Fusion Technology

ISSN: 0748-1896 (Print) (Online) Journal homepage: http://www.tandfonline.com/loi/ufst19

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Osamu Mitarai, Sean W. Wolfe, A. Hirose & Harvey M. Skarsgard

ALTERNATING CURRENT TOKAMAK REACTOR WITH LONG PULSES

FUSION REACTORS

OSAMU MITARAI *Kumamoto Institute of Technology*
Department of Electrical Engineering, Ikeda 4-22-1, Kumamoto 860, Japan

SEAN W. WOLFE, A. HIROSE, and HARVEY M. SKARSGARD
University of Saskatchewan, Department of Physics
Saskatoon, Saskatchewan S7N 0W0, Canada

Received January 26, 1988
Accepted for Publication September 22, 1988

Alternating current (ac) tokamak operation in the reactor parameter range is studied by considering the volt-second consumption. A simple condition for obtaining ac operation with nearly constant pulse length is given by $L_p/R_p < T_{d,ss}$ (L_p is the plasma inductance, R_p is the plasma resistance, and $T_{d,ss}$ is the discharge length in the standard operation), assuming time-independent plasma parameters. The discharge length for ac operation is shorter than for standard operation and is given by $T_{d,\mathrm{ac}} = T_{d,ss}(\phi_t - 2\phi_L)/(\phi_t - \phi_L)$ where ϕ_t is the total transformer flux and ϕ_L is the plasma inductive flux. Alternating current operation is found to be advantageous in a large reactor having a large ohmic transformer flux ϕ_t satisfying $\phi_L/\phi_t < \frac{1}{3}$. The superconducting magnetic energy storage system is proposed as an attractive power supply for ac operation in a large reactor.

I. INTRODUCTION

In a commercial fusion reactor, it is essential to provide a steady electric power output from the steam turbine and electric generator system. Ideally, therefore, a steady fusion burn is preferable. The tokamak has been recognized as an inherently pulsed machine, although alternative current drive techniques are being investigated,[1] including cyclic operation with an ohmic heating (OH) transformer and radio-frequency (rf) current drive.[2-4]

Recent successful ac operation in the STOR-1M tokamak[5] encourages us to consider reactor applications. Alternating current operation in a reactor can be defined as a long flattop current flowing in the positive toroidal direction, followed by a similar current in the negative direction, and so on. The plasma density decreases in the current rampdown phase, but does not reach zero at $I_p = 0$. The low-density residual plasma can be utilized for the formation of the next discharge.

Although fusion burn ceases in the relatively short (~20-s) current rampdown phase and the subsequent negative current rise phase of ac operation, the drop in steam temperature from the blanket is smaller[6] and the energy deficiency is negligible in comparison with conventional pulsed operation with unidirectional current and dwell times between discharges. In the case of cyclic operation with rf current drive and an OH transformer, the recharging time (during which there is no fusion burn) is expected to be much longer[7] than the transient time (the sum of the current rampdown and rise times) in ac operation. This is due to the fact that the rf wave has to drive the plasma current against the loop voltage induced by the transformer recharging; while in ac operation, the plasma current is induced naturally in the same direction as the loop voltage. While a large external power is necessary to maintain the plasma current during the recharging phase, no additional power is needed in the transient phase of ac operation. Thus, in an ac tokamak reactor, continuous electrical energy output could be obtained with a minimum-cost thermal storage unit and with less energy deficiency during the transient phase.

An advantage of ac operation comes from the fact that a bias flux swing is not necessary, due to the "self-bias" that occurs naturally in ac operation, and the dwell time is zero. Thus, the stored energy in the OH coil after a discharge can be utilized for the subsequent discharge without the need for any additional power for recharging.

The residual plasma density at the current reversal removes the breakdown phase and assists in the plasma evolution of the subsequent half-cycle. Hence, the delay in the plasma formation, as observed in the conventional pulsed operation even with a low breakdown voltage,[8] does not exist except for the first discharge. This implies that a slow time variation of the poloidal magnetic field in the superconducting OH coil can be used without volt-second losses for ac operation.

