Stöckel

Stöckel
nebrat!

CZECHOSLOVAK ACADEMY OF SCIENCES

CZECHOSLOVAK JOURNAL OF PHYSICS

REPRINT

VOLUME B 37 1987

INTERPRETATION OF TOROIDAL CURRENT AND LOOP VOLTAGE TEMPORAL EVOLUTION DURING RF-CURRENT DRIVE EXPERIMENT ON THE T-7 TOKAMAK

J. Stöckel, F. Žáček

Institute of Plasma Physics, Czechosl. Acad. Sci., Pod vodárenskou věží 4, 182 11 Praha 8, Czechoslovakia

A simple analytical model is developed and solved to describe time evolution of the loop voltage and toroidal current when RF and inductive current drive take place simultaneously. A relation for the real value of the RF driven current has been obtained under these conditions. Comparison with experimental data from T-7 tokamak allows to estimate the role of the skin effect during RF current drive.

1. INTRODUCTION

In a last few years non-inductive methods of generation of the toroidal current in tokamaks achieved attention. One of such methods is current generation by lower hybrid waves [1, 2]. Radio frequency electromagnetic energy is launched by a periodic structure (grill) into the plasma to generate lower hybrid waves with directional total momentum [3, 4]. When the wave number parallel to the toroidal magnetic field is suitably chosen, the waves are absorbed in plasma via Landau damping. This fact represents a force acting on electrons, which with friction force of Coulomb collisions results in steady toroidal current.

As in many other experiments [5–9], the efficiency of the RF current drive on tokamak T-7 ($\mathscr{R} = 122$ cm, $a = 26$ cm, $B_t = 1{\cdot}6-2{\cdot}3$ T) has been till now investigated in presence of simultaneous inductive current generation [10, 11]. That means, a toroidal electric field impressed to the torus by a transformer breaks down the neutral gas at the onset of the discharge and forms the plasma with given parameters. The electrical scheme of the tokamak T-7, however, does not allow to block the energy transfer between primary and secondary transformer circuits during the RF power application (as it was possible to do, e.g., on PLT experiment [12]). In consequence of this fact, not only loop voltage and plasma current (i.e., secondary transformer circuit quantities) but also quantities in primary circuit are changed on switching on the RF power. It is clear that determination of the current drive efficiency $\zeta = I_{RF}/P_{RF}$ is not straightforward in this case.

Typical temporal evolution of the toroidal current and loop voltage are depicted in fig. 1. Dashed parts of the curves correspond to the ohmic regime only, without RF application. A pulse of RF power is switched on 80–90 ms after the discharge onset and its duration is taken to be comparabe with the quasistationary discharge phase. It may be seen after RF pulse switching-on the loop drops with the time constant 30–40 ms and in the second part of the RF pulse its relative decrease reaches the value $\Delta U_p/U_p \simeq 0{\cdot}85$. At the same time toroidal current increases and is about 10–15% higher at the end of RF pulse than at its beginning. RF power was variable in the range of 30–200 kW; however, the effect saturates at the value 70–80 kW. All the effects were the most expressed at plasma densities $(3-6) \times 10^{18}\ \mathrm{m}^{-3}$.

