Detailed Design, Installation and Testing of the New Coil Protection System for JET

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The recent installed pumped divertor at JET has required an upgrade of the existing coil protection. The new Coil Protection System (CPS) detects electrical faults and protects the coils against mechanical and thermal overstressing due to operation outside safe limits. Protective actions include immediate removal of the voltage from the coils. The paper describes the design, construction, commissioning and early operation of the protection system.

1. INTRODUCTION

The plasma control and protection scheme in use at JET is shown in Fig. 1

The upgrade of the JET magnet system [1] and the general trend towards the extension of the operating region, within machine safe limits, has led to the decision to design and install a new Coil Protection System (CPS) [2]. CPS detailed design started at the beginning of March 1993, and the system became operational in May 1994. The system has required new voltage and current transducers, pick up coils, flux loops, Rogowski coils and temperature sensors for most of the circuits.

Measurements or computed quantities are compared with suitable thresholds. If a threshold is exceeded an alarm is generated and protective actions are taken.

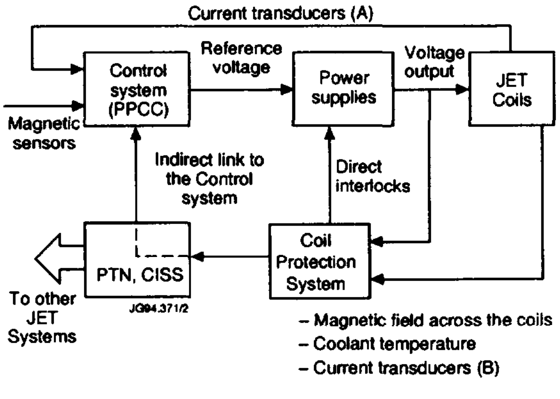

Fig. 1. Control and Protection Scheme

The protection algorithms can be classified into five categories:

C1. Conventional overcurrent and overvoltage protection for all the circuits.
C2. Thermal stresses (e.g.. I2t) in all the coils.
C3. Mechanical stresses on the coils and vacuum vessel.
C4. Circuit equation integration and comparison with the measured currents.
C5. Thermal model for the divertor coils.

2. FAULT DETECTION ALGORITHMS AND PROTECTIVE ACTIONS

The block diagram shown in Fig. 2 summarises the fault detection algorithms implemented in CPS. Details on the five categories of protection are outlined below.

C1. Overvoltage and overcurrent protection has been implemented for both poloidal and toroidal field systems. The poloidal field (PF) system includes up to 10 independent circuits and up to 22 coil elements (or subcoils). The toroidal field (TF) circuit includes up to 2 independent circuits, the first for the odd coils and the second for the even coils [2]. The protection is active all the time. A simple deglitching technique makes this protection more "robust", against unwanted intervention especially in case of plasma disruption.

During the pulse two levels of overvoltage have been defined: 95% and 100% V_{max}, with V_{max} maximum voltage,

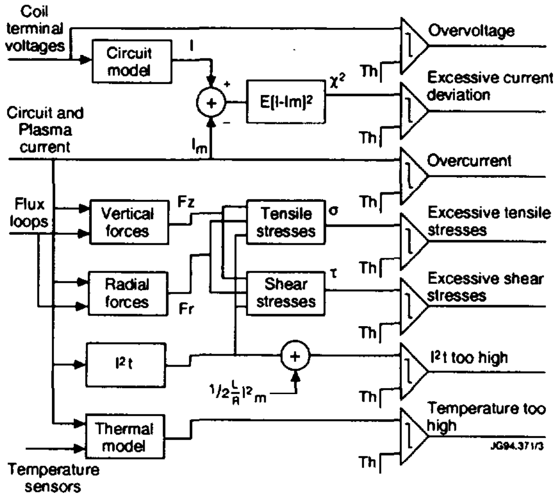

Fig. 2. Fault Detection Algorithms

whilst outside pulses only one level (10% V_{max}) is defined. V_{max} takes into account the maximum voltage of the power supply and the induced voltage during normal transients. A deglitching time of 20ms has been chosen.

Three levels of protection have also been defined for the circuit currents. Two during pulse: 5% and 10% above I_{max}, with I_{max} maximum current allowed in the circuit, and one, 10% of I_{max}, outside pulses. The deglitching time used for the overcurrent protection is 2ms.