In ac operation, the bending moment exerted on the toroidal field (TF) coils changes direction due to the electromechanical interaction between the unidirectional TF coil current and the alternating vertical field (VF). Hence, mechanical fatigue problems with the TF coils can be expected to be worse than for conventional pulsed operation after many cycles of operation. However, low-frequency or long-pulse operation (several hours) can reduce the importance of this type of fatigue.[6] We consider here a large fusion reactor, similar in size to an Ultra Long-Pulse Tokamak Reactor,[9] with a >10-h discharge length, so that coil fatigue problems are reduced.

In this paper, we study ac operation in a large fusion reactor using flux consumption theory, assuming the attainment of stable current reversal. We find that ac operation is suitable for a large fusion reactor with long pulses. We also consider how to achieve ac operation in smaller or more compact tokamaks.

In Sec. II, the simple volt-second consumption theory is presented. In Sec. III, the plasma and machine parameters of a model tokamak reactor are given. In Sec. IV, calculated results for ac operation are presented. A power supply system suitable for ac operation is discussed in Sec. V. Costs for ac operations are simply estimated in Sec. VI, and a discussion and conclusions are given in Secs. VII and VIII, respectively.

II. VOLT-SECOND CONSUMPTION

Alternating current tokamak operation is determined by the volt-second consumption, which can be derived from the plasma circuit equation,

$$L_p \frac{dI_p}{dt} + R_p I_p = \frac{d\phi}{dt} = M_{\mathrm{OH},p} \frac{dI_{\mathrm{OH}}}{dt} \quad , \tag{1}$$

where

L_p = plasma inductance composed of the external and internal inductance

R_p = plasma resistance

ϕ = flux of the OH solenoid

$M_{\mathrm{OH},p}$ = mutual inductance between the plasma and OH solenoid

I_p = plasma current

I_{OH} = OH coil current.

In this analysis, the coupling between the plasma current and equilibrium VF coil is neglected. We also consider only an air core transformer. After integrating Eq. (1), we obtain

$$L_p I_p(t) + \int_0^t R_p(t) I_p(t)\, dt = \phi(t) - \phi(0) = M_{\mathrm{OH},p}[I_{\mathrm{OH}}(t) - I_{\mathrm{OH}}(0)] \quad . \tag{2}$$

Assuming that the plasma parameters are time independent throughout the discharge length $T_{d,ss}$ in the standard operation, we obtain

$$L_p I_p + R_p I_p T_{d,ss} = \phi(t) - \phi(0) = \phi_t \quad , \tag{3}$$

where the first term on the left side is the inductive volt-second consumption, the second is the resistive one, and ϕ_t is the total transformer flux given by $\phi_t = 2\cdot\pi R_{\mathrm{OH}}^2 B_{\mathrm{OH}}$, where R_{OH} is the radius of the OH solenoid and B_{OH} is the maximum flux density in the OH solenoid. We choose $B_{\mathrm{OH}} = 10$ T and double-swing operation of the transformer. The overall behavior, such as the discharge length and the magnitude of the plasma current, is simply described by Eq. (3) as shown in Sec. III. In this calculation, we neglect the resistive volt-seconds used up during the breakdown phase in the first discharge. We also assume no resistive loss in the initial phase of successive pulses because a plasma with low temperature and density would be maintained in the current reversal phase, as demonstrated in the STOR-1M tokamak.