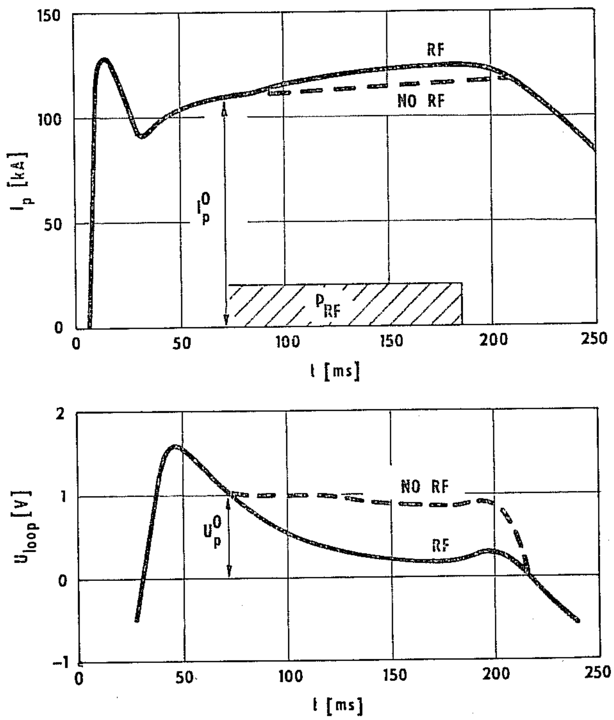

Fig. 1. Typical temporal evolution of the toroidal current and the loop voltage in the current drive experiment (T-7 device). The dashed lines correspond to the inductive current drive regime only (without RF power application). Mean electron density $\bar{n}_e \doteq 3 \times 10^{18}\ \mathrm{m}^{-3}$, input RF power $R_{RF} = 100$ kW.

Using a simple analytical model we shall try in the following to explain the measured time dependence of both quantities mentioned above. In this model a transformer for ohmic plasma heating together with an external supply of RF current I_{RF} switched on in a given moment in the secondary transformer winding are considered. Similar problems were discussed recently in [8, 13, 14] and numerically analyzed in [15].

2. MODEL

Electrical circuit of the transformer together with measuring loop, primary supply (pulse LC-line) and secondary winding (plasma column and source of RF driven current) are shown in fig. 2. The power switch S connects ohmic heating LC-line to the primary transformer winding in the starting time. Mutual inductance M_1 describes a coupling between primary winding (230 turns, inductance $L_1 = 4{\cdot}2$ H) and plasma column (approximated by one turn of conductor with inductance $L'_2 = L_1/230^2 \doteq 80\ \mu$H and ohmic resistance $R'_p = 8{\cdot}8\ \mu\Omega$). We assume that inductive

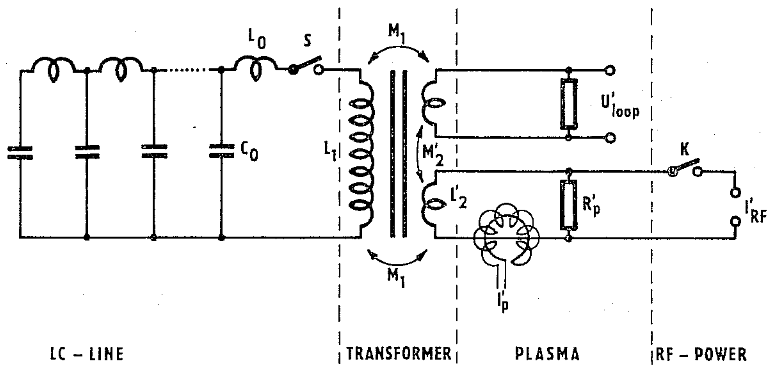

Fig. 2. The electrical circuit of the tokamak device with the inductive (LC-line + transformer) and RF sources for driving the toroidal current. The source of the RF current can be replaced by a source of equivalent voltage $V'_{RF} = I'_{RF} \cdot R'_p$, connected in series with plasma resistance. Arrangement of the main diagnostic tools (measuring loop, Rogowski coil) are depicted as well.

coupling between primary winding and measuring loop is the same as between primary winding and plasma turn. This coupling is not perfect, therefore

$$M_1 = k_1(L_1 \cdot L'_2)^{1/2},$$

where k_1 is smaller than unity. The coupling between plasma turn and measuring loop is similarly described by mutual inductance

$$M'_2 = k_2 \cdot L'_2,$$

where again $k_2 < 1$. In all following considerations we take all circuit parameters as time independent. It concerns first of all the internal inductance and ohmic resistance of plasma and the permeability of the transformer core. Further we assumed that the RF driven current is generated by a source I'_{RF} connected in parallel to the plasma ohmic resistance by a switch K.

