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ON-LINE SIMULATION OF THE JUNCTION TEMPERATURE FOR THE THERMAL PROTECTION OF HIGH POWER GATE TURN-OFF THYRISTORS USED IN PULSED DUTY INVERTERS.

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Abstract. A new high power (25 MW) amplifier system based on Gate Turn-off Thyristors (GTO's) has been procured to be used as a power amplifier in the control system of the vertical position of the plasma in the JET experiment. The new amplifier is characterised by a nominal duty cycle of 30 s every 600 s. The power dissipation in each GTO can reach peaks of almost 8.1 kW for short periods. The switching frequency of each GTO and the current during the execution of a JET pulse are somewhat unpredictable. It was therefore felt necessary to provide the power devices with a thermal protection which has to be reasonably accurate in order not to unnecessarily limit the performances of the amplifier. At the same time it should be reasonably simple and cost effective.
An on-line simulation/calculation of the junction temperature was therefore studied and adopted: the conduction losses, the turn-on and turn-off losses are taken into account; the direction of the output current together with the knowledge of which GTO's are in the ON status determine if the current is flowing in the GTO's or in the freewheeling diodes.
A detailed description of the model used and of the hardware realisation of the simulation is given in the paper.

Keywords. GTO, losses, thermal impedance, junction temperature, protection.

1 - INTRODUCTION

The JET machine is the largest device in the world presently operating in the field of research on nuclear fusion based on magnetically confined plasma, Rebut et al (1).
A new high power (25 MW) GTO inverter system (called Fast Radial Field Amplifier - FRFA) has been procured to be used in the control system of the vertical position of the plasma, Mondino et al (2). The performances required by the new amplifier are quite demanding: the rated duty cycle is of 30 seconds operation every 10 minutes; the rated "base" switching frequency of each GTO is 625 Hz for the full length of the pulse but bursts of switchings at higher frequency are possible. The actual operation of the amplifier is performed under closed loop control via the JET Plasma Position Controller; the output current and the switching frequency are quite unpredictable. Evaluations performed during the early design phase pointed at the GTO's as the limiting components of the system under the thermal point of view and that, to achieve the very demanding rated performances of the inverter, the GTO's had to be operated close to their thermal limits.
To measure the junction temperature during operation is not feasible mainly because the GTO's do not have any temperature monitoring device inside them (unlike some power mosfet). To measure the case temperature on-line with a thermo-couple is difficult since the very low signal will be lost in the noise. Even if there was not any noise it would still not give a good representation of the junction temperature due to the fact that the time constant of the thermo-couple normally is much longer than the leading time constant for the GTO junction to case thermal impedance.
It was therefore felt that a thermal protection in the form of an on-line simulator of the junction temperature of the power devices was necessary; on the other hand the thermal protection should not be too conservative to avoid imposing unnecessary limitations to the operation. Also a compromise had to be achieved between accuracy of the estimation, simplicity and cost of the actual realisation.

2 - DESCRIPTION OF THE INVERTER SYSTEM

A modular approach for the amplifier has been chosen and the FRFA is composed of two identical units connected in series (2). Each unit is composed of two identical sub-units of which one is shown in Fig. 1.
The sub-units within one unit can be connected either in parallel (Configuration A) or in series (Configuration B). Each sub-unit is provided with a DC power supply which provides a controlled DC voltage of 2.5 kV (+- 10%) to the input of the GTO inverter.