The current in the P1 six central pancakes (I_2) in principle can be raised up to 60kA with a current in the toroidal coils of 67kA, whilst the maximum current on the end coils (I_1), made of four pancakes, is 40kA. This is obtained with the poloidal flywheel generator (PFGC) connected to the end coils, and a thyristor converter unit (PFX) connected to the centre coils. A special protection has been implemented to reduce to an acceptable level the ΔI in the end coils in case of full inversion of PFX when I_1 and I_2 are close to the limits. The protection is activated when the "average current" in P1 coil, defined as $0.4I_1 + 0.6I_2$, exceeds 45kA and the current in the end coils exceeds 42kA. The above protection has been tested and operates successfully.

C2. The limits on the I^2t are a function of the initial temperature of the coolant and, for a given cooling rate of the coils, affects the pulse repetition rate.

C3. The protection system makes real time computations of the forces using flux loops and ampere-turn measurements or analytic coefficients.

The tensile and shear stress (σ and τ in Fig. 2) of each coil is computed as a linear combination of vertical force F_z, radial force F_r and temperature (computed from the energy dissipated). The radial and vertical forces on each coil are given by equations of the form:

$$F_r = NI \cdot B_z, \; F_z = NI \cdot B_r \qquad (1)$$

where NI is the measured ampere-turns of the coil and B_z and B_r the measured field crossing the coil. The total vertical force transmitted to the vacuum vessel by the divertor coils is the sum of the forces acting on the four coils. Fig. 3 shows a comparison of the vacuum vessel vertical force experienced during a pulse with currents of 16.5kA and 15.5kA in divertor coils 2 and 3, plus 10% sweeping, measured with this method and with strain-gauges mounted on the vessel restraint legs at the main vertical ports.

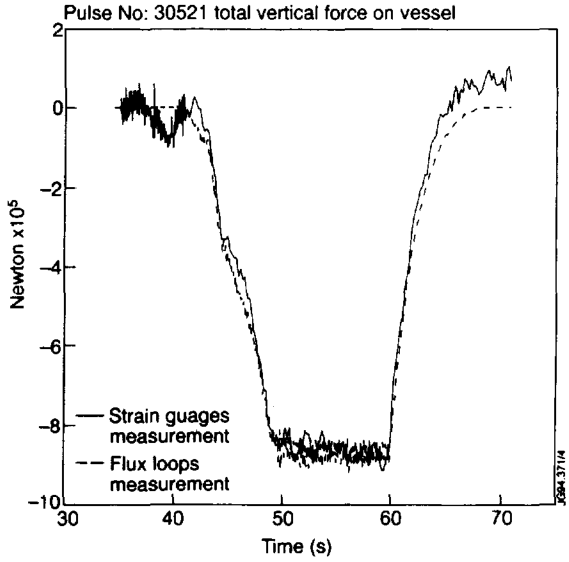

Fig. 3. Vessel Vertical Force (No. 30521)

The vertical field at the divertor coils is not measured but is estimated as a linear combination of the ampere-turns of all coils and the plasma current.

C4. This protection, based on circuit equation integration in real time, has been implemented for the toroidal field circuit and soon will also be implemented for the poloidal circuit. The inputs to the circuit models are the coil terminal voltages. In either case the computed currents are compared with the measured currents. A large difference would indicate a possible fault and would terminate the pulse.

The two models are integrated only during pulses. The poloidal and toroidal field models are decoupled and therefore they can be integrated separately.

The PF circuit equations, when the iron core is saturated, are given by:

$$L_\theta \frac{dI_\theta}{dt} + \mathrm{R}_\theta I_\theta = \mathrm{V}_\theta - \mathrm{g}^\mathrm{T} \frac{dI_p}{dt} \qquad (2)$$

where: V_θ is the vector of the input voltages, I_θ is the vector of the computed PF currents, L_θ is the circuit inductance matrix R_θ is the circuit resistance matrix and g is the vector of the mutual inductances with the plasma. The system inductance matrix is computed multiplying the single turn inductance matrix by the matrix of the number of turns with the proper sign. The unsaturated state of the iron has been modelled too.

C5. A simple model will be used to estimate the temperature of the epoxy insulation and copper windings of the divertor coil. The inputs to the model are the vessel temperature, coil case temperature, coil currents, coolant flow and coolant inlet and outlet temperatures.

During operation the temperature of the vessel is maintained at about 300°C. In spite of being protected by radiation heat shields over most of their surface, the coils are heated by the surrounding environment as well as by energy dissipation during pulses. This means that as long as the vessel is hot, the divertor coil cooling has to be maintained.