III. PARAMETERS OF MODEL TOKAMAK REACTOR: ac TOKAMAK REACTOR

We consider a model tokamak reactor called ac Tokamak Reactor (ACTR) to see how ac operation works in a reactor-sized machine. Based on the previous arguments, we choose a machine with a large OH transformer flux. Then, to examine ac behavior in a smaller machine, the major radius is somewhat reduced, with a corresponding decrease in the transformer flux. For both cases, plasma parameters are chosen in the self-ignited regime during the constant plasma current phase. Model parameters are listed in Table I, where case I corresponds to the larger machine with $R_0 = 10$ m and $\phi_t = 1005$ V·s, and case II is the smaller machine with $R_0 = 8.5$ m and $\phi_t = 392.7$ V·s. Here, the plasma current is

$$I_p = \frac{2\pi a_0^2 B_t}{\mu_0 q_a R_0} \frac{1+\kappa^2}{2} \quad ; \tag{4}$$

the plasma inductance is

$$L_p = \mu_0 R_0 \left(\ln \frac{8R_0}{a_0 l_\kappa} + \frac{l_i}{2} - 2 \right) \quad ; \tag{5}$$

and the plasma resistance is given by

$$R_p = \eta_{sp} \frac{2\pi R_0}{\pi a_0^2 \kappa} \quad , \tag{6}$$

TABLE I

Parameters of Model ACTR

	Case I	Case II
Major radius, R_0 (m)	10	8.5
Minor radius, a_0 (m)	2	2
Plasma elongation, κ	1.8	1.6 1.0
Toroidal field on axis, B_t (T)	6	6
Plasma current, I_p (MA)	10.1	10.05 (κ = 1.6) 5.647 (κ = 1.0)
Safety factor, q_a	2.5	2.5
Plasma temperature, $\bar{T}_e = \bar{T}_i$ (keV)	20	20
Plasma density, $\bar{n}$ (m^{-3})	1.0×10^{20}	1.0×10^{20}
Effective ion charge, Z_{eff}	1.5	1.5
Total fusion power, P_f (MW)	3953	3360 (κ = 1.6) 2100 (κ = 1.0)
Toroidal beta, $\bar{\beta}_t$ (%)	4.46	4.46
Plasma inductance, L_p (μH)	22.8	18.56 (κ = 1.6) 21.64 (κ = 1.0)
Plasma resistance, R_p (nΩ)	1.43	1.37 (κ = 1.6) 2.19 (κ = 1.0)
Radius of OH solenoid, R_{OH} (m)	4	2.5
Flux of OH solenoid, ϕ_t (V·s)	1005	392.7
Inductive flux, ϕ_L (V·s)	230	186.6 (κ = 1.6) 122.2 (κ = 1.0)

where

$$\kappa = b/a_0 = \text{plasma elongation}$$

$$l_\kappa = [(1 + \kappa^2)/2]^{1/2} \text{ (Ref. 10)}$$

$$\eta_{sp} = 5.22 \times 10^{-5} Z_{eff} \ln \Lambda / [\bar{T}_e \text{(eV)}]^{1.5} \; (\Omega \cdot \text{m})$$

$$= \text{Spitzer resistivity}$$

$$\Lambda = 4.1 \times 10^{11} \; [\bar{T}_e \text{(eV)}]^{1.5} / [\bar{n} \; (\text{m}^{-3})]^{1/2}$$

$$l_i = 1 ,$$

and the other notation is listed in Table I. In these analyses, the elongation is chosen to give an appropriate value of the plasma current. For simplicity, the neoclassical effect, electron trapping in the banana regime, and plasma profile effects on the resistance are neglected.

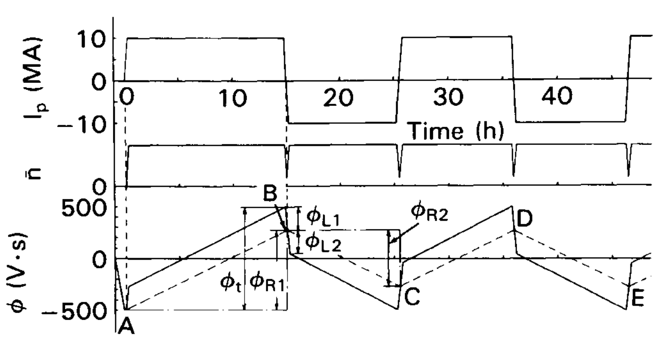

Fig. 1. Time evolution of the plasma current I_p, density n, and OH transformer flux ϕ in the ACTR for case I. The first pulse length is almost 15 h and subsequent ones are ~10.5 h.

