Control of highly vertically unstable Plasmas in TCV with internal Coils and Fast Power Supply

A. Favre, J.-M. Moret, R. Chavan, A. Elkjær*, D. Fasel, F. Hofmann, J.B. Lister, J.-M. Mayor, A. Perez

CENTRE DE RECHERCHES EN PHYSIQUE DES PLASMAS
Association EURATOM - Confédération Suisse,
Ecole Polytechnique Fédérale de Lausanne, UHD-PPB, CH - 1015 LAUSANNE, Switzerland

* Danfysik A/S, DK - 4040 Jyllinge, Denmark

The goal of TCV (Tokamak à Configuration Variable) is to investigate effects of plasma shape, in particular high elongation (up to 3), on tokamak physics. Such elongated configurations ($I_p \cong 1$ MA) are highly vertically unstable with growth rates up to $\gamma = 4000\ s^{-1}$. Control of the vertical position using the poloidal coils located outside the vessel is limited to $\gamma \leq 1000\ s^{-1}$ because of the shielding effect of the conductive vessel and because of the relative slow time response of their power supplies (0.8 ms thyristor 12 pulse switching at 120 Hz). This dictated the necessity to install a coil set inside the vacuum vessel fed with a **F**ast **P**ower **S**upply (FPS).

The choice and design of the system with a special attention to the mechanical and electrical constraints in TCV tokamak, as the results and real performances, will be presented.

1. FAST INTERNAL COIL

The fast internal coil is made of two sets of three toroidal turns located in each outer corner of the vacuum vessel (G coil in figure 1.1). Their exact position results from a trade-off between mechanical design constraints and a maximum wall separation to reduce field screening by image currents in the conductive vessel. Both coil sets are connected in anti-series to create a radial magnetic field at the plasma location. The nominal current (2 kA) was chosen such that this radial filed can restore a 1cm shift in the vertical position [2]. The rated voltage is such that this current can be established faster than the vertical instability growth rate (250 μs).

Vertical disruption or disruption of non up-down symmetric configuration has been estimated to induce currents of about 2 to 15 kA in the fast internal coil, depending on the total resistance of the coil itself, the transmission line and the crowbar internal resistance. These currents lead, in the poloidal magnetic field, to a force of about 100 to 200 kN per turn in the fast internal coil.

Figure 1.1
TCV Tokamak

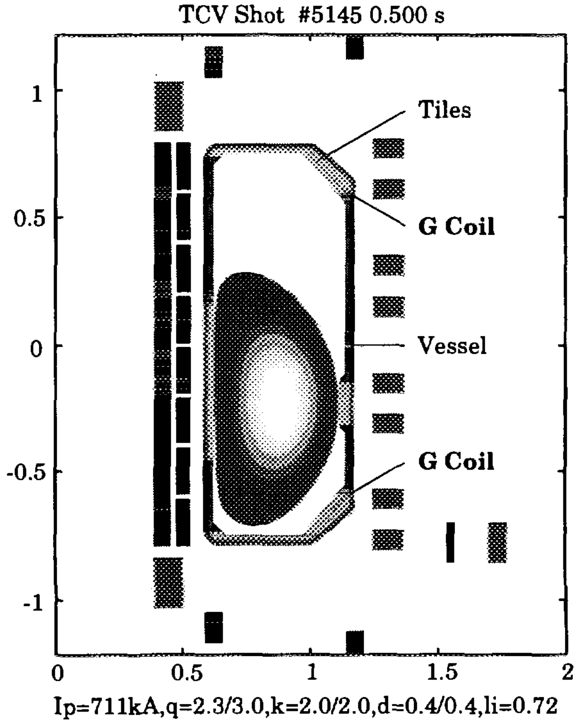
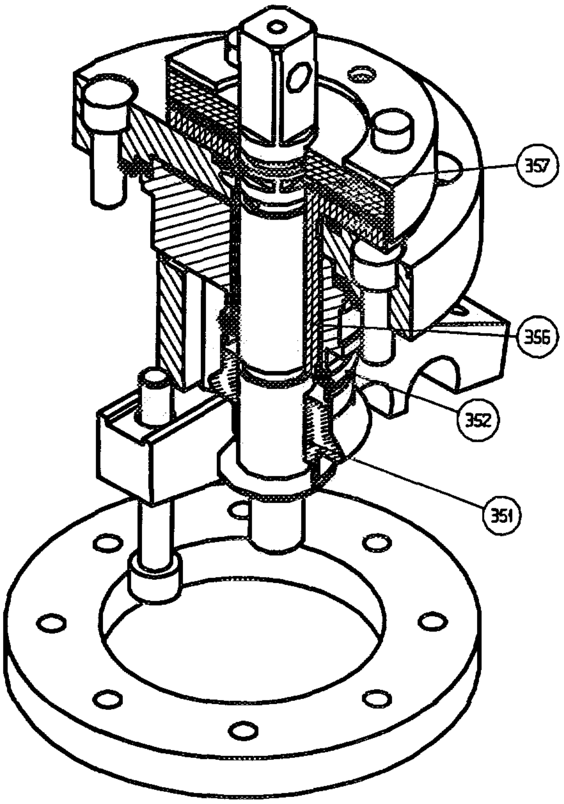