The object of the protection system is to keep the epoxy glass insulation in the main body of the coil below a safe temperature (60°C). This is achieved by limiting the differential temperature of the coolant within 20°C *(to avoid thermal stresses between turns)* and the maximum I^2t on the basis of the initial temperature of the coolant before the pulse.

Two fail-safe commands [2] are sent individually to the PF and TF power supplies (see Fig. 1): a Voltage Off and a Circuit Breaker Open command. These direct interlocks are backed-up by the actions performed via the Pulse Termination Network (PTN) and the Central Interlock and Safety System (CISS).

3. IMPLEMENTATION

CPS is a multiprocessor and multitasking system based on VME (Fig. 4). Data is continually collected from the Analogue and Digital I/O boards by the DSP Master Board, via the VME Bus. These values are used to provide continual protection of the coils.

While JET is not pulsing it is possible to suspend the protection for a short period of time and to load from the Level 1 software on the host computer a new set of operating parameters.

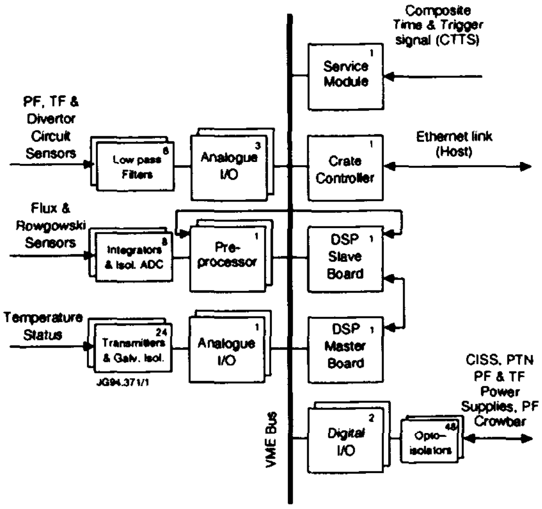

Fig. 4. CPS Hardware Configuration

As a pulse is started messages are received from the host computer via the Crate Controller, preparing the CPS software for the next pulse. The information in these messages instructs CPS what data channels to collect during the next pulse and also indicates the state of other parts of the plant. From this point on CPS monitors the progress of the pulse using the status information from the Service module together with values from some of the digital inputs.

While JET is actually pulsing, further data is collected from the Pre-processor card, by the DSP Slave board. This board provides drift and offset compensation of the integrated signals received from the Pre-processor. This data is then combined with the data already being collected by the DSP Master board, to provide the large number of inputs upon which the full range of protective algorithms are run. If a fault is detected, appropriate actions are taken directly using the digital outputs to issue commands to the remainder of the plant, while at the same time messages are sent to the host indicating the source of the fault and the actions taken.

During the pulse, samples of the collected and calculated signals are simultaneously stored in a Shared Memory block on the DSP Master board. After each pulse these stored values are collected by the GAP programme on the host, via the Crate Controller, and archived.

The code for the DSPs was mostly written in C using the facilities of the SPOX operating system both to share the CPU power between the various protection algorithms and to control the communication channels between the various boards involved.

4. OPERATING EXPERIENCE

During the first six weeks of operation, the protection system monitored the running of 815 pulses, and failed only once. Even this failure did not compromise the safety of the machine since fail safe design criteria has been adopted extensively. The majority of CPS actions took place near or after the end of the pulse without hindering the actual experiment, while several potentially damaging maloperations have been terminated. During these pulses CPS took action on 106 occasions as shown in Table 1.

Table 1. Faults detected by CPS

No.	Type of faults
7	Test pulses: produced deliberately to test the CPS system
26	I^2t trips: due to operation of the machine approaching safety limits
17	Temperature trips: due to noise on thermocouples during disruptions
8	Voltage Out of Pulse trips: due mainly to residual voltage on coils after pulses
19	Overvoltage or P1 ΔV trips: usually due to disruptions or failures of other machine components (e.g. S4A Switch, etc).
24	Overcurrent trips: mainly due to initial limits being set too low or unexpectedly high currents during disruptions
5	Central Timing System Errors

The number of trips per week is decreasing as parameters are adjusted and operational experience gained.

5. CONCLUSION

Early experience indicates that CPS will be useful and reliable. Because of its flexibility, protections not included in the original design have already been implemented and others (eg. TF Coil Torque Calculation) are planned.

6. ACKNOWLEDGEMENT

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7. REFERENCES

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