IV. ALTERNATING CURRENT TOKAMAK OPERATION

Typical ac tokamak operation is shown in Fig. 1 for the plasma current, desired plasma density, and transformer flux using parameters for case I. To obtain the maximum flux variation, the OH transformer is initially biased (point A) and then increased. Neglecting the resistive volt-second loss in the initial phase, the resistive component during the discharge, $\phi_R = R_p I_p t$, increases linearly with time as shown by the broken line. On the other hand, the inductive component, $\phi_L = L_p I_p$, increases in proportion to the plasma current during the initial phase and remains constant until it decreases in the rampdown phase. At point B on the tracer for the OH transformer flux, the plasma current becomes zero. The next plasma current pulse, with opposite direction, starts from point B and continues to point C. This cycle is then continuously repeated. The plasma density and temperature decrease in the rampdown phase, but never go to zero, as demonstrated in the STOR-1M tokamak.[5] (For clarity, the current rise and rampdown times are exaggerated in all figures.) Fusion burn is maintained during the flat plasma current phase and ceases during the rampdown and subsequent current rise phase.

At the end of the first discharge, the following condition must be satisfied,

$$\phi_t - \phi_{L1} = \phi_{R1} > \phi_{L2} , \tag{7}$$

because the available flux for the next discharge given by ϕ_{R1} (as shown in Fig. 1) must be larger than the inductive flux necessary to form the next plasma current. Assuming $|I_{p1}| = |-I_{p2}|$ and hence $\phi_{L1} = \phi_{L2}$, we obtain from the inequality in the above relation,

$$\phi_{R1} > \phi_{L1} , \tag{8}$$

which gives

$$R_p I_p T_{d,ss} > L_p I_p \quad \text{or} \quad L_p/R_p < T_{d,ss} . \tag{9}$$

[Note that Eq. (7) can also be rewritten as $\phi_t > 2\phi_L$ with $\phi_{L1} = \phi_{L2} = \phi_L$.] Thus, the condition that the resistive component must be larger than the inductive one at the end of the first discharge is equivalent to requiring that the discharge length $T_{d,ss}$ in the standard operating scenario is longer than the resistive diffusion time L_p/R_p. This is a simple criterion to ensure that one discharge can be followed by a subsequent alternating current discharge with the same amplitude. In fact, $L_p/R_p \sim 3.8$ h obtained for case I in Table I is much shorter than $T_{d,ss} \sim 15$ h as shown in Fig. 1.

In case II with a smaller major radius, ac operation with long pulses is not obtained, as shown in Fig. 2, where the second and subsequent pulse lengths are shorter. This is due to the fact that $L_p/R_p \sim 3.8$ h is close to the discharge length of the first pulse, $T_{d,ss} \sim 4$ h. Some improvement can be achieved by reducing the plasma current while keeping the other parameters the same. An example is shown in Fig. 3. A decrease in the inductive component increases the length of the first discharge to $T_{d,ss} \sim 6$ h, which is sufficiently larger than L_p/R_p to give ac operation with long pulses. Note that for the sake of simplicity we did not take the beta effects into account in spite of exceeding the critical value ($\beta_{crit} = 1.86\%$ for case II).

The above arguments can also be understood by the relationship of the discharge length in ac and standard operation. In standard operation such as the first discharge in Fig. 1, the discharge length is given by Eq. (7):

$$\phi_{R1} = R_p I_p T_{d,ss} = \phi_t - \phi_L \tag{7'}$$

for $\phi_{L1} = \phi_{L2} = \phi_L$. On the other hand, the discharge length in ac operation $T_{d,\mathrm{ac}}$, for example, the second discharge in Fig. 1, is obtained from

$$\phi_{R2} = R_p I_p T_{d,\mathrm{ac}} = \phi_t - 2\phi_L \tag{10}$$

for the same conditions. Using the above equations (7′) and (10), the following relation is obtained:

$$\frac{T_{d,\mathrm{ac}}}{T_{d,ss}} = \frac{\phi_t - 2\phi_L}{\phi_t - \phi_L} . \tag{11}$$

