The harmonic power filters of the JET Poloidal Divertor Field Amplifiers

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The harmonic components of the currents flowing in the in-vessel divertor field coils produce a magnetic flux which is strongly coupled to the pick-up coils used for the detection of plasma displacements, impairing the control of the plasma vertical position. New power filters were therefore installed at the output of the Poloidal Divertor Field Amplifiers. The criteria for the selection of the filter elements and the results of the calculations of its characteristics are reported. After extensive commissioning and acceptance testing, the filters were connected to the coils and their performances were proved. Attenuation factors better than the specified -32 dB were obtained at the dominant voltage harmonic frequencies (600 Hz and 1200 Hz) and better than -20 dB for all the other components. Some problems, met within the plasma initiation scenario, are being tackled.

1. BACKGROUND

Since the beginning of the '94-'95 experimental campaign, the magnetic configuration of the JET machine has been characterised by four divertor field coils, installed inside the vacuum vessel [1].

The four coils are supplied by four independent 12-pulse line commutated thyristor converters (Poloidal Divertor Field Amplifiers, PDFA's) [2].

Each PDFA is composed of two identical 6-pulse modules, which can be connected either in parallel or series configuration with copper busbars and air cooled reactors (45 μH). Each module is protected against overvoltage, which may be produced by plasma disruptions, by a bipolar thyristor crowbar. Table 1 gives the main ratings of the four PDFA units for the parallel configuration.

Table 1
Main ratings of the PDFA's (parallel configuration)

Rating	PDFA 1 & 4	PDFA 2 & 3
Duty Cycle	20s/580s	20s/580 s
Output current	40 kA	40 kA
No-load voltage	910 V	1180 V(tap 1)
		930 V (tap 2)

The operation of the PDFA's generates, on the DC side, characteristic voltage harmonics at a frequency multiple of 600 Hz. Typically, the 600 Hz harmonic (rms) can be 12% and the 1200 Hz harmonic ca. 6 % of the DC no-load voltage [3].

In addition non-characteristic harmonics may also be present. In particular, a small 300 Hz component may be expected as the result of unequally spaced firing angles between the two 6-pulse modules.

2. INTERFERENCE WITH THE VERTICAL STABILISATION SYSTEM

The four in-vessel divertor coils are strongly coupled to the magnetic field detectors used for the measurement of the plasma displacements and, in particular, with the pick-up coils which provide an essential part of the feedback signal used in the vertical position stabilisation system. The harmonic currents generate a variation of the magnetic field which is detected by the pick-up coils, essentially masking the signal associated with actual plasma movements. The amplitude of these coupled signals is so large that the reference signal fed to the power amplifier (Fast Radial Field Amplifier, FRFA [4]), used to actively stabilise the plasma vertical position, could easily reach the full scale value. In Fig. 1, the PDFA's are blocked until t=40.52 s and therefore no voltage ripple is present. The FRFA reference signal is only affected by a high frequency noise and no voltage is applied at the output of the FRFA. As soon as the PDFA's firing pulses are released, a large ripple voltage appears with a dominant frequency of 600 Hz which is reflected into the FRFA reference and, consequently, output voltages.

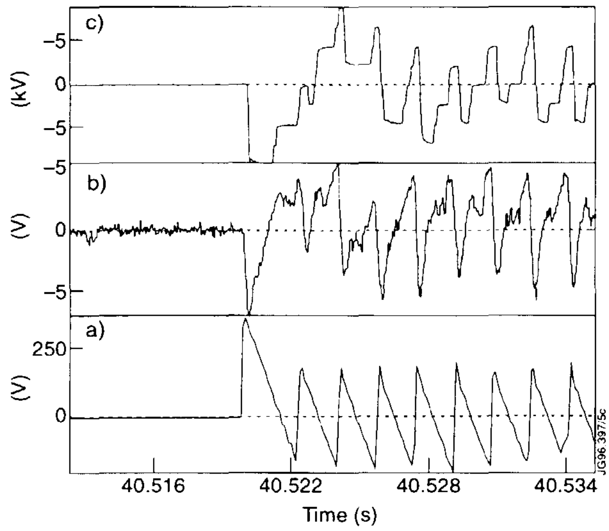

Fig. 1 - Effect of PDFA output voltage ripple
a) PDFA1 output voltage
b) FRFA reference voltage
c) FRFA output voltage

3. SPECIFICATION AND DESIGN OF THE FILTERS

3.1 Essential specifications

Attempts to correct the magnetic signals by compensating the effects of the divertor coil currents did not yield any significant improvement. The system is in fact very complex, the relation between divertor coil currents and magnetic signals is affected by the presence of plasma and by the steel casing of the divertor coils. Harmonic power filters looked therefore the most effective and radical solution.

