AN OHMIC HEATING CIRCUIT FOR THE CASTOR TOKAMAK

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A simple ohmic heating circuit for the CASTOR tokamak is described. A test 19 kA discharge with duration of 40 ms is presented.

1. Introduction

The CASTOR tokamak is a small-size device having major and minor radii $R_0 = 0{\cdot}4$ m and $a = 0{\cdot}085$ m respectively. Up to now, it operated with a delay LC-line as an ohmic heating power supply. It provided discharges with stationary plasma parameters not longer than 4 ms (see e.g. [1]). This time interval is very short for the choice of optimum plasma dynamics. Longer pulses are also needed due to the limited time resolution of a number of diagnostics. Finally, larger time scale is necessary for lower-hybrid-current-drive experiments. The present work describes the simple ohmic heating circuit which prolongs the stationary phase on the CASTOR tokamak.

2. The circuit

The possible duration of the discharge on the CASTOR is limited by the half-sine-pulse length of the toroidal magnetic field (85 ms) and by volt-seconds of the iron core transformer (0·15 Vs without pre-magnetisation; see fig. 1). These parameters allow to prolong the plasma current flat-top phase to about 40 ms.

The diagram of the proposed circuit is shown in fig. 2. It belongs to the class of capacitance schemes widely used on the small tokamaks [2]. The working cycle begins by charging the condenser banks C_1 and C_2 to the different voltages U_1 and U_2 ($U_1 \gg U_2$). Firing the ignitron IG, the high voltage bank C_1 is discharged through the external inductance L to cause the fast primary current ramp-up. During this phase, neutral gas is ionised and plasma current rises to its stationary value. When the diodes D_1, D_2 become open, the low voltage bank C_2 is discharged and the primary current increases slowly. During this period plasma current is constant. The flat-top phase is terminated using the thyristor switch T.

To obtain the desired plasma current waveform the circuit must fulfil certain relations which link together the values of circuit elements and characteristics of plasma loop. These formulas can be simply derived from the circuit equations.

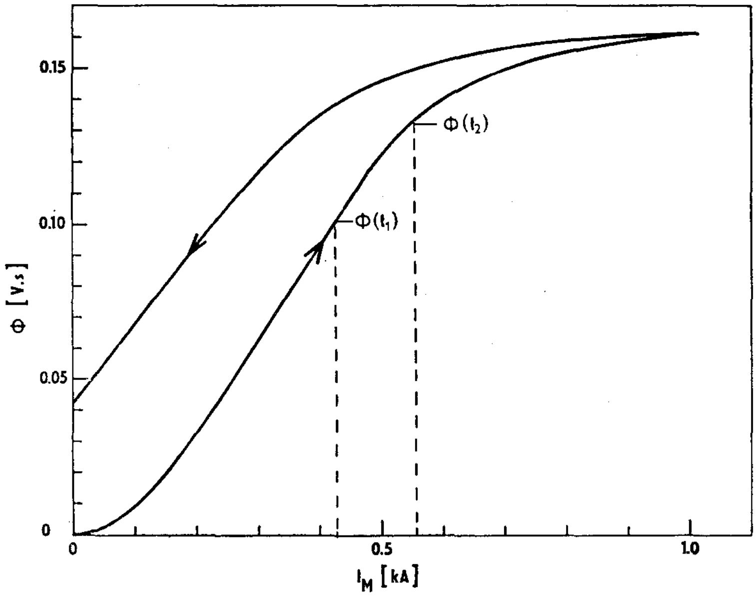

Fig. 1. Magnetisation curve of the transformer on the CASTOR tokamak ($I_M = I_1 - I_p/N$).

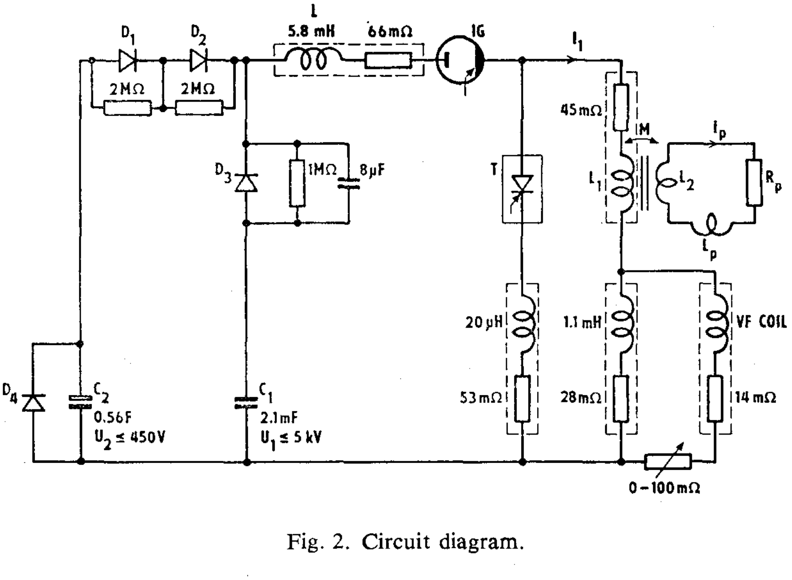

Fig. 2. Circuit diagram.