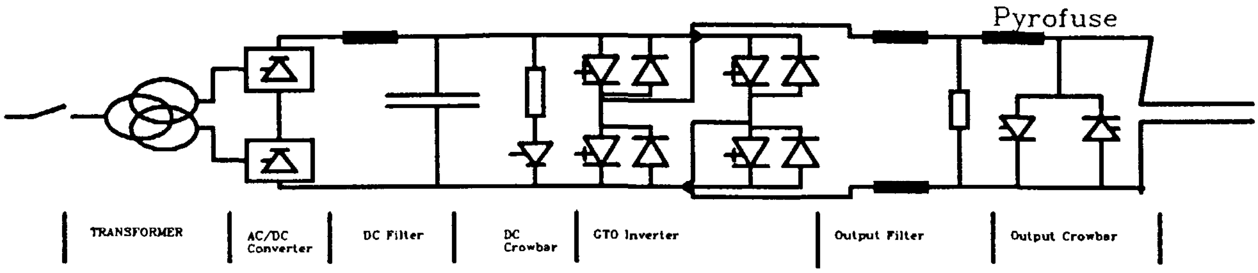

Fig.1 - Simplified schematic of one sub-unit

A simplified schematic of the inverter is given in Fig. 2a. Each "switch" of the inverter is actually composed of two parallel connected GTO's. An inverter is physically sub-divided into two GTO modules; each module (Fig. 2b) includes four GTO's, the associated freewheeling and snubber diodes, the snubber circuits and the drive units. The snubber circuit is of Marquardt-Undeland type with one common discharge resistor per GTO module, Undeland et al (3). The GTO's, the freewheeling diodes, the snubber diodes and the snubber discharge resistor are water cooled. The current sharing between the two parallel GTO's is controlled both passively and actively. The passive current sharing is done by means of a current sharing transformer and the active current sharing by firing the more loaded GTO with a delay proportional to the current difference. The main data for an inverter module are given in Table I.

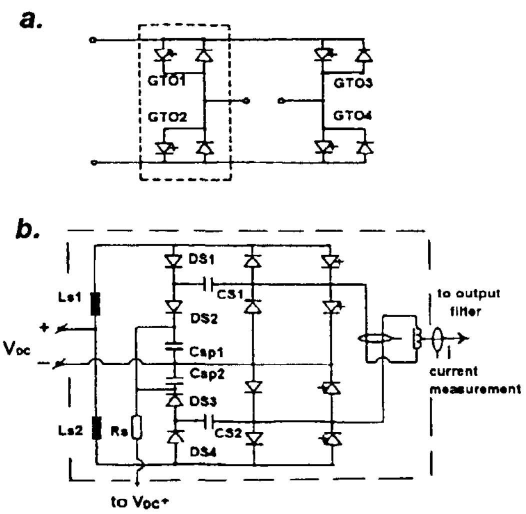

Fig. 2 GTO Inverter
a. Basic structure of the Inverter
b. Schematic of an Inverter Module

The GTO's used were the largest available on the market at the time the supply contract was placed; the main data are given in Table II. Some data are taken directly from the data sheet, whereas others are taken from the data sheet and scaled for di/dt, DC voltage, load current etc. Also the impact on the switching losses by the snubber circuit has been taken into account (as explained in paragraph 3).

Table I - Main data for an inverter module

GTO type	SG 3000 GXH24
Freewheeling diodes	SSi R62 F250
Diodes DS1 - DS4	SSi R62 F250
Capacitor CS1, CS2	6 uF
Capacitor CSP1, CSP2	90 uF
Snubber Resistor	0.4 Ω
Inductor LS1, LS2	15 uH

The GTO's have been specially selected by the manufacturer to have as little spread as possible in parameters such as voltage drop, switching times etc. For the switching losses the "typical" values can be used for the calculation and furthermore the turn-off losses corresponds to a GTO with high conduction voltage drop (according to the data sheet a GTO with high voltage drop has lower turn-off losses than a GTO with low voltage drop).

Table II -	The main parameters for the GTO's (SG 3000 GXH24)
V DRM	4500 V
I TGQM	3000 A
I T(RMS)	1200 A
V T	1.93 V @ 200A
V T	3.18 V @ 1500A
E(turn-on)	2.4 J @ 400A load current in GTO 3.4J @ 1500A load current in GTO
E(turn-off)	0.7 J @ 400A load current in GTO 3.2 J @ 1500A load current in GTO
Rth (J-C)	16 K/kW, double side cooling

The actual operation of the system is not fully predictable since it will depend on the feedback from the Plasma Position Controller which, via the FRFA, is controlling the vertical, inherently unstable, position of the plasma.

For contractual reasons therefore a nominal pulse has been defined which is deemed to be equal (or in excess) to the most demanding operational pulses from the losses and junction temperature point of view. Fig. 3 shows the nominal pulse; the switching frequency for an individual GTO is 625Hz with current corresponding to 500A load current (excluding filter current) lasting 240ms followed by 1kHz switching at 2.5kA for 10ms. This pattern is repeated for the full length of the pulse (30 sec).