Let us replace for the simplicity at first the pulse LC-line by a source of time independent voltage E with internal resistance R_i. This approximation is valid in the time comparable with the duration of tokamak inductive discharge. More-

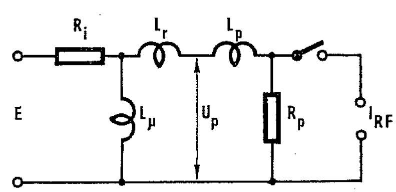

Fig. 3. The equivalent circuit of the tokamak with RF current drive source. It is a modification of the circuit depicted in the previous figure. The following relations are used: $R_i = (L_0/C_0)^{1/2}$, $L_\mu = L_1$, $R_p = q^2 \cdot R'_p$, $U_p = q \cdot U'_{loop}$, $I_p = I'_p/q$, $I_{RF} = I'_{RF}/q$, $L_r + L_p = (1 - k_1^2) \cdot L_1$, $L_p = (1 - k_2) \cdot L_1$ (see text).

over, we can modify the electrical circuit of the transformer to the form commonly used in the theory of pulse transformers [16], see fig. 3. The mutual inductances M are replaced in this equivalent circuit by inductance of magnetization L_μ ($L_\mu \doteq L_1$) and by total leakage inductance of the transformer $L_r + L_p$. The part of this total leakage inductance, denoted as L_r, characterizes a leakage magnetic flux between the measuring loop and the iron core of the tokamak transformer, the part denoted as L_p, characterizes a leakage magnetic flux between the centre of the plasma column and the measuring loop. It is evident, that the value of L_p is predominantly given by the internal inductance of the plasma column. Let us note, that in the equivalent scheme of fig. 3 all parameters of the secondary transformer circuit must be transformed in following way:

$$U = q \,.\, U' , \quad I = I'/q , \quad R = q^2 \,.\, R' , \quad L = q^2 \,.\, L' ,$$

where q = transformation ratio ($q = W_1/W_2$),
W_1 = number of primary winding turns ($W_1 = 230$),
W_2 = number of secondary winding turns ($W_2 = 1$).

Table I

I_p [A]	U_p [V]	R_p [Ω]	L_μ [mH]	L_r [mH]	L_p [mH]	R_i [Ω]
596	230	0·46	4200	13	77	2·5

Values of the parameters occurring in fig. 3 are for the experiment described (T-7 device) summarized in table I[1]). Take us notice the fact, that the values of the inductance of magnetization L_μ and of the total leakage inductance $L_r + L_p$ are very different ($L_\mu \gg L_r + L_p$). In consequence of this fact we can easily find the solution of the equivalent circuit of fig. 3 for two extreme cases:

A) for a time immediately after the moment when K is switched-on the inductance of magnetization L_μ doesn't play virtually any role ($L_\mu \to \infty$) and so the equivalent circuit can be reduced to a very simple serial one (see fig. 4a) with the characteristic time constant

(1) $$\tau = \frac{L_r + L_p}{R_i + R_p} ,$$

which equals $\tau \doteq 31$ ms for the experiment under study;

B) for a time $t \gg \tau$ on the contrary, the serial leakage inductances L_r and L_p do not play any role and so the equivalent circuit can be reduced to a simple parallel

[1]) Private communication from A. Ya. Kislov.

one (see fig. 4b) with the characteristic time constant

(2) $$\theta = L_\mu \left(\frac{1}{R_i} + \frac{1}{R_p}\right),$$

which equals $\theta \doteq 10$ s in our case.

It is obvious that for interpretation of the toroidal current and loop voltage time variations at tokamak T-7 with a RF pulse length $t_{RF} = 100-200$ ms it is sufficient to analyze only the first case A. The evolution of the both mentioned parameters for $t \simeq \theta$ is given in appendix for completeness.

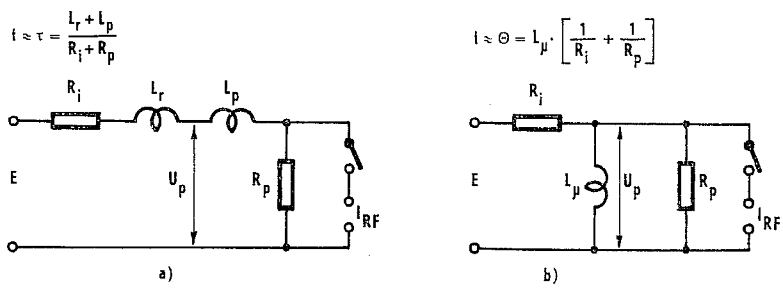

Fig. 4. The two possible extreme modifications of the equivalent circuit depicted in fig. 3: a) the simplification for the time range comparable with the time constant τ ($\tau = 30$ ms for T-7 case); b) the simplification for the time range comparable with the time constant θ ($\theta = 10$ s for T-7 case); for basic equations of this case see appendix.

