

# OPTIMIZATION OF THE RFX-MOD TOROIDAL POWER SUPPLY FOR $m=0$ PLASMA MODE CONTROL

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**1. Introduction.** In the RFX-mod, high performance plasmas with improved confinement are obtained at high current (above 1.5MA) thanks to the spontaneous self-generation of magnetic helical states [1]. The transitions to the helical state are experimentally found to be favored by a very particular equilibrium condition, characterized by shallow reversal parameter  $F$ , defined as the ratio between the toroidal field at the edge and the average toroidal field. A full explanation of the beneficial effect of shallow reversals in RFX-mod discharges is currently not established; some conjecture is made about the role of the non-linear coupling between  $m=0$  and  $m=1$  modes [2]. In the traditional view,  $m=0$  modes are originated by the non-linear coupling effect of several  $m=1$  modes, which creates an  $m=0, n=1$

sausage-like instability. Since this process is non-linear, it can be considered the other way round:  $m=0$  modes can excite a broad spectrum of  $m=1$  modes, so distorting the core helix. In this view, since at shallow reversal

the growth of  $m=0$  modes is prevented, the dominant  $m=1$  mode is free to grow without energy exchange with the secondary modes. Experimental hints supporting this description is found in RFX-mod. Fig. 1 shows the normalized amplitude of the  $m=0, n=1$  and  $n=2$  components of the radial field at the resonance plotted versus the reversal parameter. At the same time, as shown in fig. 2, the amplitude of the  $m=1, n=-7$  toroidal field component increases while the amplitude of the secondary modes decreases. The

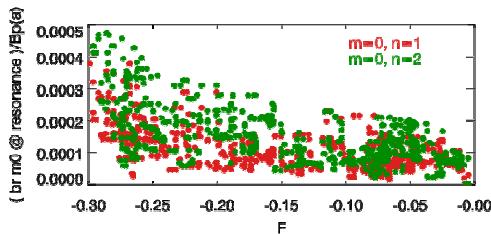


Fig. 1 – Normalized amplitude of  $m=0, n=1$  and  $n=2$  components of the radial field.

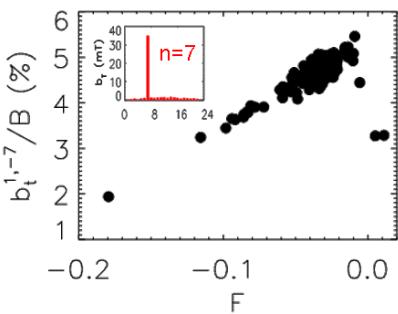


Fig. 2 – Normalized amplitude of  $m=1, n=-7$  mode versus  $F$ .

reduction and control of  $m=0$  modes have therefore a key role in establishing good conditions for the transition to enhanced confinement states. The most natural candidate for  $m=0$  control is the toroidal field coil system, which is composed by 12

toroidal winding sectors, each one independently driven by a large four-quadrant power converter [3]. The attempt of controlling  $m=0$  modes by means of the toroidal power supply has been up to now severely limited either by the inadequate precision and the slow response of the toroidal power supply units, which are requested to compensate for fast and small unbalances (few percent of the rated current) between the sector windings. The unsatisfactory behavior originates from an un-optimized design of the unit control system. In order to enhance the control of  $m=0$  modes, an optimization of the toroidal power supply has been carried out. Such optimization is a first necessary step towards a more effective dedicated  $m=0$  controller, presently under development. In this paper, the preliminary results of such optimization are reported.

**2. Requirements for optimal  $m=0$  control and limitations of the toroidal power supply.** In typical shallow F RFX-mod shots, the  $m=0$ , low  $n$  order amplitude is such that the toroidal power supply has to control currents as low as tens of A. As for the dynamic performance point of view, it turns out that the faster the control reacts in response to the  $m=0$  instability, the higher is the reduction of the mode amplitude

achievable. The design of the toroidal power supply was based on a set of specifications coming from the operation of the former RFX machine: a current as high as 16kA in the coils during the bias phase (corresponding to 600mT) and 6kA (230mT) during the reversal phase. Instead, the best plasma performance is obtained at much lower currents and fields, as low as some hundreds of amperes (tens of mT), corresponding to less than 10% of the current capability of the toroidal power supply switching converters. The current in the toroidal

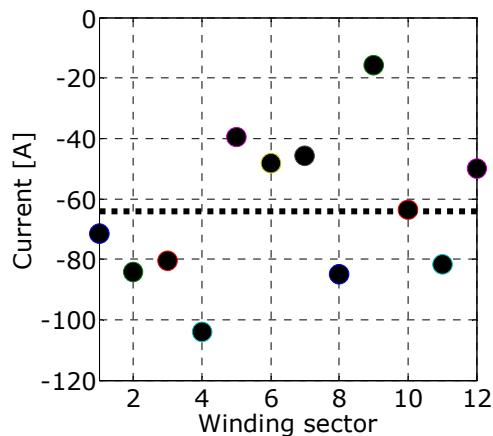


Fig. 3 – Spread of toroidal winding sector currents with respect to the average current.