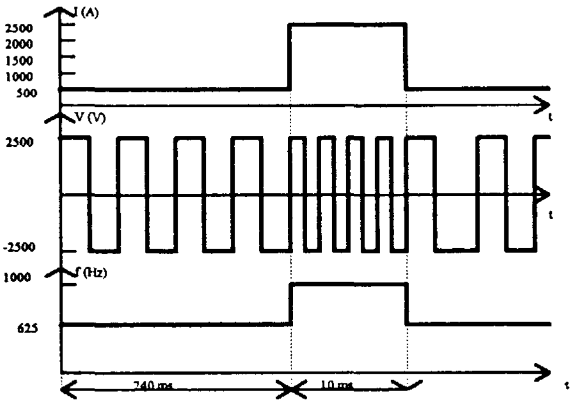

Fig. 3 - Nominal pulse (ideal); the sequence is repeated for the full length (30s) of the pulse

Also a longer pulse (60sec) has been defined with 70% of the current at the same frequency and repetition pattern (though this pulse is slightly less demanding from the thermal point of view). These requirements (especially the switching frequency) are well in excess of the ones adopted in more conventional applications.

It is expected that the FRFA will operate below the nominal performances for most of the duration of a pulse. The GTO junction temperature will therefore normally be lower than what corresponds to the nominal pulse. Both switching frequency and load current will instead increase when the plasma vertical position is disturbed.

The switching frequency of the GTO's is limited only by the interlocks introduced at the driver level on minimum on and off times and by the blocking time. An additional feature is that if the same GTO has been fired twice in less than 500us, any further firing command to that GTO is inhibited for 500us; therefore a switching frequency in excess of 2kHz could be achieved.

Such a switching frequency would rapidly cause over dissipation in the device. On the other hand the control of the plasma vertical position may require a high switching frequency for short periods.

It was therefore decided that the best way to protect the semiconductors but, at the same time, keep the system as flexible as possible was to adopt an on-line thermal simulation of the junction temperature.

3 - THE JUNCTION TEMPERATURE SIMULATION

General. It was reckoned to be advisable to provide each inverter with two junction temperature simulations; one associated with the upper and one with the lower GTO's in the "right" module of the inverter (GTO3 and GTO4 in Fig. 2a). In this way it is ensured that, even if the output current is only of one polarity, the more loaded GTO is monitored. Since an "alternating zero output voltage" is adopted, the GTO's in the "left" module are loaded in an almost identical way as the ones in the right module. Because of that it is not necessary to provide each arm with an individual temperature estimation. The good control of the current sharing ensures finally that the output current can be assumed evenly split between the two parallel GTO's in each arm, Bonicelli et al (4).

Thermal model. A simplified model, in form of a block diagram, for the on-line simulator is shown in Fig. 4. The simulation consists principally of three parts; the loss model, the thermal impedance model and the protection and monitoring part. The output of the loss model (which is a voltage proportional to the instantaneous losses in the GTO) is supplied as input to the thermal impedance model. The output of the thermal impedance model is the instantaneous value of the difference between junction temperature and cooling water ($\Delta\Theta3$ and $\Delta\Theta4$ respectively).

The temperature of the cooling water (measured at the outlet of the cooling system) is added to the maximum value of $\Delta\Theta3$ and $\Delta\Theta4$ to get the junction temperature for the hottest of GTO3 and GTO4. To add some degree of conservativeness a selectable "safety margin" can, if desired, be added at the output to the warning and to the trip of the amplifier.

The main parameters for the loss model are:

- conduction, turn-on and turn-off losses as function of the instantaneous output current from the inverter (including output filter current);
- status (ON or OFF) of the GTO's;
- polarity and amplitude of the output current.

The gate losses are very small but have been included in the switching losses; for turn-on and turn-off approximately 50mJ has been added respectively.

The off state losses are normally very small (in the order of 75 W and only applicable when current is going in "opposite" GTO or diode in the same module) and have therefore not been taken into account. The current is assumed to be evenly split between parallel GTO's.