Figure 1.2
Feed Through



The windings are made of 10 mm diameter non insulated copper bars held in 48 ceramic rings per turn and protected from direct plasma exposure by graphite tiles (see figure 1.1). In practice, each turn is divided in four quarters for easier installation and to have the possibility for controlling non axisymetric perturbations with four independent power supplies. Quarters are connected with flexible parts having the form of two turn springs to compensate thermal expansion of the conducting bar (3 mm per quarter at 350° C). Special attention has been given to the current feed through, whose design is sketched in figure 1.2. In this design, the problem of the forces on the conductor and of the vacuum have been separated. In figure 1.2, parts #356 and #357, made of Pamitherm, ensure the mechanical rigidity of the system, while the brased ceramic #351 ensures vacuum. This fragile piece is mechanically decoupled with a bellow #352. The whole system is air-cooled to protect the insulation material of the connected transmission line during baking of the vacuum vessel. The internal coil main parameters are listed in table 1.3.

Table 1.3
Coils Parameters

Parameter	Value
Coil Impedance (frequency dependent)	40 µH to 100 µH 10 mΩ to 100 mΩ
Coil Current (plasma disruption)	15 kA - 10 MA^2s (Coil short-circuited)
Coil Voltage (plasma disruption)	2 kV (Coil in open circuit)

2. POWER SUPPLY DESIGN

Considering that the poloidal field system is able to take over the plasma vertical control after a few ms, it has been decided to choose a non-linear (switching mode) power supply and to specify it in terms of voltage reaction time and current controllability rather in terms of bandwidth and accuracy.

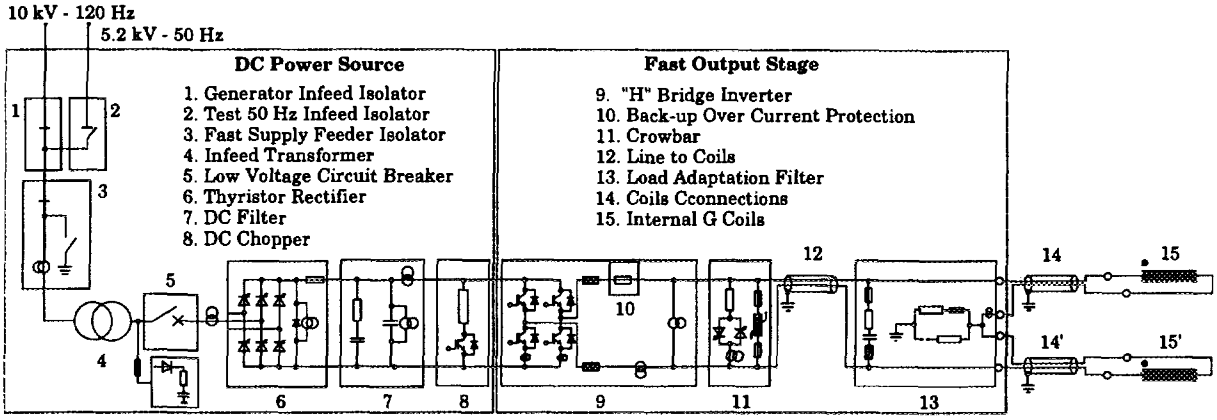
The main difficulties concerns the low inductance of the load and the high constraints caused by plasma disruptions. This has dictated the whole power supply design.

The selected structure [1] consists of two main elements, the *DC Power Source* which produces the regulated DC voltage and the *Fast Output Stage* which is able to apply the fast voltage pulses to the load.

The DC Power Source is constituted of a controllable *Thyristor Rectifier* (block 6 of figure 2.1) able to adapt the Fast Output Stage output voltage envelop during the plasma discharge. A damped *R-L-C DC Filter* (block 7) is placed at DC output to limit the voltage ripple and to provide fast current pulse to the Fast Output Stage. It is constituted of two capacitor banks, damping resistors and the leakage inductance of the Infeed Transformer. The *DC Chopper* (block

Figure 2.1

Power Supply Block Diagram



8), constituted of IGBTs in series with power resistors, is added for dissipation of the energy which can be reflected from plasma or other tokamak coils without output crowbar firing what would imply system loss of control.