According to fig. 4a, the time variation of the toroidal current I_p after switching-on of the key $K(t = 0)$ is given by following equation:

(3) $$E + I_{RF} \, . \, R_p = (R_i + R_p) \, . \, I_p + (L_r + L_p) \frac{dI_p}{dt} \, .$$

Eq. (3) can be simply solved for the initial condition

$$I_p(0) \equiv I_p^0 = \frac{E}{R_i + R_p}$$

and assuming $I_{RF}(t) = I_{RF} = \text{const}$ for $t \geqq 0$. This solution can be written as follows:

(4) $$\frac{I_p(t)}{I_p^0} = 1 + \frac{I_{RF}}{I_p^0} (1 - \eta)(1 - e^{-t/\tau}) \, .$$

Here

(5) $$\eta = R_i/(R_i + R_p)$$

and time constant τ is given by (1). Similarly the time variation of the loop voltage has following form:

(6) $$U_p(t) = E - R_i \, . \, I_p(t) - L_r \frac{dI_p(t)}{dt} \, ,$$

or

(7)
$$\frac{U_p(t)}{U_p^0} = 1 - \frac{I_{RF}}{I_p^0} \eta \left[1 - \left(1 - \frac{\lambda}{\eta} \right) e^{-t/\tau} \right],$$

where

(8)
$$\lambda = L_r/(L_r + L_p)$$

and $U_p^0 = I_p^0 \cdot R_p$ is a loop voltage value just before the RF power is applied.

It may be seen from eqs. (4) and (7) that for $t \gg \tau$ (but still for $t \ll \theta$) the time course of both quantities (current and voltage) saturates and their relative changes achieve in this limit the following values:

(9)
$$\frac{\Delta U_p}{U_p^0} \equiv \frac{U_p^0 - U_p}{U_p^0} = \eta \frac{I_{RF}}{I_p^0},$$

(10)
$$\frac{\Delta I_p}{I_p^0} \equiv \frac{I_p - I_p^0}{I_p^0} = (1 - \eta) \frac{I_{RF}}{I_p^0}.$$

As follows from relations (9), (10) for correct determination of the real value of the RF driven current I_{RF} it is necessary to add the both measured relative changes:

(11)
$$I_{RF} = I_p^0 \left(\frac{\Delta I_p}{I_p^0} + \frac{\Delta U_p}{U_p^0} \right).$$

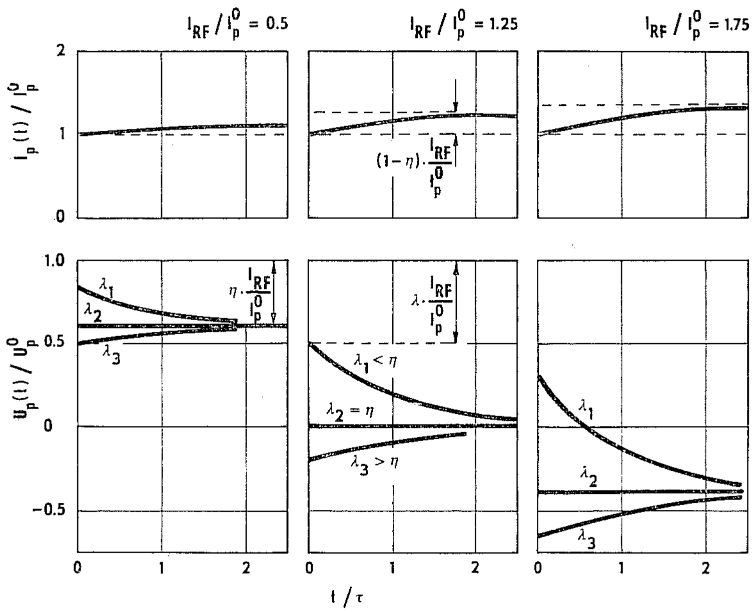

Fig. 5. The typical time evolution of the relative values of the toroidal current and the loop voltage according to the described model for $\eta = 0{\cdot}8$. A few different values of the other parameters I_{RF}/I_p^0 and λ are given for illustration.

