# Analysis and Specification of the Performances of the new JET Amplifier for the Vertical Stabilisation

T Bonicelli, M Garribba, P L Mondino[1], P Noll.

JET Joint Undertaking, Abingdon, Oxon, OX14 3EA.
[1] Present address: ITER–EDA, Naka Joint Work site, Mukouyama,
Naka-machi, Naka-gun, Ibaraki-ken, Japan.

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T Bonicelli, M Garribba, PL Mondino#, P Noll
JET Joint Undertaking
Abingdon, Oxfordshire, OX14 3EA, United Kingdom

#Present address: ITER EDA, Naka Joint Work Site
801-1, Mukouyama, Naka-machi, Naka-gun, Ibaraki-ken, 311-01 Japan

## ABSTRACT

**A new 25 MW power amplifier based on GTO inverters has been procured to cope with configurations of the JET plasma characterised by high growth rates of the vertical instability. The analysis of the future JET configurations, including a new set of four divertor field coils, resulted in the specification of the required performances of the amplifier and led to the choice of the technical solution. The new amplifier has now been fully commissioned on dummy load at the JET site.**

## INTRODUCTION

The vertical position of the JET plasma is unstable due to the destabilising effect of the iron magnetic circuit and of the quadrupolar component of the equilibrium magnetic field which is needed to obtain an elongated cross-section.

Active stabilisation by means of feedback techniques is therefore necessary.

An analysis of the stabilisation system based on simplified assumptions for the load and on a linear model for the amplifier shows that the response time of the amplifier must be smaller than the inverse of the "open loop" growth rate of the vertical instability [1].

Until the end of the last experimental period (February 1992), the vertical position was stabilised by controlling the current in the radial field coils with a 12-pulse line-frequency phase controlled thyristor converter (PRFA) rated for 12 MW [2].

The speed of response of the PRFA to a large amplitude variation of the reference signal is basically dependant upon the frequency of the supply voltage. The transition between maximum and minimum value of the output voltage is therefore accomplished (with a 50 Hz system and taking into account some limitations on the possible excursion of the firing angle) in ca 8 ms.

The response time to a small amplitude variation of the reference signal (up to approximately 20% of the full value) is also dependant upon the number of pulses of the converter and, for the PRFA, it is about 2 ms.

The original design of the stabilisation system was based on a limiter D-shaped plasma with an elongation ratio of 1.65.

The PRFA allowed actually even more demanding single and double-null configurations and quiescent plasmas with elongation ratios of up to ca 1.9 with growth rates of up to ca $300\ s^{-1}$ to be controlled.

## NEED FOR IMPROVED STABILISATION

The stabilisation system showed some shortcomings when it was attempted to move the X-point at a distance of about 10 cm from the wall. The control of the vertical position following plasma disruptions was also impaired in some conditions by the too long response time and the insufficient peak power of the amplifier.

Vertical instabilities can produce large forces on the JET vacuum vessel (up to 8 MN can be expected) and therefore the occurrence of such events must be limited to the maximum possible extent. This has become a more severe problem with Beryllium limiters since the plasma current $I_p$ is sustained in cleaner plasmas during the vertical displacements $z_p$ and the resulting forces (approximately proportional to $I_p^{2} * z_p$) become larger.

Of 317 disruptions at currents above 2.7 MA during Beryllium operation (until Oct.'90), 59 resulted in a vertical force exceeding 500 kN on the vessel supports[3].

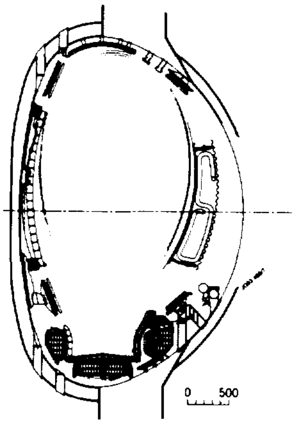

Fig. 1 Flux plot for "slim" plasma.

The need for an improved vertical position stabilisation system became even more indisputable when the analysis of the future JET divertor configurations resulted in expected growth rates of up to 800 $s^{-1}$ (Fig. 1) [4], far beyond the capability of the PRFA.

The analysis of the possible improvements [5] resulted in the decision to procure a new Fast Radial Field Amplifier (FRFA) and to completely re-design the plasma position and current control system to cope with the more complex magnetic configurations [6].

