compensating the energy losses during fast transients.

At very low frequency the coupling with the external conductors (mechanical structure, vessel, other circuits, etc.) does not count and the radial field circuit with the standard turns has the following estimated values of resistance and inductance:

$$R_{Erfa} = 35m\Omega, L_{Erfa} = 49 \text{ mH}.$$

At the higher frequencies of operation of the VS system, the equivalent inductance connected to ERFA becomes $L_{eq} = L_{Erfa} - M^2/L_{eddy}$. The PCU and ERFA projects, based on both model predictions and experimental data, assumed a reference value of 20mH. The parameters of the capacitor bank were then designed taking into account the values of L_{eq} reported in Table I.

The same scheme can be used to estimate the losses as a function of the frequency. At a given angular frequency $\omega = 2\pi f$, the equivalent impedance Z_{eq} connected to ERFA becomes:

$$Z_{eq} = R_{eq} + j\,\omega\, L_{eq} = R_{Erfa} + jL_{Erfa} + (\omega\, M)^2/(R_{eddy} + j\,\omega\, L_{eddy})$$

yielding surprising high values of R_{eq} even at relatively low frequencies. From the model R_{eq}, only 35mΩ in DC, is about 500mΩ at 10Hz. From the experimental data of Pulse No:78232, where also higher frequency were excited, the equivalent resistance is more than 2Ω.

Neglecting other terms like the switching losses, a simplified expression for the power balance is:

$$dE_L/dt + dE_C/dtt + R_{eq}I^2E_{rfat} = P_{ch}$$

where

- $E_C = 4C_bV_b^2/2$ is the energy stored in the capacitor banks of the four units; $E_c = 1.35MJ$ for $C_b = 75mF$ and $V_b = V_{Erfa}/4 = 3kV$;
- $E_L = L_{Erfa}I_{Erfa}^2/2+L_{eddy}I_{eddy}^2/2MI_{Erfa}I_{eddy}$ is the energy stored in the magnetic field; at the frequencies of interest $E_L = L_{eq}I_{Erfa}^2/2$ ($E_L = 0$ for $I_{Erfa} = 0$, $E_L = 0.25MJ$ for $L = 20$ mH and $I = 5$ kA)
- $P_{ch} = 4V_bI_{ch}$ is the power input from the converter ($P_{ch} = 1.2MW$ for $V_b = 3kV$ and $I_{ch} =$ 100A, i.e., the initial value selected by the ERFA project);
- $P_{res} = R_{Erfa}I_{Erfa}^2 + R_{eddy}I_{eddy}^2$ (approximately $R_{eq}I_{Erfa}^2$ at the frequencies of interest) is the ohmic power.

An alternative power balance that guarantees steady state is $<P_{Erfa}> \leq \max(P_{ch})$, where $<P_{Erfa}> = <V_{Erfa}I_{Erfa}>$ is the average value of the power absorbed by the load. The PCU project evaluated <P> as a function of the time (averaging in a time interval of 50ms) for a wide number of pulses and conditions with FRFA and the first plasmaless pulses for ERFA commissioning. It turned out that $<P_{Erfa}> < 1.2MW$ was met in all cases except the ERFA acceptance tests in plasmaless pulses, for which $<P_{Erfa}>$ exceeded 2.5MW (corresponding to a required value of 220A for I_{ch}). Therefore, the PCU project defined a target value of 300A for the charging capability of the converter. However, the current waveform of Pulse No: 78246 did not match the desired 7.5kA swing of the acceptance test. In this case a larger power dissipation would be needed, requiring about 500A in the charger. So, to allow testing with a 300A charger, the PCU project modified the frequency of the acceptance test (12.5Hz instead of 25).

The ERFA project brought the charging capability of the converter up to the target value requested by the PCU project. Plasmaless Pulse No's: 78876 and 78880, aiming to run the modified acceptance test, showed that the capacitors were recharged at the enhanced rate of 300 A, maintaining then the output voltage at the desired reference level. Figure 2 shows the comparison between the charger capability before and after the intervention (to this purpose in Pulse No: 78882 the maximum converter current was temporarily set to its original value of 100A).

CONCLUSIONS

The implementation of the JET Enhancement Project for Plasma Control Upgrade (PCU) included a modeling activity and related simulations tools, which revealed to be quite useful not only for the future JET experimental campaigns but also for ITER studies presently in course. As illustrated in the bulk of the paper, thanks to the availability of a fully validated closed loop for the JET VS system the following issues could be carefully analyzed:

- undesired vertical oscillations of the plasma, linked to the plasma shape control;

- change of the number of turns of the control coils and related coil turn optimization;
- on-line estimation of growth rate of the vertical instability;
- indication of limits for kick duration;
- shielding effects on the magnetic sensors and related new VS controlled variable usable with the new ITER like wall;
- breakdown models, predicting the region of plasma formation, and providing useful indication for radial field feedback;
- evaluation of the target value for the charging capability of ERFA converter (300A) and definition of modified acceptance tests.