Note that $\phi_t - 2\phi_L > 0$ must be satisfied to make ac operation ($T_{d,\mathrm{ac}} > 0$) possible as obtained before. We also see that $T_{d,\mathrm{ac}} \geq T_{d,ss}/2$ holds for $\phi_L/\phi_t \leq \frac{1}{3}$, where the discharge length of one cycle in ac operation is longer than one single pulse in the standard operation.

A second method to produce satisfactory ac operation, without reducing the plasma current, is to enhance the plasma resistance somehow in each current rampdown phase. As shown in Fig. 4a, the available transformer flux for the second discharge increases due to an increase in the resistive component and a reduction of the inductive one in the rampdown phase

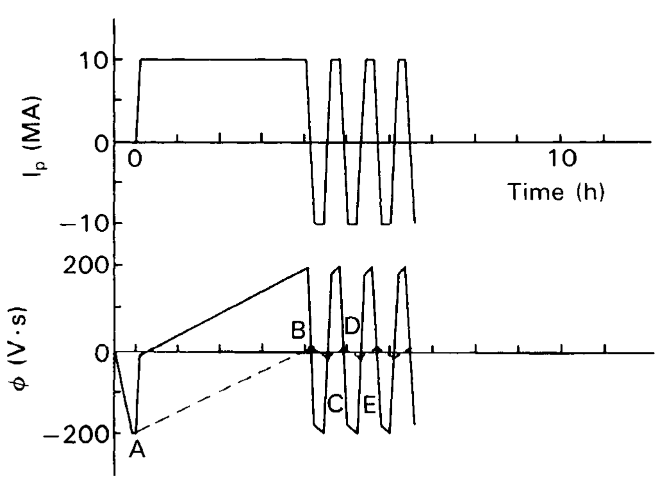

Fig. 2. Time evolution of the plasma current I_p and OH transformer flux ϕ in the reduced-size ACTR for case II with $I_p = 10$ MA. The first pulse length is almost 4 h and subsequent ones are ~0.4 h.

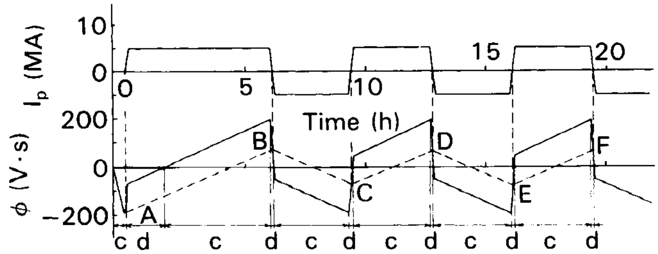

Fig. 3. Effect of a decrease in the plasma current on ac operation for case II. The first pulse length is almost 6 h and subsequent ones are ~3.3 h. Symbols "c" and "d" indicate the charging and discharging to and from the OH transformer, respectively.