## DEFINITION OF THE PERFORMANCES

Two fundamental aspects of the control of the plasma vertical position were considered:

- the stabilisation of quiescent plasmas
- the response to large perturbations.

### *A. Stabilisation of quiescent plasmas*

The performance of the amplifier in stabilising quiescent plasmas (or, in other words, its small signal behaviour) is intrinsically determined by its speed. Under this point of view, the power of the amplifier is unimportant.

A linear simplified analysis of the stabilisation system demonstrated that, in order to stabilise plasma with growth rates of the vertical instability of 800 $s^{-1}$, an amplifier with response time of less than .5 ms was required (allowing for some safety margin). In fact, Class A linear amplifiers in the range of tens of megawatts are not a practicable solution on the ground of cost and poor efficiency.

High power amplifiers faster than the naturally line-commutated thyristor converters can be obtained by making use of switch-mode inverters supplied from a DC voltage power supply. The output voltage for this sort of amplifier can assume only discrete levels and the input/output characteristic of the amplifier is therefore inherently non-linear.

A switch-mode amplifier can be regarded, in its most basic form, as a bistable voltage source. The corresponding input/output characteristic can be of the type shown in Fig. 2a where an hysteretic control has been chosen: every time the control voltage "e " becomes larger than +H or smaller than -H an output voltage transition occurs, ideally, instantaneously.

More complex control characteristics can of course be adopted like the one shown in Fig. 2b which includes the zero output voltage level.

The study of the stability of the system was carried out by adopting a simplified linear model of the load which is described by a set of equations representing the coupling between the radial field coils, the vessel and the plasma current vertical displacement [7]. The amplifier was instead modelled as an ideal voltage source with the input/output characteristic shown in Fig. 2a. The block diagram of the system is shown in Fig. 3 where G(s) is the transfer function of the load.

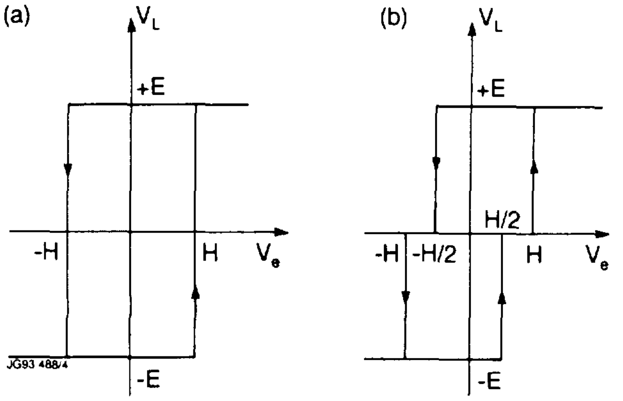

Fig. 2 Ideal Control characteristic
a) two-level hysterisis b) three-level hysteresis

A simple unity feedback speed control was adopted even though, in order to define the plasma position, a "weak" position control is added in practice.

Although the model presents some limitations and inaccuracies (for instance it does not take into account the JET mechanical shell and the double layer structure of the vessel walls), its application allows a good qualitative analysis to be carried out and some general guidelines for the specification of the amplifier to be drawn.

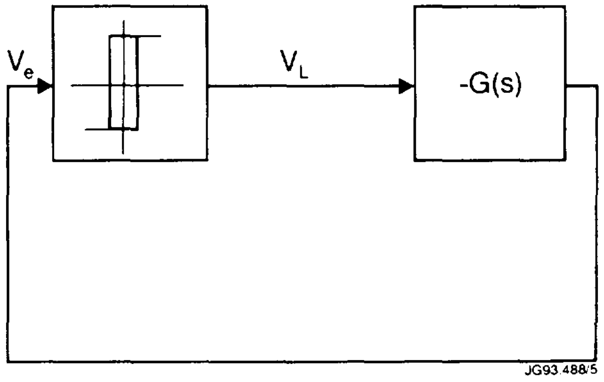

Fig. 3 Block diagram of the system

The system can be solved analytically; the plasma vertical speed settles on a stable limit cycle and oscillates between +H and -H at a frequency (disregarding the resistance of the radial field coils):

$$f = \frac{\gamma}{2}\left(\ln\frac{\frac{aE}{\gamma}+H}{\frac{aE}{\gamma}-H}\right)^{-1} \quad \text{(Hz)}$$

where : $\gamma$ = growth rate of the vertical instability ($s^{-1}$)
E = voltage per turn on the coils (V)
H = half-width of the hysterisis band (m/s)
a = parameter from the load model ($m/Vs^2$) including plasma current magnitude

Smaller H give higher frequencies of the limit cycle and "closer" control around zero of the vertical speed.

