Technology Progress in Real-time Control of MHD Modes at RFX-mod

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Abstract. The RFX-mod reverse field pinch (RFP) experiment applies active control on the MHD instabilities by acting on the magnetic field configuration at the boundary. These studies aim at acquiring expertise on the control of MHD modes that is also relevant for high beta discharges in tokamaks. To control the MHD activity, 192 saddle coils are installed, covering the entire torus surface. A large number of field and current measurements are acquired and processed in real-time (3x192=576 channels). Excellent results have been achieved by exploiting the real-time MHD mode control system, especially on MHD mode suppression at the boundary, toroidal loop voltage reduction, particle and energy time increase and duration of the plasma discharge. The paper discusses the technological enhancement developed in the last two years. Two new techniques have been introduced recently. The first one is referred to as Clean Mode Control (CMC). It consists in the correction of the aliasing, due to the sidebands produced by the discrete grid of coils, which determines a systematic error on the Fourier analysis of the measurements. As the CMC correction requires the simultaneous availability in the same real-time station of all acquired channels, a significant upgrade of the architecture of the real-time feedback system was necessary. The second technique consists in the introduction of a Multiple Input Multiple Output (MIMO) approach to substitute the Single Input Single Output model used so far, whose dynamic behaviour is not satisfactory. The MIMO approach relies on a full electromagnetic model of the coil and sensor system in the presence of passive structures. The MIMO controller has been developed following the concept of model decoupling. To compute the new algorithms without exceeding the real-time constraints, faster CPUs have been introduced and the data throughput in the real-time network has been optimized.

1. Introduction

A broad spectrum of MHD modes characterizes the RFX-mod plasma. It includes internally and externally non-resonant Resistive Wall Modes (RWM) ($m=1$, $-7<n<0$ and $n>0$, where m and n are the poloidal and toroidal mode numbers, respectively) and internally resonant Tearing Modes (TM) ($m=1$, $n<-7$) that are responsible for the dynamo effect and, hence, for the sustainment of the RFP configuration. TM typically lock in phase to each other and then to the wall, perturbing locally the last closed magnetic surface and enhancing the plasma wall-interactions. Hence, to achieve high-current operation, a reduction of the radial field component at the edge and mode unlocking with respect to the wall are mandatory.

The active control of MHD modes, which acts on the magnetic field configuration at the boundary, is one of the main scientific goals of RFX-mod. To this purpose the machine has been equipped with 192 independently fed saddle coils, covering the entire torus surface. In addition, a thin copper shell with a time constant of 50 ms has replaced the previous aluminium one whose time constant was 8 times bigger. An equal number of saddle probes, located on the projection of the saddle coils on the vessel outer surface, provide equispaced samples of the magnetic flux. The poloidal and toroidal components of the magnetic field are measured by 192 pick-up coils placed on the inner surface of the shell. These measures are processed in real time by a distributed digital control system, including a total of eight computing nodes, to produce the reference waveforms and to drive the saddle coil power supply units [1, 2].

Two basic control strategies have been implemented and experimentally tested: the Selective Virtual Shell (SVS) and the Mode Control (MC) [3]. The former aims at cancelling the magnetic flux at the sensors by excluding selected components (for instance the m=1, n=0 equilibrium field), the latter acts independently on different modes taking into account their dynamic characteristics. A complete stabilization of RWM was achieved initially by adopting the SVS strategy with significant results in terms of toroidal loop voltage reduction, an increase in particle and energy confinement time, and plasma discharge duration in pulses with currents up to 0.8-1 MA [4]. Later, a refined action on TM was performed by adopting the MC approach after eliminating a systematic error in the evaluation of the harmonic components of the magnetic fields due to the high poloidal and toroidal order sidebands produced by the saddle coils. A real-time correction of the 2D Discrete Fourier components of the radial magnetic field measurements was implemented and the MC algorithm was applied to “clean” feedback signals [5]. The Clean Mode Control (CMC) allowed a partial phase and wall unlocking of m=1 resistive kink tearing modes [6], ushering in 1.5 MA operation, which is now routinely executed [7, 8].