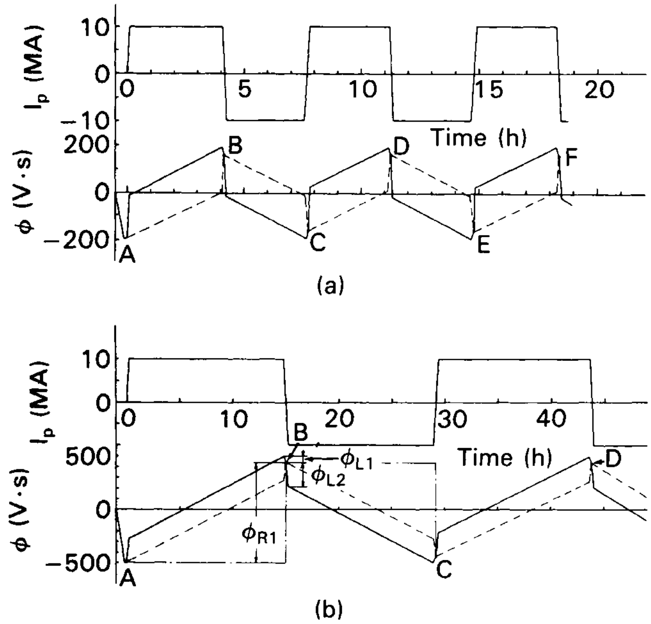

Fig. 4. Effect of plasma resistance enhancement in the current rampdown phase on the ac discharge length for (a) case II, where the first pulse length is almost 4 h and subsequent ones are ~3.5 h, and (b) case I, where the first pulse length is almost 15 h and subsequent ones are ~14 h.

of the first discharge. We assume that the resistive flux increases by 156.6 V·s as a result of the resistivity enhancement. This could be brought about, for example, by impurity injection or plasma radius reduction with a moving limiter. In Fig. 4b, the effect of plasma resistance enhancement in the tokamak with the larger major radius of case I is also shown. Discharges of almost equal length are obtained by increase of 170 V·s in the resistive flux in each current rampdown phase.

The third way to obtain smooth ac operation is to apply rf current drive in each current rise phase. The direction of the rf wave can be controlled by an electronic phase shifter. Since the inductive volt-second consumption can be compensated for by the current drive, the transformer flux is kept constant during the current rise phase, as shown in Fig. 5 for case II. Here, the current rampdown is again induced by the OH flux. The first discharge is ~8 h long and subsequent discharges are 4 h long. Thus, the flux saving achieved through the use of rf current drive in the current start-up phase is found to be helpful for ac operation in a smaller tokamak; this improvement is at the expense of additional rf power and a thermal storage unit. It should be noted that this ac mode of operation is different from cyclic operation with an OH transformer and rf current drive.

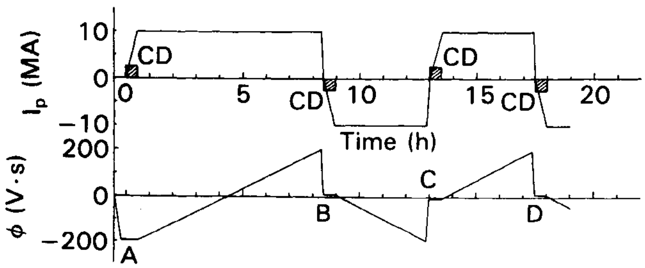

Fig. 5. Alternating current operation with the help of rf current drive in each current start-up phase for case II. The symbol CD indicates the rf current drive, whose duration is exaggerated.

V. POWER SUPPLY FOR ac TOKAMAK OPERATIONS

In the STOR-1M tokamak, ac operation was accomplished with an ac series circuit consisting of an inductor, capacitor, and resistor,[5] in which the capacitor and the OH coil served as the energy storage system. In such a system, the energy initially stored in the capacitor is transferred to the OH coil and vice versa until the coil current damps away. Thus, ac operation makes efficient use of the stored energy.

In a reactor, however, a capacitor is not practical for storing the large energy needed. [In this case, the energies stored in the OH and equilibrium field (EF) coils are ~30 GJ and 5 to 10 GJ, respectively, for case I.] A more appropriate power supply system, which does not disturb the power grid and has a fast response, would be a superconducting magnetic energy storage (SMES) system.[11] A schematic of the OH circuit in this system is shown in Fig. 6. The energy stored in SMES as a dc can be transferred to the OH coil through an energy transfer system consisting of an inductor-convertor using thyristor bridges[12] or a chopper circuit system.[13] Reversing the direction of the energy transfer is also possible with these circuits. A part of the initially stored energy will be dissipated in the energy transfer system due to the forward voltage losses in the thyristor bridges. The small energy dissipated in this way must be supplied to SMES by the external power source while energy is returned from the OH solenoid. This might be accomplished using a parallel charging circuit. Thus, a continuous back and forth flow of energy between the OH coil