As H approaches the value of $aE/\gamma$ (ie for "looser" control of the speed), the frequency of the limit cycle decreases; if H exceeds that value, no stable limit cycle can be found. In principle, a stable limit cycle could therefore be reached even at a very low frequency. In practice, the region where H gets close to the limit $aE/\gamma$ is not accessible since any small variation of the parameters of the system (or any inaccuracy of the model) would lead to the loss of control of the vertical position.

A more realistic limit for the minimum frequency is obtained from the "describing function" method: a stable limit cycle can be established, for the same system described in Fig. 3, only at frequencies above:

$$f_{\min} = \frac{\gamma}{2\pi} \quad (\mathrm{Hz})$$

It is sensible that, in a practical stabilisation system, the normal working point is chosen with a good safety factor (eg 5 or 6) far from the limit also to make up for the non-idealities of the power amplifier (eg delays) and for the small disturbances always present in the plasma.

An amplifier capable of operating at frequencies in excess of at least 1 kHz was therefore deemed to be required for the new stabilisation system.

### *B. Response to large perturbations*

Large perturbations in the plasma (for instance sudden changes in the input power) or disruptions may generate vertical instabilities [8].

If the perturbation of the vertical position is represented as a vertical force $F_z = F_{z0}\, e^{-\beta t}$, it can be shown that the capability of the stabilisation system to recover from large perturbations strongly depends upon the peak power and the amplifier delay time.

The estimated approximate scaling is [9]:

$$F_{z_{\max}} \propto I_p \sqrt{P_{amp}}\, e^{-\gamma t_d}\, \frac{1+\dfrac{\beta}{\gamma}}{\sqrt{\gamma T_v\left(1+\gamma T_v\right)}}$$

where : $P_{amp}$ = power of the amplifier
$t_d$ = amplifier (dead) delay time
$T_v$ = vessel time constant
$I_p$ = plasma current

In practice, the power of the amplifier is limited by cost constraints while the delay time strongly depends upon the switching device on which the inverter is based.

At the time when the contract for the FRFA system was placed, Gate Turn Off Thyristors (GTO's) with repetitive off-state voltage ($V_{DRM}$) of 4500 V and peak turn-off current ($I_{TGQM}$) of 3000 A were available giving a power handling capability 30-40 times higher than the one of the largest Insulated Gate Bipolar Transistor (IGBT). On the other hand, the typical delay time for large GTOs is of the order of 100 μs and, though longer than the one for IGBT's (typical delays: 5-10 μs), is acceptable for the JET application.

A rated peak power for the system of 25 MVA satisfied the budgetary limits.

The maximum force $F_z$, *normalised* to the plasma current, which can be successfully counteracted is given in Fig. 4 in function of the growth rate $\gamma$ for $\beta=0$ (step force) and for $\beta = 100\ \mathrm{s}^{-1}$ both for the old PRFA and the new FRFA.

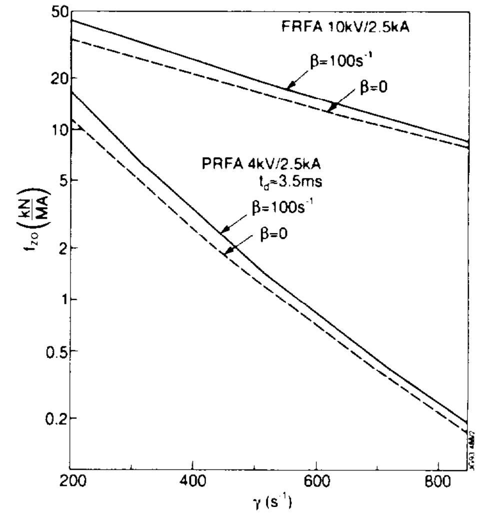

Fig. 4 Maximum vertical force permitting recovery

For growth rates of ca 300 $\mathrm{s}^{-1}$ (i.e. at the limit of the PRFA range of stabilisation) , the new amplifier would be capable to counteract forces up to 150 kN (for a 5 MA plasma), five times larger than the old one would do.