2. Clean Mode Control

In a discrete grid made up of a finite number of M x N saddle coils (M and N along the poloidal and toroidal directions, respectively) the generation of a generic harmonic component $B^{m,n}$ ($m<M/2$ and $n<N/2$) of the magnetic field distribution is accompanied by an infinite number of sidebands $B^{m',n'}$ according to the equation $m'=m\pm hM$, $n'=n\pm kN$, $h=0, 1, \ldots$, $k=0, 1, \ldots$. The aliasing of the sideband harmonics produced by the active coils introduces a systematic error in the Fourier analysis of the measurements. On the basis of the coil current measurements, a real-time correction algorithm to subtract the sideband effect has been implemented to obtain “clean” feedback signals. Different versions have been elaborated, making possible to feed back the control system with the corrected signals evaluated either at

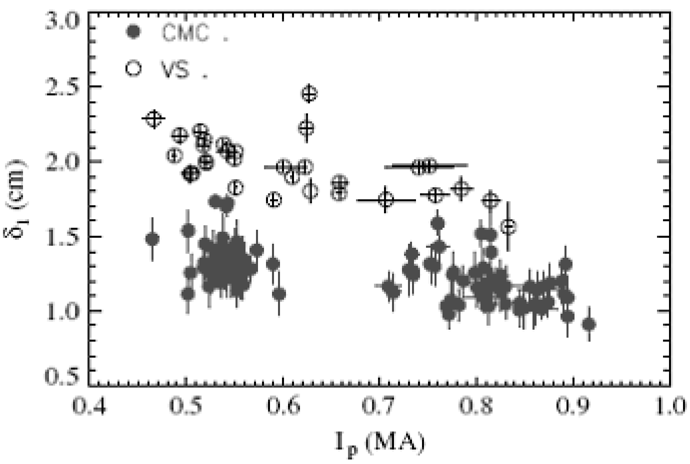

FIG. 1. Maximum non-axisymmetric displacement of the plasma column in CMC (filled circles) and SVS (transparent circles) shots. Maximum is averaged in flat-top

the sensor radius (0.507 m) or at the first wall radius, i.e. at the plasma boundary (0.459 m). In the latter case the measures of the toroidal components provided by the 4x48 pick-up coils placed on the shell's inner surface are used to obtain the extrapolated radial component. The CMC scheme proved more successful in reducing the amplitude of each TM at the plasma edge than the SVS. Moreover, by accurate selection of the gains, different mode rotation frequencies up to 100 Hz could be achieved allowing a partial phase unlocking between the modes and with respect to the wall and spreading the thermal load onto the plasma facing components. In particular, since the DFT harmonic coefficients are complex numbers, complex proportional gains have been tried inducing a spatial phase shift between the error signal and the control action. In spite of a less effective cancellation of the edge field, a reproducible phase rotation of the modes could be observed with more frequent phase unlocking. The result in terms of lower deformation of the last closed magnetic surface is represented in fig.1, where the flat-top averaged maximum non-axisymmetric displacement is plotted in both CMC and SVS cases.

The improvement in the magnetic boundary entailed a decrease of the magnetic chaos throughout the plasma with frequent onset of Quasi Single Helicity (QSH) state, i.e. a condition where only one TM is largely dominant to sustain the RFP configuration with lower transport losses and longer energy confinement time. These results allowed the step forward to 1.5 MA operation, where they are routinely achieved with 60% of the discharge in QSH states and QSH continuous time intervals lasting up to 50 ms.

The present control system consists of PID controllers, whose gains may be set independently for each mode and which have been empirically tuned. The correction algorithm has been obtained in a cylindrical, thin shell approximation, where the diffusion of the (m, n) components of the magnetic field is described by first order differential equations.

In a cylindrical geometry, the study of the magnetic field penetration dynamics in terms of Fourier components allows to assume a diagonal structure model, overcoming the considerable electromagnetic coupling between each coil and many underlying sensors. In fact, in the case of RFX-mod, the toroidal geometry of the machine and the presence of gaps in the shell and the support structure bring about a non negligible coupling between different (m, n) modes. Undesired modes and associated sidebands are unavoidably produced together with the targeted ones. This was considered a drawback of the present active control action, particularly in view of higher current operation. They can excite plasma modes that increase magnetic chaos and are a useless cause of additional power consumption. Thus, in order to further improve the experimental results, it is considered important to go beyond the SISO scheme and to implement a MIMO control system designed on the basis of a model which could take into account the intrinsically coupled nature of the system.