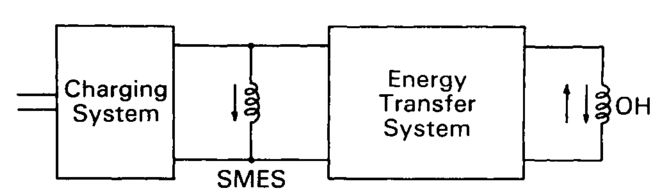

Fig. 6. Schematic of the power supply system for ac operation using an SMES coil.

and SMES would facilitate continuous ac operation of the reactor.

Energy losses in the above system increase with the number of energy transfers between SMES and the OH solenoid. This differs for ac and conventional pulsed operation. As shown in Fig. 3, the charging phase (to the OH solenoid) is indicated by "c" and the discharging phase (from the OH solenoid) is shown by "d." After the second discharge, a sequence of charging and discharging is needed to make one pulse. On the other hand, the behavior of the OH transformer flux in standard operation with dwell times is shown in Fig. 7a. It is apparent that two sequences of charging and discharging are necessary for one pulse. Thus, the number of energy transfers is twice that needed for ac operation. If the discharge length of one cycle for ac operation is shorter than the standard operation pulse, as in the case of $\phi_L/\phi_t > \frac{1}{3}$, ac operation is no longer advantageous with regard to the number of energy transfers. However, in the case of $\phi_L/\phi_t < \frac{1}{3}$, the total number of energy transfers in ac operation is less than that in standard operation. Hence, utilization of SMES becomes advantageous. This is also true for the case of enhancement of the plasma resistance in the current rampdown phase.

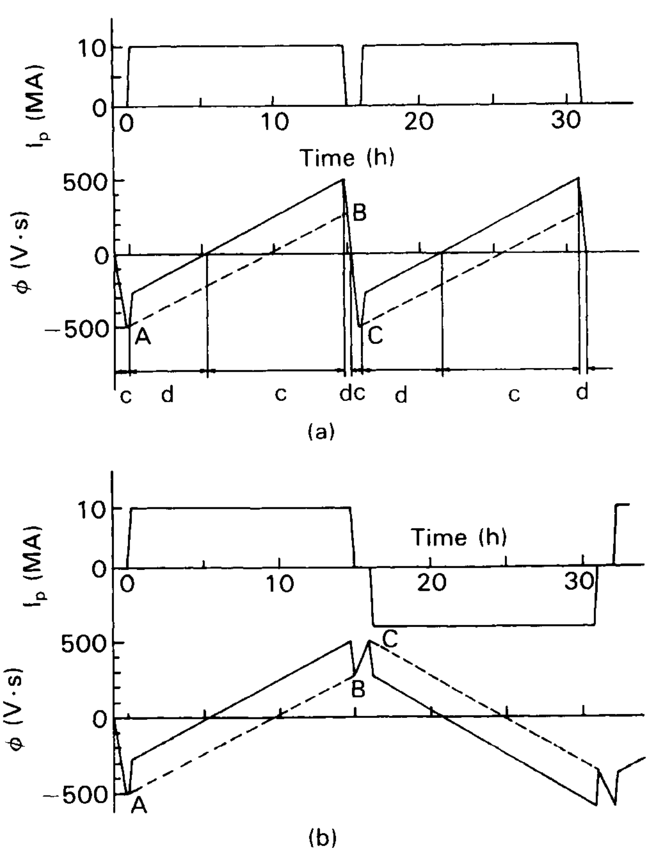

Fig. 7. Behavior of the transformer flux in (a) conventional pulsed operation (single-swing operation) and (b) double-swing operation for case I. Symbols "c" and "d" indicate charging and discharging to and from the OH transformer, respectively.

In the case of cyclic operation with unidirectional plasma current using rf current drive and an OH coil, the number of energy transfers is the same as in the case of conventional pulsed operation.