For a given peak power of the amplifier, an "optimal" voltage/current rating can be found in dependence of the growth rate $\gamma$ and of the number of turns N of the radial field coils. For $\gamma = 800\ \mathrm{s}^{-1}$ and $N = 72$ (number of turns of the JET coils) , the optimal rating for a 25 MVA amplifier is V = 10 kV, I = 2.5 kA.

In fact, the analysis of vertical instabilities in JET shows that the apparent force perturbing the plasma vertical position could be in excess of the one which can be stabilised by the new FRFA especially in case of disruptions characterised by sudden changes of $\beta_p$ or abrupt readjustements of the current profile . The vessel structure and the in-vessel components must therefore be able to withstand occasional severe vertical instabilities though it is expected that the new FRFA will help in reducing the number of such events .

Table I
Basic Performances of the FRFA system

| | Config A | Config. B |
|---|---|---|
| Nominal Duty Cycle | 30 s / 600 s | |
| Nominal output voltage | ± 5000 V | ± 10000 V |
| Base output current (29 s) | ± 1000 A | ± 500 A |
| Short-time output current (1 s) | ± 5000 A | ± 2500 A |
| Output switching frequency at the base current | 2.5 kHz (2500 V step) | 2.5 kHz (5000 V step) |
| Output switching frequency at the short-time current | 1 kHz | |
| Maximum response delay time | 200 µs | |

## SPECIFICATION OF THE PERFORMANCES

The basic performances of the system are summarised in Table I.

The system is composed of four identical subunits (each capable of delivering 2500 A/2500 V) which can be connected in two configurations [10]. For example, Configuration B, which should provide the best performances in recovering from large perturbations, is achieved by series connecting the four subunits. Five output voltage levels are available in Config. A and nine levels in Config. B.

It is expected that the FRFA is required to deliver its full power only for short time during a pulse (i.e. when large perturbations are present) while the power requirements during the quiescent periods are much reduced (20 % of the peak power was considered an adequate design value). This approach leads to a more economical design.

The nominal pulse was defined as shown in Fig. 5.

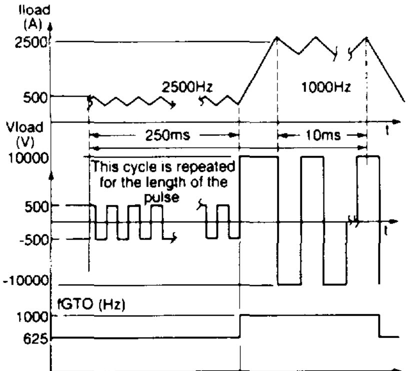

Fig. 5 Nominal pulse

The switching frequency of each GTO is limited by the thermal dissipation. Large GTO's have relatively high turn-on and turn-off losses which result in switching frequency of 200 - 300 Hz in industrial applications.

The specified output voltage switching frequency (see Table I) of the FRFA system is achieved by switching each GTO at 625 Hz during the base current periods and by switching the series connected subunits on a rota basis.

The operation of GTO's requires the respect of some interlock times to allow for the non-ideal characteristics of the devices. The response time to a voltage request will not exceed 200 µs in the worst situation.

Vertical instabilities can induce high currents in the radial field coils. The FRFA system was designed to cope with induced overcurrent of up to 20 kA which are diverted from the GTO inverters by triggering thyristor crowbars installed at the output of each subunit.

## CONCLUSIONS

The FRFA system has now been installed at the JET site and commissioned with execution of power tests up to the rated performances on a 25 mH dummy load.

The final series of tests on the radial field coils and the integration with the new plasma position control system will take place at the end of the present shut-down of the JET machine at the beginning of 1994.

The new power amplifier will improve the ability to control vertical instabilities. It is expected that the highly unstable plasmas of the new JET divertor configuration can be stabilised and that recovery from minor disruptions and other perturbations is possible. Though occasional losses of the vertical position control as observed previously during major disruptions cannot be ruled out, it is believed that the number of such events will be reduced and fatigue effects on the vessel components will be lessened.

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