The first important characteristics, the ramp-up rate of the loop voltage U_L before the breakdown, is given by the formula:

$$\dot{U}_L(0) = \frac{R_l M U_1}{L(L_l + L_2)},$$

where the dot denotes the time derivative. Here, during the pre-breakdown phase, the plasma resistance and inductance (as defined in fig. 2) are formally changed by their values for the liner: $R_l = 9{\cdot}2\ \mathrm{m\Omega}$, $L_l = 0{\cdot}5\ \mathrm{\mu H}$. M denotes the mutual inductance ($M = 0{\cdot}31$ mH in the linear part of the magnetisation curve) and $L_2 = M/N$, where $N = 12$ is the transformer ratio. The loop voltage rate together with the neutral gas pressure p control the breakdown value of reduced electric field E/p by a functional dependence: $E/p = f(\dot{U}_\mathrm{L}(0)/p^2)$ [3].

The plasma current ramp-up rate is equal to $\dot{I}_\mathrm{p} \approx I_\mathrm{p}(t_1)/t_1$, where $t_1 = \frac{1}{2}\pi \times (LC_1)^{1/2} \cos(U_2/U_1)$. The value of the plasma current reached at the end of the ramp-up $I_\mathrm{p}(t_1)$ is governed by the volt-second balance. In the approximations for primary current $I_1(t_1) \approx U_1(C_1/L)^{1/2}$ and $M = \mathrm{const}$ one finds:

$$I_\mathrm{p}(t_1) \approx \frac{NU_1}{1 + L_\mathrm{p}/L_2}\left(\frac{C_1}{L}\right)^{1/2} - \frac{\phi_R}{L_2}, \tag{1}$$

where $L_\mathrm{p} \approx 1\ \mathrm{\mu H}$ is the plasma inductance and

$$\phi_R = \int_0^{t_1} R_\mathrm{p} I_\mathrm{p}\, \mathrm{d}t$$

are the resistive volt-seconds, where R_p is the plasma resistance.

The maximum duration of the flat-top phase is limited by the quarter-period $\frac{1}{2}\pi(LC_2)^{1/2}$ and by the time constant L/R, where R is the total resistance of the primary circuit. In fact, the flat-top phase is shorter and is given by the capability of the loop voltage to maintain the constant plasma current. U_L is restricted by the following relation:

$$U_\mathrm{L} \leqq U_\mathrm{L}(t_1) \approx \frac{M}{L}\left[U_2 - U_1\left(\frac{C_1}{L}\right)^{1/2} R\right].$$

The above conditions, together with practical restrictions, led to the circuit parameters shown in fig. 2. The bank C_1 is built from 14 oil condensers. It is discharged through the diode D_3 to avoid the oscillations which are excited by opening the diodes D_1 and D_2. The bank C_2 consists of 1440 electrolytic condensers which are protected by the diode D_4. The external inductance L is wound from 50 mm^2 Cu-cable. All diodes are 5 kV, 0.3 kA^{2}s-devices. The switch T consists of three 3 kV, 0·3 kA^{2}s-thyristors [4].

On the CASTOR tokamak, the bias vertical magnetic field is generated by a coil system supplied by the primary current. For longer pulses, the current waveform in this coil must be modified by a shunt inductance and by a resistance in series (see fig. 2).

The most critical parameter of the circuit is its relatively large resistance R. For higher plasma currents, it can limit the loop voltage and thus shorten the flat-top phase.

Since the two reduced values, plasma resistance ($N^2R_\mathrm{p} \approx 10\ \mathrm{m\Omega}$) and inductance ($N^2L_\mathrm{p} \approx 0{\cdot}1$ mH), are smaller than those of the primary circuit, the system is not very sensitive to the changes in the plasma loop. Especially, if a part of or the whole plasma current will be driven noninductively, the effect on the primary current will be small. However, during the instabilities (with time scale of $\approx 50\,\mu s$), a small decrease of plasma internal inductance ($\approx 0{\cdot}1\,\mu H$) is equivalent to a considerable change in primary impedance ($N^2\dot{L}_p \approx 300\,m\Omega$) which will cause a jump in the primary current.