Conduction losses are calculated as the instantaneous value of voltage drop times current in the GTO. The instantaneous voltage drop is modelled as the sum of threshold voltage, V_{TO}, and differential resistance, R_T, times the current in the GTO. The values of

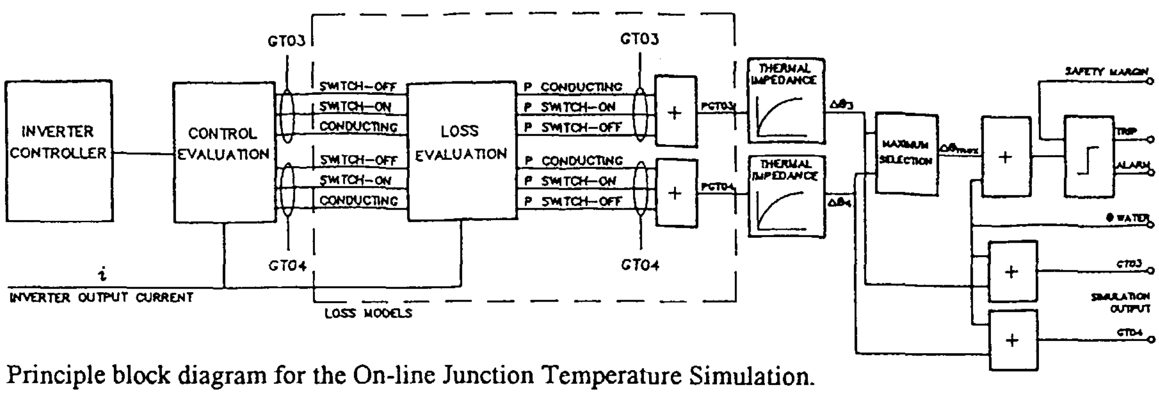

Fig. 4 - Principle block diagram for the On-line Junction Temperature Simulation.

V_{TO} and R_T are calculated from Table II as 1.74 V and 0.96mΩ respectively. Only the actual conducting periods of a GTO are considered, ie no conduction losses are applied when the GTO is off or when the current is flowing in the freewheeling diodes.

Switching losses are modelled as impulses of energy activated at every turn-on and turn-off. To be on the safe side the losses are calculated assuming the junction temperature to be 125°C (the switching losses increase with temperature).

For the turn-on losses the peak current (load current in GTO plus snubber current through the GTO) during turn-on has been used on the abscissa of the diagram showing turn-on losses as function of current. The over current in the GTO during turn-on can be estimated to 1700 A (3) and are consistent with measurements.

The energy in the GTO during turn-on is therefore modelled as a constant term (2.2 J) plus a term proportional to the load current (before the output filter, measured at that moment) as shown in eq.1.

The turn-off losses are easier to extract from the data sheet and are modelled as being proportional to the inverter output current as shown in eq.2 (and only valid for the GTO's which have been conducting the current). To be on the safe side the losses are calculated assuming the junction temperature to be 125°C (the switching losses increase with temperature).

$$E(on) = E_O + dE(on)/di = 2.2 + 4 \times 10^{-4} \times i \quad (J) \quad \text{eq.1}$$

$$E(off) = dE(off)/di = 1.1 \times 10^{-3} \times i \quad (J) \quad \text{eq.2}$$

(i is inverter output current)

For the contractual pulse (Fig. 3) the switching losses are far greater than the conduction losses; during the 500A, 625Hz interval the switching losses are circa 1900W and the conduction losses about 320W whereas for the 2500A, 1000Hz interval the figures are circa 6100W and 1950W respectively. If the high current interval were to continue for the full length of the pulse (30 sec) the junction temperature increase would be (assuming the same model to apply) almost 250 K which, obviously, would lead to destruction.

Thermal impedance. The thermal impedance from junction to water was obtained by, point by point, adding the impedance's as functions of time read from the data sheet for the GTO's and, for the heatsink, from tests carried out on one of the inverters in the manufacturers laboratory. A series of five e-functions have then been fitted to the points describing the impedance from junction to water as shown in eq. 3.

$$Zth(J\text{-}W) = 1.51(1-e^{-t/0.02}) + 3.03(1-e^{-t/0.1}) + 7.57(1-e^{-t/1.2}) + 14.75(1-e^{-t/6.44}) + 4.54(1-e^{-t/7.92}) \quad (K/kW) \quad \text{eq. 3}$$

$$\Delta\Theta(t) = P \times Z_{th}(t) \quad (K) \quad \text{eq. 4}$$

It is worth mentioning that it is principle wrong to say that the thermal impedance from junction to water (as function of time) is found by simply adding the individual thermal impedances (as functions of time). That approach actually assumes that the input power to the heatsink is, in every instant, exactly the same as the input power to the junction of the GTO (which is the power loss). In the short time scale (say, less than one times the leading time constant for the GTO, which is about one second) the output power from the GTO (input power to the heatsink) depends on the thermal capacitance of the GTO. In the short time scale it therefore always leads to an overestimation in the junction temperature. In the longer time scale (a few time constants) it is, of course, correct. The only correct way to find the overall thermal impedance would be from tests carried out on the GTO mounted on the heatsink. The GTO should then be submitted to a power step and the junction temperature measured as function of time (as eq. 4 indicates).