winding sectors is individually feedback controlled based on a PI controller. At these current levels, the precision of the overall current control chain decreases, resulting in a significant current unbalance among the 12 toroidal winding sectors. A calibration shot with no plasma has been used to check the raw current unbalance at different current levels. This unbalance is due both to offsets in the control loop chain (measurements and references) and to small differences in the calibration gains. As an

example, the spread of the currents in the 12 sectors with respect to the average current for shallow F shots is shown in fig. 3. It can be noted that peak to peak unbalances reach values as high as about 100A, corresponding to about 4mT. The standard deviation is  $\sigma = 24.8A$  (about 1mT). This scattering in the current values directly translates into  $m=0$  error fields introduced and is a complication for the  $m=0$  control. Additional source of error is the fact that the overall control chain is based on a digital system. The feedback measurements and references are sampled and converted via 12-bit ADCs. Being 6kA the full scale with both positive and negative numbers represented, this leads to a quantization error of about 5A, intrinsic to the structure of the system. From the dynamic point of view, the toroidal power supply control system shows a fixed delay between the current request and the effective production of current in the coils, as shown in fig. 4 for one sector. The delay has been ascribed to the structure of the control software, based on a digital controller cycling every 720 $\mu$ s. It is of the order of 1.5 - 2.2 ms, corresponding to 2 - 3 samples

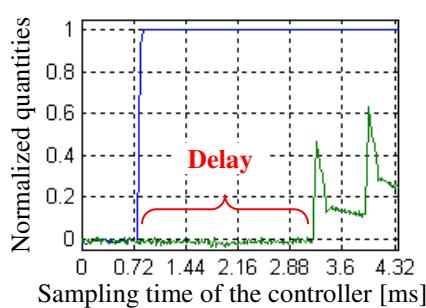


Fig. 4 – Response delay of the output current (green line) of the power supply to a step function applied to the input voltage reference (blue line)

of the control cycle (Fig. 4). Of course this has a strong impact on the performance of the  $m=0$  control.

**3. Optimisation of the toroidal power supply.** The first optimisation steps aim at improving the precision of the toroidal power supply control system. Two modifications have been implemented: a real-time elimination of the offset in the control signals

and an improvement of the internal structure of the toroidal power supply controller. The second one, in particular, consisted in the introduction of a feed-forward input in order to speed-up the dynamics especially as a reaction to external disturbances (e.g. the plasma): this is a mandatory tool for an effective  $m=0$  control. The real-time offset compensation is performed immediately before the pulse: the measurements and the references exchanged with the toroidal power supply control unit are sampled and averaged, the result is subtracted via software from the signals themselves. After the implementation of this feature, the calibration shot has been repeated and the result is shown in fig. 5. As compared to fig. 3, it can be noted that the spread has been greatly reduced. The standard deviation is  $\sigma = 4.9A$ , which is in line with the unavoidable

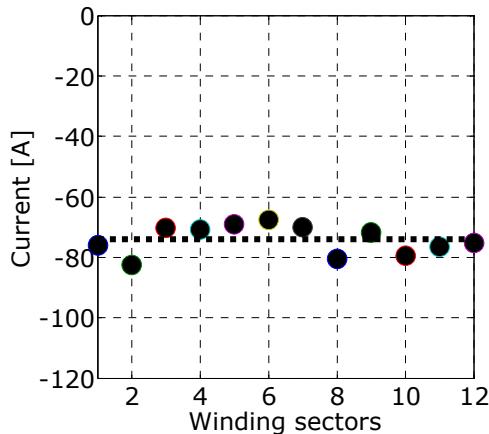


Fig. 5 – Spread of toroidal winding sector currents with respect to the average current after offset correction.

normalized and added to the output of the PI feedback controller. The new part of the controller has been tested extensively and is now ready to be integrated in the design of the  $m=0$  controller.

**4.  $m=0$  controller and future work.** The new features of the toroidal power supply system will be exploited in the new  $m=0$  mode controller, presently under development. In particular, the feed-forward input will be used to compensate the

poloidal loop voltage due to the coupling between the toroidal circuit and the plasma. This contribution is too fast to be compensated by the feedback loop, and can be anticipated on the basis of the plasma current derivative. In parallel to the

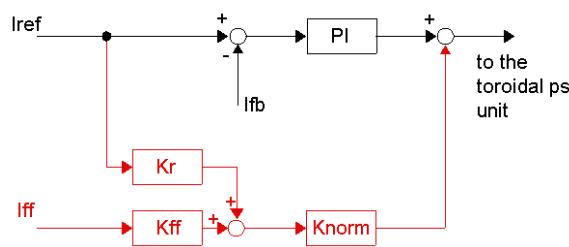


Fig. 6 – Structure of the toroidal power supply control system.

development of the controller, some optimisation of the software structure is planned to reduce the response delay of the toroidal power supply, which at present seems to be the only real severe limitation to an effective  $m=0$  control.

## References

- [1] Lorenzini R. et al. Nat. Phys. 2009
- [2] Cavazzana R. et al., 38th EPS Conference on Plasma Physics, Strasbourg, 27/6-1/7-2011, ECA
- [3] V. Toigo, R. Piovan, L. Zanotto, M. Perna, A. Coffetti, M. Freghieri and M. Povolero, The control system of the RFX toroidal power supply, Fusion Engineering and Design Volumes 75-79, November 2005, 55-59