3. The test shot

The operation of the circuit is illustrated on a 1·9 kA discharge shown in fig. 3.

The breakdown value of $E/p = 240$ V/m Pa is determined by the pressure of neutral hydrogen $p = 57$ m Pa and by the loop voltage rate $\dot{U}_L(0) = 4{\cdot}10^4$ V/s.

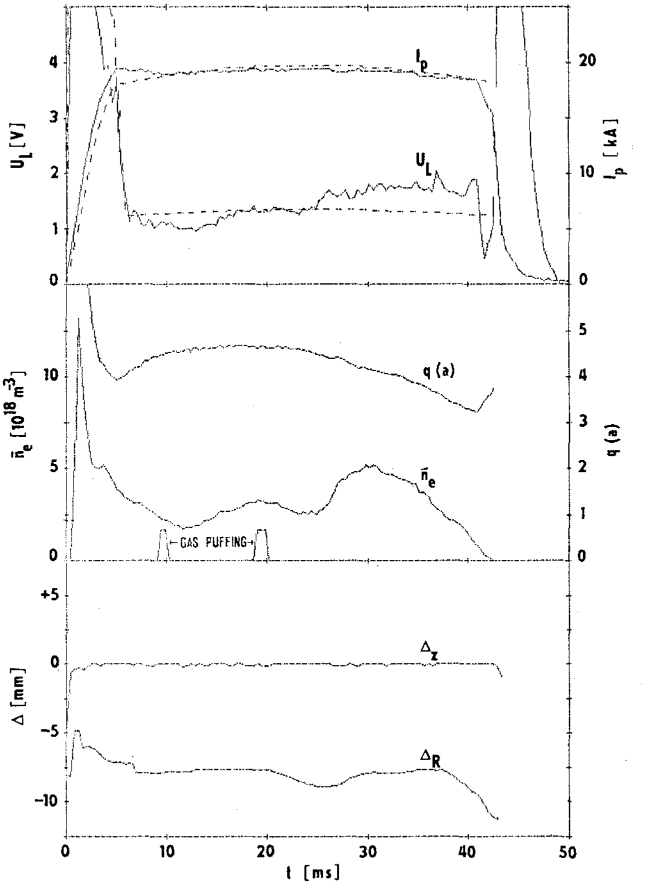

Fig. 3. Test discharge with $U_1 = 3475$ V, $U_2 = 425$ V. U_L — loop voltage, I_p — plasma current, $\bar{n}_e$ — line averaged electron ensity, $q(a)$ — safety factor, Δ_R and Δ_z — radial and vertical plasma displacements. Dashed lines are the calculated waveforms.

For this E/p, the drift component of electron velocity is somewhat less then their chaotic part and therefore a moderate generation of run-away electrons is expected.

The current ramp-up phase lasts $t_1 = 5$ ms. At the end of this interval, the magnetisation current is equal to $I_M(t_1) = I_1 - I_p/N = 428$ A $(I_1(t_1) = 1{\cdot}9$ kA$)$. This value corresponds, on the magnetisation curve, to the flux $\phi(t_1) = 0{\cdot}10$ Vs (fig. 1). The resistive volt-seconds,

$$\phi_R(t_1) = \phi - L_p I_p \approx 0{\cdot}10 - 0{\cdot}02 = 0{\cdot}08 \text{ Vs},$$

are in a good agreement with the formula (1).

The flat-top phase is terminated by the thyristor at $t_2 = 40$ ms. At this instant, $I_M(t_2) = 567$ A so that the iron core flux $\phi(t_2) = 0{\cdot}13$ Vs (fig. 1). The time evolution of the safety factor $q(a) = 2\pi a^2 B_T/(\mu_0 I_p R_0)$ shows about 20% change of the toroidal magnetic field B_T during the flat-top. The instability in the ramp-down phase is caused by a fall of the plasma density which is not controlled by gas puffing at the end of the discharge.

Dashed lines in fig. 3 represent the numerical simulation of the circuit behavior during the ramp-up and flat-top phases. This simple code calculates the Kirchhoff's equations for primary and secondary loops and includes nonlinear magnetisation of the iron core. The plasma resistance $R_p = U_L/I_p$ is prescribed to fit the experimental value and the plasma inductance was kept constant ($L_p = 1$ μH). This code was also used to check the proposed circuit parameters in the design phase.

4. Conclusion

The ohmic heating circuit presented here is a simple, low-cost system which allows to prolong the CASTOR discharges to a limit given by the toroidal magnetic field pulse. Higher plasma currents can be attained by a reduction of the circuit resistance and by a pre-magnetisation of the iron core transformer. It will, however, imply a different scheme for the bias vertical magnetic field.

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