3. Enhancement of control system architecture

The implementation of the CMC concept required the acquisition of a new set of analogue channels, the saddle coil currents, and their processing along with the radial and toroidal components of the magnetic field in the same real-time node. Two factors pushed forward in the direction of a system hardware and software improvement: first, the control system was no longer able to fulfil the requirements for the total cycle time (400 µs) due to the computational complexity introduced by the cleaning algorithm and the extrapolation of the radial field along the radial direction; second, the real-time communication was no longer suitable to cope with the total cycle time. The original real-time control system had been designed considering, as real time communication requirement, the exchange of only a subset of the total 2D harmonic components of the radial field. This simplifying hypothesis seemed reasonable as the system target was the cancellation, at the radial sensor radius, of only the modes with the highest amplitudes, such as the m= 1, n =6-12 modes. This hypothesis was compatible with the requirement on the total cycle time fixed at 400 µs, whereas the transmission of all modes as 32 bit floating point numbers was not. To implement the CMC algorithm, it was necessary to enhance the system topology and upgrade the hardware technology. Fig. 2 shows the system architecture after modification. The figure underlines the introduction of a new node, the Coil Current Processor, with the corresponding introduction of 192 additional control input signals, representing the coil currents (increasing the total number of input signals from 384 to 576). It was also necessary to upgrade the processing and communication capability of three crucial nodes (the radial and

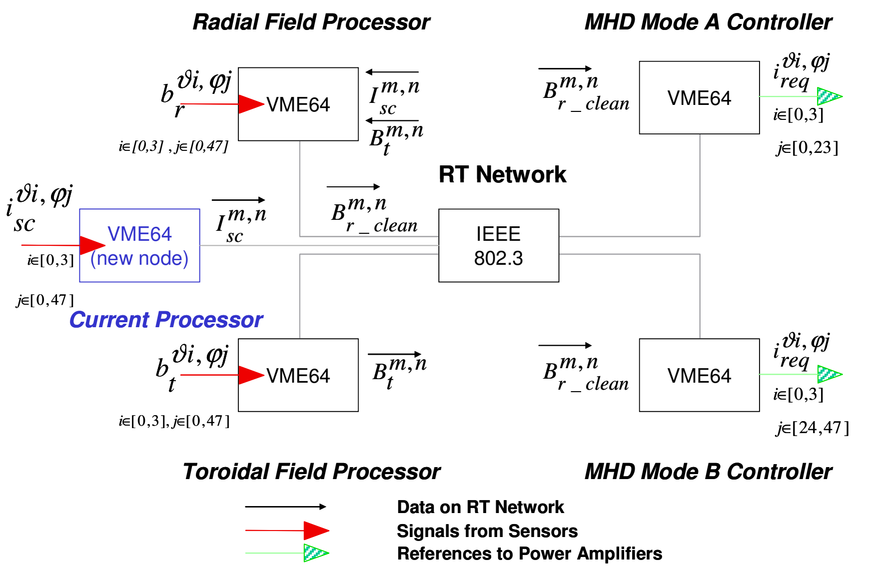

FIG. 2. Architecture of the enhanced RFX-mod real-time control system to implement the Clean Mode Control strategy.

toroidal field processors and the coil current processors). The clock frequency of their PowerPC-based CPUs was upgraded from 500 to 1000 MHz and their communication ports from 100 to 1000 MByte/s. The doubling of the clock frequency resulted in an immediate halving of the computation time, whereas the increase of the communication throughput required a fine tuning of the communication layer to achieve a real improvement [9, 10].

4. Limits of the present MHD mode controls

The results achieved in control of MHD modes were obtained by using a Single Input Single Output (SISO) control system, consisting of 192 PID regulators, whose parameters were empirically tuned. In a cylindrical geometry the problem of the electromagnetic coupling between each coil and many underlying sensors is overcome by describing the magnetic field configuration at the edge in terms of Fourier components which provides a diagonal structure model. This holds only in a first approximation in RFX-mod, where the toroidal geometry of the machine and the presence of gaps in the shell and the support structure determine a non negligible coupling between different (m, n) modes. Undesired modes and associated sidebands are unavoidably produced along with the targeted ones. This is considered the major drawback of the present active control action, particularly in view of higher current operation. On one hand, they can excite plasma modes increasing magnetic chaos; on the other, they represent a useless cause of additional power consumption. Thus, implementing a MIMO control system designed on the basis of a model which could take into account the intrinsically coupled nature of the system seems a useful step to further improve the experimental results. The possibility of removing undesired harmonics in the control action will be in any case limited by the available bandwidth of the implemented decoupling system.