It is evident, that two extreme cases can be distinguished with respect to the parameter η:

a) $R_i \gg R_p$, i.e. the ohmic heating LC-line works as a current source; in this case we can expect as a RF pulse response a decrease of the loop voltage only;

b) $R_i \ll R_p$, i.e., LC-line works as a voltage source; in this opposite case we shall observe a change of the toroidal current only. In most current drive experiments the relation $R_i > R_p$ is valid (no sharp inequality) and so responses on both quantities are observed. However, the voltage change is usually much more expressed. Such situation ($\eta = 0{\cdot}8$) is demonstrated in fig. 5 for three different values of the FR driven current I_{RF}. It may be seen from this figure that while the toroidal current changes smoothly, the loop voltage has a jump in the time when the current drive is switched-on ($t = 0$). The relative value of this jump is proportional to the parameter λ, i.e., it characterizes the influence of leakage inductances. To illustrate this effect the time dependences in fig. 5 are shown for three values of the parameter λ ($\lambda_1 = 0{\cdot}4$, $\lambda_2 = 0{\cdot}8$, $\lambda_3 = 0{\cdot}95$).

3. COMPARISON OF THE MODEL WITH EXPERIMENT

Relative changes of the toroidal current and loop voltage observed experimentally on the tokamak T-7 are shown in fig. 6. Using eq. (11) from their values at time $t \gtrsim 100$ ms we can immediately determine the value of the driven current as $I_{RF}/I_p^0 = 0{\cdot}97$. It means that practically the whole toroidal current is taken over by RF current drive. Note us, that using the expressions (9) and (10) we may estimate the value of parameter η as $\eta = 0{\cdot}87$. This value is in a very good agreement with definition (5) for parameters of tokamak T-7 (see tab. I): $\eta = 2{\cdot}5/(2{\cdot}5 + 0{\cdot}46) = 0{\cdot}84$.

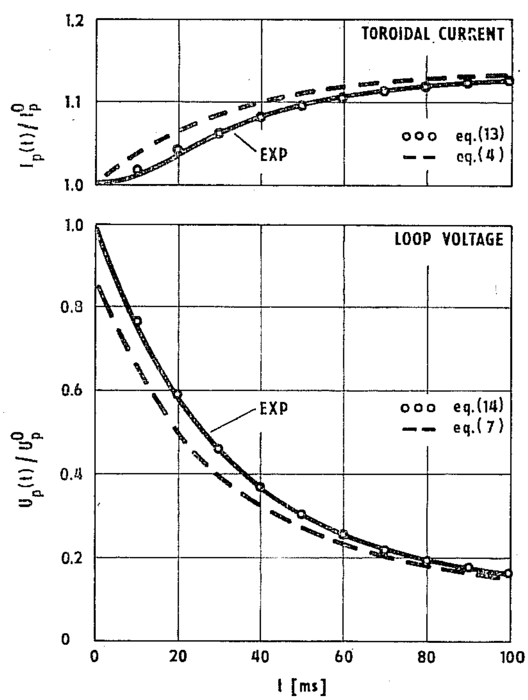

Fig. 6. Comparison of the experimental temporal evolution of the toroidal current and the loop voltage (full lines) with results of calculation according to the model. Dashed lines — the step time variation of the RF driven current is assumed; open circles — the smooth increase of the RF driven current (skin effect is taken into account).

The character of the measured time dependences given in fig. 6 corresponds satisfactorily to those calculated from eqs. (4), (7) which are shown by the dashed lines in fig. 6 as well. In accordance with tab. I we used for this calculation the following parameters:

$$\tau = \frac{L_r + L_p}{R_i + R_p} = 31 \text{ ms}, \quad \lambda = \frac{L_r}{L_r + L_p} = 0{\cdot}145 .$$

At the very beginning of the transient phase, however, there are some perceptible departures between experimental and calculated curves. First of all, the jump in the loop voltage predicted from the suggested model is not observed experimentally. Second, the onset of the increase of the toroidal current seems to be delayed compared to the onset of the current drive. These discrepancies are probably due to the simplification, which on the other hand enables us to solve the problem analytically. In the following we shall try to discuss these questions.