Because three different possible output voltage levels has been found sufficient, the Fast Output Stage is composed of a single *H-Bridge IGBT Inverter*. This inverter (block 9 of figure 2.1), constituted of IGBT switches, is designed to be able to operate with a rated switching frequency of 10 kHz (up to 25 kHz) with voltage reaction time delay and minimum on time in the μs range. This is necessary for sufficient current control on the connected low inductance load. To protect the power supply against plasma disruption, a

Table 2.2

Power Supply Parameters

Parameter	Value
Output Current	± 2000 A
Output no load Voltage	± 566 V
Current Rise Time	0.25 ms
Current Controllability	± 100 A at ±2000 A ±40 A at ±50 A
Voltage Reaction Time	5 μs
Switching Frequency:	10 kHz Typical 25 kHz Max.

thyristor *Crowbar* (block 11), used as over-voltage and over-current protection device, is located at output, while a *Back-up Over Current Protection* (block 10) is added to avoid major damage in the case where all electronic over-current interlocks fail. A *Load Adaptation Filter* (block 13) is located near the tokamak coils. It include an RC filter acting as transmission line HF termination, the circuits necessary to refer the coil to ground and the terminals requested for serial connection of the two half coils. The Power Supply parameters are listed in table 2.2.

The control electronics are based on a central microcomputer Control Board and especially designed modules for the control of each sub-part. The heart of the power supply electronics is constituted of the H-Bridge Control Module in which the control modes as the fast interlocks and sequences are implemented using Field Programmed Gate Array (FPGA) chips. The power supply can be used as a current source (double band hysteresis current regulator), as a voltage source (open loop voltage PWM modulator) or as a three levels voltage source (H-Bridge switches directly driven through digital signals). The H-Bridge and its drivers are fitted with fast short-circuit (IGBT de-saturation) and over-current (serial collector resistors) detectors which allow detection of an over-load (not only a short-circuit) in less than one μs. For fault detection and diagnostic, the Power Supply is fitted with fast measurements (200 kHz range) for all AC / DC voltages and currents connected to TCV Data Acquisition System.

3. TCV PLANT IMPLEMENTATION

TCV plasma control is processed by an hybrid analog-digital matrix multiplier. For vertical control, the real-time position observer ($I_p \bullet z$), built upon tokamak magnetic probes, is used to provide FPS analog voltage or current reference as it is the case for poloidal field system.

With the implementation of the TCV Digital Plasma Control System, the control of the H-Bridge switches could be directly processed through a digital interface.

4. TESTS AND RESULTS

Because the real tokamak load is complex to modelize and the power supply exact requested output wave forms were not well known, it has been chosen to define and test performances with specified voltage and current *Reference Wave Forms,* the power supply being connected to a dummy load. After improvement to Fast Output Stage, performances better than requested has been reached. Figure 4.1 and 4.2 show examples of Reference Wave Forms obtained supplying the tokamak G coil set.

Low current plasmas has been first chosen to limit risks of system failure. Then elongation (κ) and as a consequence the growth rate (γ) has been progressively increased to tune the vertical position feed-back corrector. Growth rate higher than never reached with poloidal field system only has been achieved in the first weeks of operation ($I_p = 250$ kA, $\kappa = 1.8$, $\gamma = 1700\ s^{-1}$). Progressive increase of plasma current and elongation will follow up to TCV rated parameter ($I_p = 1$ MA, $\kappa = 3$).

5. CONCLUSION

The possibility to implement a high stress withstand coil system and to adapt an industrial based and relative low cost power supply in a tokamak particular environment has been demonstrated. The efficiency and reliability of the whole system during TCV tokamak long term operation remain to be proved.

6. REFERENCES

1. A. Favre et al. Fast Power Supply for Vertical Stabilization of TCV Tokamak Plasmas, CERN EP2 Forum 95, Vol. ETG 43 e A15, 1995.
2. F. Hofmann, G. Tonetti et al. LRP 426/91, CRPP Lausanne, 1991.

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Figure 4.1

Power Supply PWM Voltage Control

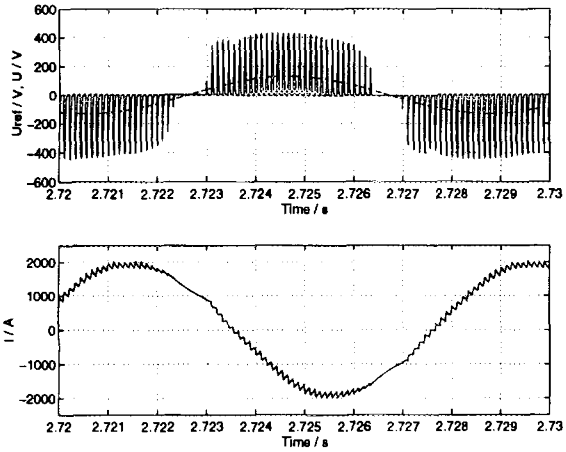

Figure 4.2

Power Supply Closed Loop Current Control