That is very difficult to do, especially for a manufacturer of inverters who is using (perhaps specially designed for his costumer) heatsinks for which he has managed to measure the thermal impedance. So the above mentioned method by simply adding the impedances is simple, but will lead to an overestimation in the short time scale. For the FRFA inverters the overestimation is about 1.8 K at 1 sec, almost negligible!

Protection. The protection is based on two thresholds: the first one at 108°C, gives a warning while the second one, set at 120°C, causes a trip and the immediate turn-off of the inverter. The reasons for these relatively high thresholds are the belief that the simulation is accurate (or slightly conservative) and the fact that the GTO's are specified for up to 125°C operating temperature. Furthermore, the thresholds include the (selectable) safety margin.

Hardware. The junction temperature calculation has been implemented partly with analogue electronics and partly with Logic Cell Arrays (LCA) which are used for the fast control of the inverter and which generates the turn-on and turn-off commands to the GTO's.

The measured output current (Fig. 2b) is used as one of the inputs to the calculation of the losses. The sign is passed to the LCA where, together with the knowledge of the status of the GTO's, the conducting and non-conducting status of the GTO is defined.

Example: if output current is positive and GTO4 has an ON-signal it means that GTO4 actually is conducting the current. If instead the current is negative when GTO4 has an ON-signal it means that the antiparallel diode is conducting.

The LCA also generates short time pulses, about twenty microseconds of duration, which are used to simulate the turn-on and turn-off losses (which themselves are functions of the output current as shown in eq.1 and eq.2). The three terms (conduction, turn-on and turn-off losses) are then added up in an operational amplifier. Only if the GTO is conducting (and not the anti-parallel diode) the conduction and the turn-off losses are taken into account. On the other hand, the turn-on losses are always taken into account irrespective of the direction of current. This gives an overestimation for the GTO which is not conducting the current (eg GTO3 in case of positive output current). The overestimation is negligible for low current values whereas for 2500 A load current it is about 3 J per switching. To put the turn-on losses to zero for the non conducting GTO would instead be an underestimation. It is therefore deemed safer to always take the turn-on losses into account.

For pulses with uni-polar output current (like the contractual pulses shown in Fig. 3) the overestimation is not important since the trip, if any, will always come from the GTO which is conducting the current (GTO4 in case of positive current). If instead the current is bi-polar and perhaps changes polarity several times during a pulse the overestimation could lead to an unnecessary trip. Relatively simple hardware modifications could be done to avoid the problem, if deemed necessary.

The total dissipated power thus determined is then used in the analogue part as input to an operational amplifier, with a series connection of five RC-links as feedback, representing the thermal impedance (junction to water) of the system (as shown in eq. 4). The output is proportional to the temperature difference between junction and water. The water temperature, measured at the outlet, is finally added up thus giving the absolute junction temperature.

4 - TESTS

The most demanding condition, as far as the junction temperature is concerned, occurs during the 30 sec pulse with the system configured in Configuration A (two sub-units in parallel giving a peak current of 5000A during the 10ms intervals). Configuration A is more demanding than Configuration B since there can be a current imbalance between the two parallel connected sub-units (in addition to the possible imbalance between parallel GTO's within the same inverter).

The specification requires that the current imbalance must always be less than 125 A (5%). During the tests at JET the imbalance was always found to be substantially less than 100 A.

The load consisted of a dummy load reactor of 6.25 mH and only one of the series connected units was active (therefore only 2500 V was available at the load). The load current (without ripple) therefore had the shape shown in Fig.5 (compare with Fig.3 which shows the ideal current for the nominal pulse).