The design of the filters was based on the following essential specifications:
- attenuation of the 600 Hz and 1200 Hz voltage harmonic components by a factor of 40 (i.e. -32 dB);
- attenuation of all other characteristic harmonics (i.e. 1800 Hz and above) by a factor of 10 (-20 dB).

In addition, the positive resonance should be of limited amplitude (e.g. 5 dB) and should not coincide to any sensitive harmonic component (e.g. 300 Hz).

3.2 Design of the filter

The large attenuation factor specified for the dominant harmonic components can only be achieved by adopting resonant circuits tuned at the desired frequencies (Fig. 2).

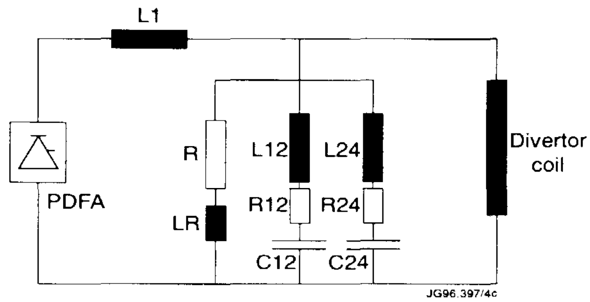

Fig. 2 - Simplified diagram of the harmonic filter

The inductance value of the smoothing reactor L1 was defined on the basis of the admissible voltage drop at the low frequencies. Since the low frequency inductance values of the divertor field coils range between 1 and 4 mH, the inductance of L1 was fixed at 100 μH. Two additional values (200 μH and 400 μ H) are also obtainable, to be used especially when the PDFA modules are in series configuration and a higher voltage is therefore available. The two LC circuits have resonance frequencies tuned at 600 Hz (L12 and C12) and 1200 Hz (L24 and C24). The resistor R is used to damp the positive resonance and to provide, together with the two LC circuits, the specified attenuation at the higher frequencies. The essential ratings of the main components are given in Table 2.

The main compromises were:
- larger capacitances in the tuned branches produce a wider well for the attenuation, thus giving allowance for parametric variations. On the other hand, they accentuate the amplitude of the positive resonance and make the tuned circuits more sensitive to the length of the connections;
- lower resistance values of R result in better damping of the positive resonance and in higher attenuation but, conversely, increase substantially the dissipation in the resistor itself.

The damping resistor and the tuned circuits were connected to the main PDFA busbars by means of coaxial busbars, rated for the full short-circuit current, in order to minimise the value of the stray inductance (which affects the tuning) and to better exploit the limited area available for the installation.

Table 2
Characteristics and ratings of the main components of the PDFA filter

Component	RLC Values R(mΩ)	L(μH)	C(mF)	Rated current Rated voltage	Ins. Volt.	Duty Cycle or Pulse duty	Peak current	Remarks
L1(parallel)	0.5	110	-	40 kA DC plus 310 Arms	20 kV rms	20/580 (DC) 120/480 rms	172 kA	Natural air cooled
R(parallel)	250	6	-	2 kA DC plus 723 A rms	20 kV rms	80 MJ/ 10min	10 kA	Forced air cooled
L12 (L24)	4	19 (13)	-	435 A rms	20 kV rms	continuous	32 kA	Natural air cooled
Type 1 (Type 2)	<0.01 tanδ	- -	1/0.1/0.1 (0.8/0.1/0.1)	3 kV DC	20 kVrms 6 kVDC btw terms	continuous	8 kA/1 mF	
Coax Busbars	15 μΩ/m	0.31 μH/m		2 kA DC plus 311 A rms	20 kV rms	60/540 s DC contin. rms	172 kA	

The typical calculated frequency response of the filter is shown in Fig. 3.

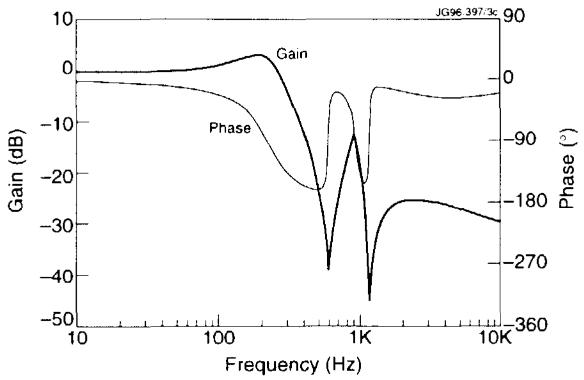

Fig. 3 - Frequency response of a filter (Fig. 2):
L1=100 μH , R=0.25 Ω , LR=6 μH
C12=3 mF , L12=23.5 μH, R12= 5 mΩ
C24=1 mF , L24=18 μH ; R24=5 mΩ

The width of the well for which the attenuation is better than -32 dB is +/- 35 Hz around 600 Hz and -90/+140 Hz around 1200 Hz.