Firstly, we have supposed in our model that primary winding of the transformer is supplied by a fixed voltage supply with a constant internal resistance. In the starting phase of the current drive, however, the actual capacitively-inductive character of the supply LC-line plays evidently a significant role (especially the parameters of a few last cells are important). This fact must be taken into account in the arrangement and solution of the equivalent scheme. It may influence the time constant of the changes of the macroscopic parameters, but not the smooth character of the loop voltage experimentally observed.

Secondly, we have supposed in our model that we obtain the data of the toroidal current and the loop voltage without any time delay (thin wire approximation). In general, however, the driven current may be generated anywhere in the inner part of plasma column while its manifestation measured by Rogowski coil and voltage measuring loop is delayed by the skin time (time of the penetration of the driven current magnetic field outwards across the plasma column). It means, that from the point of view of the used diagnostic tools the result is the same as if the driven current I_{RF} would be created not immediately, but continuously from zero to the steady state value I^0_{RF}, with a certain time constant T (corresponding to the skin time τ_{sk}):

$$I_{RF}(t) = I^0_{RF}(1 - e^{-t/T}) . \tag{12}$$

Substituting such time dependence of the generated driven current (12) into the eqs. (3) and (6) we obtain the following expressions for relative changes of toroidal current and loop voltage:

$$\frac{\Delta I_p}{I^0_p} = \frac{I^0_{RF}}{I^0_p}(1 - \eta)\left[1 - \frac{\tau}{\tau - T} e^{-t/\tau} - \frac{T}{\tau - T} e^{-t/T}\right], \tag{13}$$

$$\frac{\Delta U_p}{U^0_p} = \frac{I^0_{RF}}{I^0_p}\eta\left[1 - \frac{\tau - \tau_1}{\tau - T} e^{-t/\tau} + \frac{T - \tau_1}{\tau - T} e^{-t/T}\right]. \tag{14}$$

Here $\tau_1 = L_r/R_i$. It may be seen that for $T = 0$ these dependences turn into the previous case (4) and (7). The best agreement between these dependences (13), (14) (circles in fig. 6) and those experimentally found (full lines in fig. 6) has been obtained by choosing the time constant $T = 8$ ms. If this value of T corresponds only to the skin time τ_{sk}, then, knowing the mean plasma conductivity $\bar{\sigma}$

$$\bar{\sigma} = \frac{2\mathscr{R} I_p^0}{a^2 U_p^0} = 3{\cdot}1 \times 10^6\, \Omega^{-1}\, m^{-1}$$

($\mathscr{R}$ and a beeing major and minor plasma radius), we are able to estimate the characteristic length of magnetic field diffusion as

$$d = (\tau_{sk}/\mu_0 \bar{\sigma})^{1/2} = 4 - 5\ \text{cm}\,.$$

From this fact it would be possible to draw a conclusion that the driven current is not generated on the plasma periphery, but somewhere inside the plasma column, in the region within radius $r_{RF} \sim a - d \sim 20$ cm.

In addition to the discussion above there is still another fact which must delay the manifestation of the current-drive phenomenon in the time. This is the energy requirement for building-up of the population of the energetic electrons carrying the driven current. If we suppose that the energy of these electrons is of the order of 100 keV, then the whole energy needed for current $\sim$100 kA is about 0·5 kJ. Such amount of energy can be delivered by RF power of 100 kW, even at its total absorption, only after 5 ms. This means that this fact would have to be taken into account too. Moreover, the efficiency of the electron dragging, especially in the very beginning of the process, remains an open question.

4. SUMMARY

The main results of the paper may be summarized in the following way:

(i) It was shown that for the correct interpretation of the time behaviour of toroidal current and loop voltage during a simultaneous inductive and RF current drive in tokamaks it is necessary to take into account the primary circuit of the tokamak transformer.

(ii) A simplified equivalent model describing the actual experimental situation in the case of iron transformer was suggested. An analytical solution of this model enables us to find the time evolution of the toroidal current and loop voltage and the real value of the RF driven current.