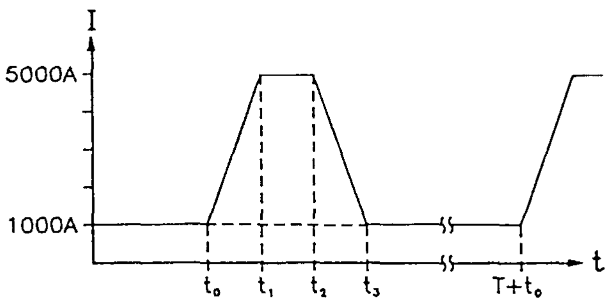

Fig. 5 -The shape of the actual load current (ripple not shown)

During the rise of current from 1000 A to 5000 A ($t_1 - t_0$ = 10 ms) only conduction losses occurs in the GTO and are on average 3100 W during the 10 ms. During the high current interval ($t_2 - t_1$ = 10 ms) both turn-on, turn-off and conduction losses occur (almost 8100 W). The decay of the current from 5000 A to 1000 A takes 10 ms ($t_3 - t_2$) and no losses occur (apart from off-state losses, about 75 W).

Fig.6 shows, for the case described above, the comparison between the output of the on-line junction temperature simulation and the computer calculation for the most thermally loaded GTO (GTO4) for one of the two sub-units in parallel.

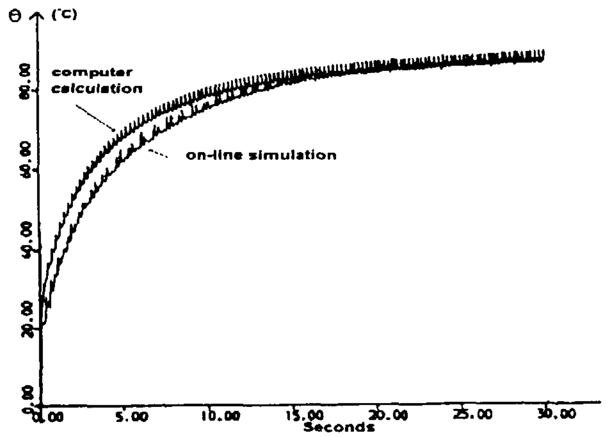

Fig.6 - Comparison between computer calculation and on-line simulation for the nominal pulse in Configuration A.

The on-line simulation shows 85 °C and the computer calculation shows 87 °C ("base" value during the 250 ms periods) at the end of the pulse with water temperature of 16 °C.
The difference between computer calculation and the on-line simulation is bigger for times between circa 100 ms and 10 sec (up to 5 - 7K) but very small for times less than 100 ms. This is mainly due to the fact that for the computer calculation eight e-functions, instead of five, are used for the thermal impedance from junction to water (eq.3). So the on-line simulation might give a few degrees of underestimation in the short to medium time scale. For times longer than about 10 to 15 sec the accuracy is very good.

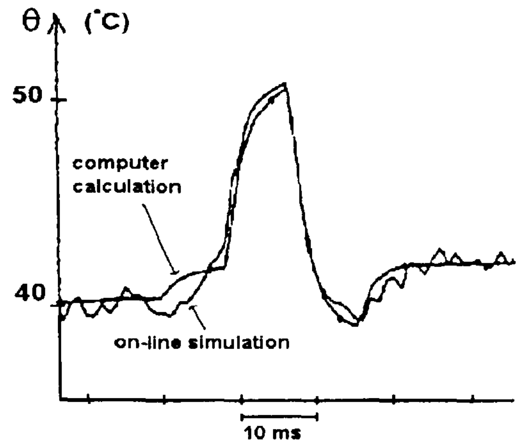

Fig. 7 - Comparison between on-line simulation and computer calculated junction temperature during a high current interval transient.

Fig. 7 shows a comparison between the on-line simulation and the computer calculated transient increase in junction temperature during the high current interval (measured at about 2 sec after the beginning of the pulse, but the same at the end of the pulse). Measured and calculated values as functions of time are very similar and both shows 10 to 11 K increase in the peak value.
The simulation and the calculated values have been compared also for less demanding pulses and have always shown a very good consistency and little spread between sub-units.
The availability of the on-line simulation and protection during all the stages of the power tests was very useful; during those tests in fact the GTO's were operated very close to their thermal limit which, in absence of the protection, could have been easily exceeded.

5 - CONCLUSIONS

A thermal protection in the form of an on-line simulator for the junction temperature has been studied, designed and implemented for the protection of the GTO's in the inverter. The simulator takes into account conduction, turn-on and turn-off losses as functions of current, thermal impedance from junction to water as function of time, and water temperature. The tests have shown a good agreement (in the longer time scale as well as during transients) between computer calculated temperatures and the ouput of the junction temperature simulator for the contractual pulses.

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