5. Model refinement and dynamic decoupling

A “black-box” MIMO model of the electromagnetic system, including coils, sensors and passive structures, was developed in the past years on the basis of experimental data of magnetic fluxes measured by the sensors and currents in the active coils [11]. To keep the model dimensions manageable only a limited set of coupling terms were considered (about 25% of the torus surface), but this approximation entailed an error in reproducing low n modes. To improve the model accuracy, two actions were undertaken. First, a new experimental campaign, where selected coils were fed, was dedicated to acquire a larger set of measurements and assess the actual relative weight of couplings and, second, a finite element model of the MHD mode active control system was built by the code CARIDDI [12]. In particular, this new model (white-box model) was aimed at providing “virtual measures” where they are not available or too noisy (white-box model). The results of the two models have been compared both in terms of electromagnetic mutual inductances between the active coils and the sensors and in terms of mode amplitudes and phases. An example of the white-box model validation is given in fig. 3 where a satisfactory agreement is observed between the absolute values of couplings computed by the white box model and those ones experimentally measured.

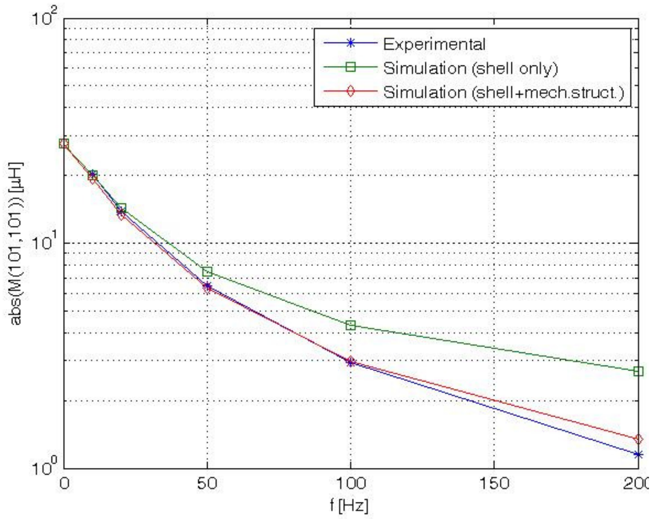

FIG.3. Comparison between absolute values of couplings computed by the white box model and experimentally measured

The problem of decoupling can be tackled considering either the magnetic fluxes or the modes. The most general approach to achieve a satisfactory dynamic performance starts from the knowledge of the dynamic coupling matrix **G**(jω) between active coils and sensors. This procedure unavoidably neglects the issue of decoupling field harmonics after removing undesired sidebands. On the basis of the original version of the black-box model a first MIMO decoupling control system has been designed [13]. Due to the complete covering of the torus surface, **G**(jω) must satisfy the magnetic field solenoidality condition and therefore can not be inverted. The Moore-Penrose pseudo-inversion is still applicable to a scaled, symmetrised model $\tilde{\mathbf{G}}$(jω) meeting the physical condition on the flux. Using the singular value (SVD) decomposition, the pseudo-inverse $\tilde{\mathbf{W}}$(jω)=pinv[$\tilde{\mathbf{G}}$(jω)] can be computed (pseudo-decoupler). By inspection it was observed that the matrix elements could be approximated in the frequency range of interest (0-200 Hz) by transfer functions with a couple of zeros with two poles added to meet the realisability condition. A state space representation was then calculated and discretized introducing the saturation limits of the real machine. A schematic view of the control system is presented in fig. 4. A feedback loop was added to cope with disturbances and parameter uncertainties. The implementation of the pseudo-decoupler algorithm on one of the real-time processing nodes was implemented and an execution time of about 160 μs was measured, compatible with the overall requirements of the mode control system (latency time equal to 400 μs). Tests are planned in the next experimental campaigns.