The LC circuits were tuned by adjusting the capacitance value in steps of 0.1 mF. Each capacitor unit is in fact provided with four output terminals which can be connected to obtain three different capacitance values (for instance 0.8/0.9/1 mF). A variation of 0.1 mF in the capacitance changes the tuning frequency by about 10 Hz for the 600 Hz circuit (which means that the ideal frequency can be met within +/- 5 Hz) and by 56 Hz for the 1200 Hz branch (i.e. +/- 28 Hz on the ideal frequency).

3.3 Computer simulations

A detailed computer model of the system was set up to analyse the effect of the filters on the operation of the PDFA's and the consequences of plasma disruptions. The model included the detailed description of the two 6-pulse PDFA modules (both in series and parallel configurations), the voltage control loop and the sequence of protective actions.In particular, the threshold for the overvoltage protection (bipolar thyristor crowbar) at the PDFA output was considered.

Of particular interest was the overvoltage appearing across the output filter in case of disruptions. It was found that, on occurrence of a 6 MA downward disruption in the most demanding scenario (PDFA in series configuration, L1 set at 400 μH), a voltage of 5.6 kV would develop. This had an impact on the rating of the filter components (especially on the rated voltage of the capacitors).

4. COMMISSIONING OF THE FILTER

After installation, all main components were tested on site. The acceptance tests included measurement of parameters, peak current withstand tests on smoothing reactors and coaxial busbars, rated current operation on smoothing reactors, damping resistors and coaxial busbars, continuous operation with harmonics of the tuned circuits.

The tuning of the 600 Hz and 1200 Hz LC circuits was carried out by using a frequency response analyser and adjusting the capacitance value until the resonant frequency was as close as possible to the ideal one. The expected tuning accuracy was achieved for all the circuits.

After connecting to the divertor coils, reference power pulses (PDFA's operated at 5 kA) were executed without and with the filters. The performances of the filters were checked by comparing the output signals from the pick-up coils and the derivatives of the currents in the divertor coils. The attenuation of the signals from the set of lower pick-up coils was better than the specified values (Fig. 4) reaching -40 dB for the 600 Hz component, and -35 dB for the 1200 Hz component. Attenuation of the higher frequencies was equally better than specified (e.g. -25 dB for the 1800 Hz component). After filtering, the 300 Hz component becomes the dominant harmonic.

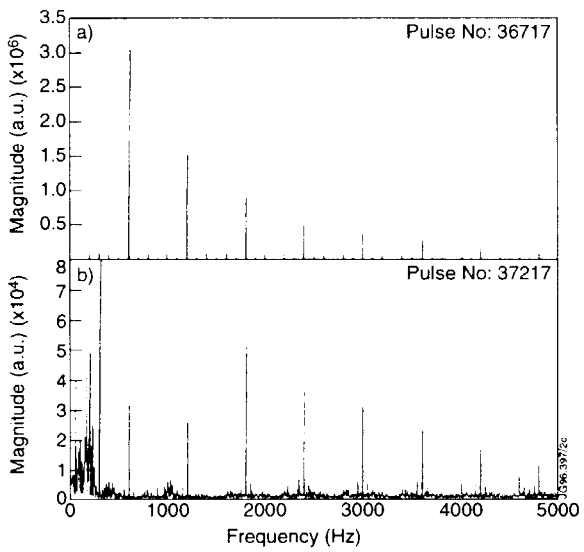

Fig. 4 - Spectra of the lower pick-up coil signals without (a) and with (b) filters (Divertor coil 3, PDFA 3 only at 5 kA)

The results were confirmed by the measurements of the current derivatives which show very similar attenuation factors.

5. COMMISSIONING WITH PLASMA

The commissioning with plasma revealed that the breakdown at plasma initiation could not be sustained. The current induced in the divertor coils and circulating in the filters produced an additional stray field which displaced the null of the magnetic field outside the vacuum vessel. Breakdown could be achieved only in particular circuit configurations (e.g. disconnecting the filters of the D1 and D4 coils and setting the damping resistors to 1 Ω).

The filter is now being modified to include a resistor (typically 10 Ω) in series with each power filter during the breakdown phase. The resistor will be switched-in by means of a HV DC contactor, parallel connected. The total induced ampereturns will be reduced to about 5% of those induced in the divertor structure.

6. CONCLUSIONS

The PDFA filters produce a substantial reduction of the harmonic content of the DC voltage applied to the divertor field coils. While the modification of the filter circuits will shortly overcome the problems encountered with the plasma breakdown, the performances achieved, in excess of the demanding specifications, are very encouraging and point to a successful solution of the difficulties experienced with the control of the plasma vertical position.

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