(iii) It was shown that toroidal current and loop voltage change with the time constant depending first of all on the total leakage inductance of the transformer and on the internal resistance of the feeding LC-line.

(iv) The best agreement of the suggested model with experiment was achieved taking the RF driven current continuously increasing from zero with time constant $T = 10$ ms. Two probable mechanisms and the physical interpretation of such driven current behaviour were discussed.

(v) Generally, all parameters of the plasma (especially internal inductive and ohmic resistance) it is necessary to consider as time depending during the process of current drive. However, consideration of all these effects goes out of the frame of the analytical approach suggested.

APPENDIX

The time evolution of the loop voltage and toroidal current can be calculated for time comparable with the time constant θ, using the simplified circuit given in fig. 4b, as follows:

$$\frac{U_p(t)}{U_p^0} = \left(1 - \eta \frac{I_{RF}}{I_p^0}\right) e^{-t/\theta}, \quad \frac{I_p(t)}{I_p^0} = \frac{I_{RF}}{I_p^0} + \left(1 - \eta \frac{I_{RF}}{I_p^0}\right) e^{-t/\theta}.$$

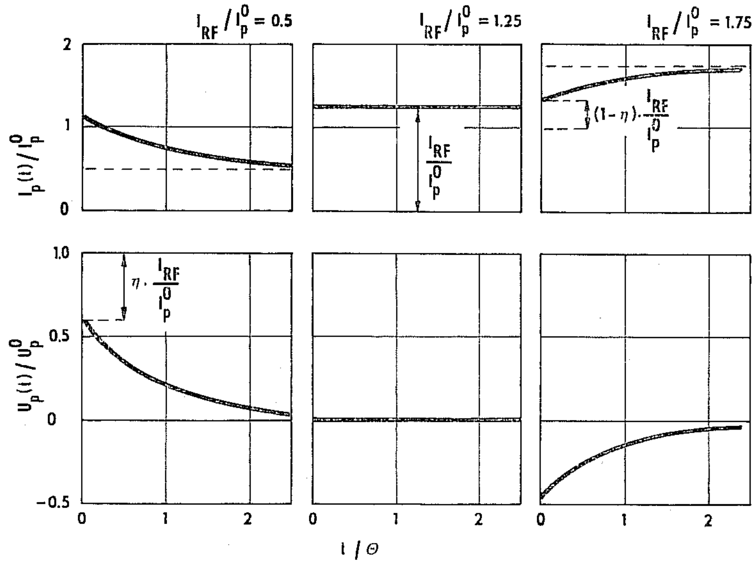

Fig. 7. Typical time evolution of the relative values of the toroidal current and the loop voltage if a RF pulse long enough is applied to the plasma. An example of the calculation is presented in the appendix.

Fig. 7. shows these time dependences for three different values of the ratio I_{RF}/I and a typical parameter $\eta = 0{\cdot}8$. It is clearly seen that the efficiency of the inductive drive falls to zero for $t \gtrsim (2 - 3)\,\theta$, as it may be expected from the brief analysis of the equivalent circuit as well.

The authors would like to thank A. Ya. Kislov for the basic data on the T-7 tokamak transformer. They are also indebted to V. V. Parail and G.V. Pereverzev for many clarifying discussions.

Received 14. 11. 1985.

References

[1] Klíma R., Longinov V. A.: Fiz. Plazmy *5* (1979) 496.

[2] Karney F. F., Fisch N. J.: Phys. Fluids 22 (1979) 1817.

[3] Ďatlov J., Žáček F., Klíma R., Kopecký Vl., Preinhaelter J., Stöckel J., Jakubka K.: Res. Rep. IPPCZ 4/82, Inst. of Plasma Physics, Cz. Acad. Sci., Prague, 1982.

[4] Parail V. V., Pereverzev G. N.: Fiz. Plazmy *9* (1983) 585.

[5] Tanaka S., Terumichi Y., Maekawa T., Cho T., Nakamura M., Nakao S., Kubo S., Shimozuma T., Hamada Y.: *in* Proc. 9th Int. Conf. on Plasma Phys. and Contr. Fusion Res., Baltimore, 1982. Vol. I, p. 199;
Nakamura M., Cho T., Kubo S., Shimozuma T., Kawai H., Yamazaki K., Maekawa T., Terumichi Y., Hamada Y., Tanaka S.: Phys. Rev. Lett. *47* (1981) 1902.