Independently of the pseudo-decoupler approach, a simplified solution is also under investigation that starts from the modal representation including the

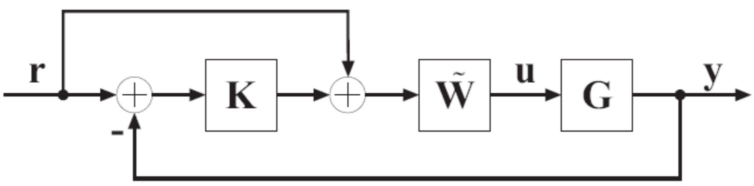

FIG. 4. Block diagram of the control system with pseudo-decoupler $\tilde{\mathbf{W}}$

cleaning algorithm. It would have a more limited scope, since it is aimed at removing only the most important cross harmonic components, but it would retain the interesting property of decoupling the selected clean harmonic components. First, simplified transfer functions of the direct and main cross modes need to be identified, then a control gain matrix with not-null off-diagonal terms must be designed to cancel the mode. A preliminary numerical result is shown in fig. 5, where a (1,7) step reference, with phase constantly equal to zero, was applied and a static cancellation of (0,7) mode was successfully accomplished.

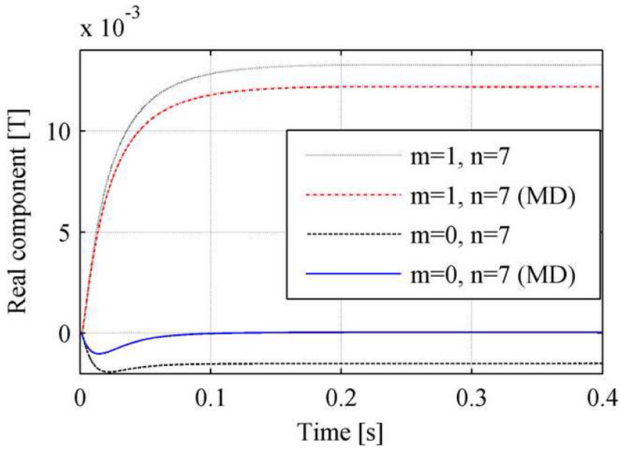

FIG. 5. Comparison of simulated open-loop time response to m=1, n=7 step reference with and w/o static Mode Decoupler (MD).

6. Power supply optimization

After an initial phase in which the maximum current was limited to 200 A, the saddle coil power supplies have been commissioned up to their nominal current of 400 A. As a result of a premature rupture of some IGBT modules, the operation PWM frequency was reduced from 10 to 5 kHz to decrease the thermal stress and increase their expected life duration. Halving the PWM frequency had no negative effects on the dynamic response of the system. In addition the inverter control system was optimised. The current reference signals to the inverters supplying the saddle coils are generally sinusoidal waveforms, whereas the inverter internal current regulator, a PI controller, had been optimized for step response. In operation it was noted that, in presence of a sinusoidal reference, the currents actually generated had a delay ranging from 1.5 to 2 ms. Changing the inverter controller into a pure proportional one and increasing the proportional gain, the closed loop bandwidth of the current control system was increased and the delay was reduced to about 0.7 ms. The zeroing of the regulator integral component causes the introduction of a steady state error between the reference and the supplied current, that, however, has no negative effects on the dynamic response of the MHD mode control. The increased system bandwidth permitted also to cancel the current oscillations arising in some coils in shots without plasma.

7. Conclusions

The use of the CMC algorithm in the RFX-mod MHD mode control system has permitted a partial phase and wall unlocking of m=1 resistive kink tearing modes, ushering in routinely

1.5 MA operation. Its implementation required the increase of the number of the input channels, the amount of data exchanged in real-time and the computational time. To keep the system control cycle within the required value a change of the control system architecture was necessary along with the upgrade of the processors and the optimization of the software communication layer. A MIMO decoupling control system has been designed to improve the system dynamic response, and a new model is being developed by using the finite element code CARIDDI to overcome some remaining inaccuracies in reproducing low n modes. Tests with the new MIMO controller are envisaged in the next experimental campaigns.

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