The design choices made on the base of the modeling, supported and confirmed by the experimental tests during the commissioning of the new VS system, show that the original requirements can be met with ERFA for plasmas with a growth rate of $200s^{-1}$ with a low inductance turn option.

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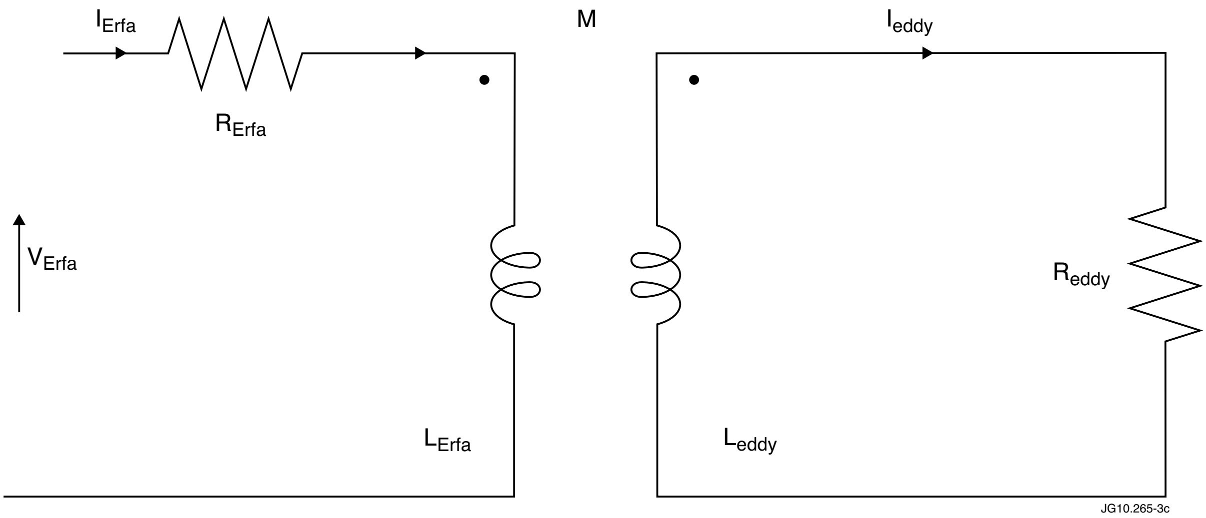

Figure 2: Simplified equivalent scheme of ERFA circuit downstream of the output filter, inductively coupled to the eddy currents flowing in the external conductors.

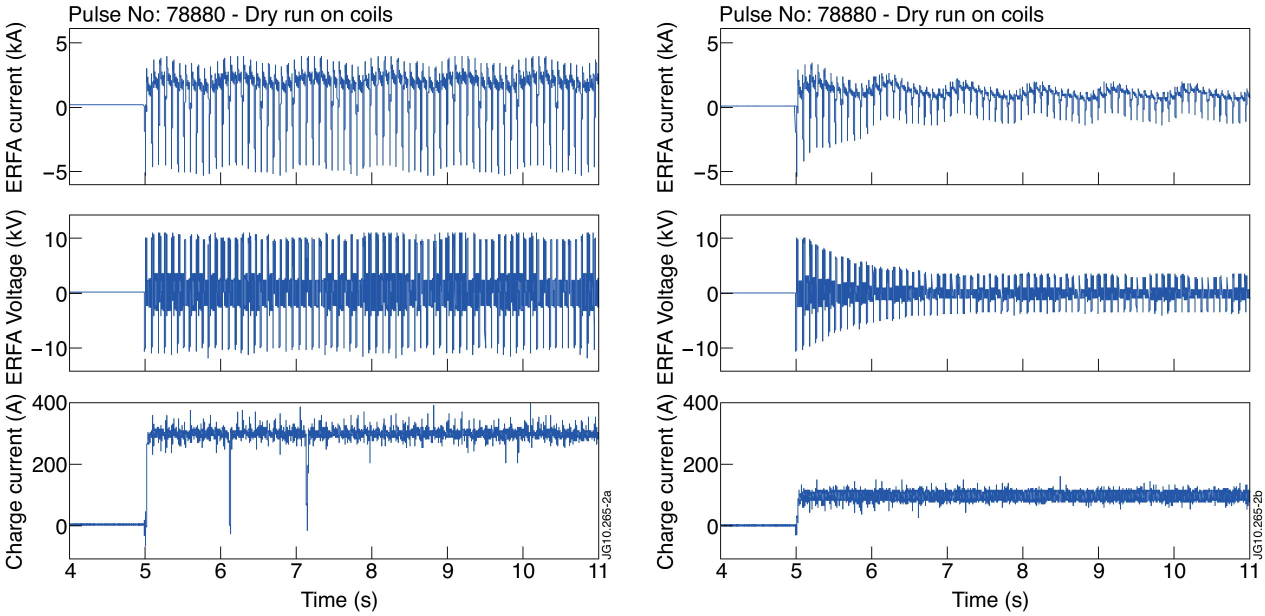

Figure 2: Similar dry run tests carried out with different charging capabilities (300A in Pulse No: 78880, 100A in Pulse No: 778882).