[6] Lloyd B., Porkolab M., Schuss J. J., Takase Y., Texter S., Watterson R., Fiore C., Gandy R., Granetz R., Greenwald M., Gwinn D., Lipschultz B., Marmar E., Mc Cool S., Pappas D., Parker R., Pribyl P., Rice J., Terry J., Wolfe S. Luckhardt S. C., Chen. K. I., Knowlton S. F., Bekefi G., Mayberry M. J., Mc Dermott S., Porkolab M., Rohatgi R., Terumichi Y.: *in* Proc. IAEA Technical Committee Meeting on Non-Inductive Current Drive in Tokamaks CLM-CD (1983), Culham, 1983, Vol. I, p. 250.

[7] Tonon G., Blanc P., Gormezano C., El Shaer M., Hess W., Ichtchenko G., Magne R., Melin G., Moulin D., O'Connor P., Pacher G. W., Pacher H. D., Soeldner F., Wegrowe J. G.: *in* Proc. 9th Int. Conf. on Plasma Phys. and Contr. Fusion Res., Baltimore, 1982, Vol. I, p. 179.

[8] Budnikov V. N., Gerasimenko G. V., Djachenko V. V., Jesipov L. A., Obuchov A. A., Pavlov I. L., Stepanov A. Ju., Scherbinin D. N.: *in* Proc. 12th Czech. Seminar on Plasma Phys. and Technology, Prague, 1983, p. 123.

[9] Gormezano C., Bibet P., Blanc P., Briand P., Brifford G., Clement M., Grelot P., Hess W., Ichtchenko G., Melin G., Moulin B., Panzarella A., Parlange F., Porrot E., Rey G., Taquet B., Ternay F., Van Houtet D.: *in* Proc. 11th Europ. Conf. on Contr. Fusion and Plasma Phys., Aachen, 1983, Part I, p. 325.

[10] Alikaev V.V., Vdovin V. L., Ivanov D. P., Ivanov N. V., Iljin V. I., Kakurin A. M., Kislov A. Ya., Kovrov P. E., Kochin V. A., Khvostenko P. P., Khromkov I. N., Chistyakov V. V., Ďatlov J., Žáček F., Klíma R., Kopecký Vl., Preinhaelter J., Jakubka K.: *in* Proc. 9th Int. Conf. on Plasma Phys. and Contr. Fusion Res., Baltimore, 1982. Vol. II, p. 153.

[11] Ďatlov J., Jakubka K.: Res. Rep. IPPCZ 18/82, Inst. of Plasma Physics, Cz. Acad. Sci., Prague, 1982.

[12] Hooke W., Bernabei S., Boyd D., Cavallo A., Chu T. K., Cohen S., Colestock P., Daughney C., Davis S., Dimock D., Efthimion P., Herndon D., Furth H., Hosea J., Hovey J., Jobes F., Kaita R., Martin A., Mazzucato E., Mc Neill D., Meservey E., Motley R., Ruzic D., Schwartz R., Stevens J., Strachan J., Suckewer S., Taylor G., Timberlake J., Valeo E., Wilson R., von Goeler S.: *in* Proc. 9th Int. Conf. on Plasma Phys. and Contr. Fusion Res., Baltimore, 1982. Vol. I, p. 239.

[13] Yamamoto T., Imai T., Shimada M., Suzuki N., Maemo M., Konoshima S., Fujii T., Uehara K., Nagashima T., Funahashi A., Fujisawa N.: Phys. Rev. Lett. *45* (1980) 716.

[14] La Haye R. J., Armentrout C. J., Harvey R. W., Moeller C. P., Stambaugh R. D.: Nucl. Fusion *20* (1980) 218.

[15] Mitarai O., Hirose A.: Report PPL-67. University of Saskatchewan (Canada), 1983.

[16] Icchoku Ya. S., Ovchinnikov N. I.: Impulsnye i cifrovye ustroistva. Sov. Radio, Moscow, 1972, p. 63.