The recent discovery of high-temperature superconducting materials[14,15] could enhance the practicability of SMES in the future.

VI. COST DIFFERENCES BETWEEN ac AND OTHER MODES OF OPERATION

Although a detailed comparison of the construction and operational cost for an ac tokamak with that for other tokamaks is beyond the scope of this paper, we attempt here to estimate the relative costs of the energy transfer systems and the thermal storage unit according to Refs. 4 and 6.

We use a silicon-controlled rectifier (SCR) circuit rather than dump resistors for the current rampup and rampdown, and recharging phases to utilize the stored energy efficiently. The cost of the SCR circuit is proportional to the power requirement and is assumed to be given by \$0.1/W (Refs. 4 and 6). For the conventional single-swing operation as shown in Fig. 7a, the cost of the energy transfer system including the thermal storage unit may be given by

$$\begin{aligned} C_{ETS}(ss) = {} & \$0.1 \times [P_{\mathrm{OH}} + P_{\mathrm{OH},dw}(ss) + P_{\mathrm{EF}}] \\ & + C_{ps} + \$70 \times 10^6 + \$3.7 \times 10^6 \\ & \times [t_{down}(ss) - 10] \ , \end{aligned} \tag{12}$$

where

P_{OH} = reactive power isolation requirement of the SCR system for the OH rampdown phase

$P_{\mathrm{OH},dw}(ss)$ = OH recharging requirement during the dwell time for single-swing operation

$t_{down}(ss)$ = downtime with no fusion power

P_{EF} = EF reactive power isolation requirement

C_{ps} = cost of the SMES power supply.

The last two terms are the cost of the thermal storage unit for a water-cooled Li_2O blanket, which is designed for a 4000-MW(thermal) power reactor similar to case I.

For double-swing operation as shown in Fig. 7b, the following equation is obtained:

$$\begin{aligned} C_{ETS}(ds) = {} & \$0.1 \times [P_{\mathrm{OH}} + P_{\mathrm{OH},dw}(ds) + P_{\mathrm{EF}}] \\ & + C_{ps} + \$70 \times 10^6 + \$3.7 \times 10^6 \\ & \times [t_{down}(ds) - 10] \ , \end{aligned} \tag{13}$$

where $P_{OH,dw}(ds)$ is the OH recharging requirement during the dwell time. For ac operation, which has no dwell time $[P_{OH,dw}(ac) = 0]$, the cost equation is given by

$$C_{ETS}(ac) = \$0.1 \times (P_{OH} + P_{EF}) + C_{ps} + \$70 \times 10^6 + \$3.7 \times 10^6 \times [t_{down}(ac) - 10] \ . \quad (14)$$

The downtimes t_{down} in the above equations are

$$t_{down}(ss) = 2t_{OH} + t_{EF} + t_{dw}(ss)$$
$$t_{down}(ds) = 2t_{OH} + t_{EF} + t_{dw}(ds)$$

and

$$t_{down}(ac) = 2t_{OH} + t_{EF} \ , \quad (15)$$

respectively, where t_{OH} is the OH rampdown or rampup time, t_{EF} is the equilibrium rampup time during auxiliary heating, $t_{dw}(ss)$ and $t_{dw}(ds)$ is the dwell time for single- and double-swing operation, respectively.

Assuming the same rampdown and rampup time, the same power for OH and EF, and the same power supply for all three types of discharges, the cost difference between them can be estimated as follows:

$$\Delta C_{ETS}(ss\text{-}ac) = C_{ETS}(ss) - C_{ETS}(ac) = \$0.1 \times P_{OH,dw}(ss) + \$3.7 \times 10^6 \times t_{dw}(ss) \quad (16)$$

and

$$\Delta C_{ETS}(ds\text{-}ac) = C_{ETS}(ds) - C_{ETS}(ac) = \$0.1 \times P_{OH,dw}(ds) + \$3.7 \times 10^6 \times t_{dw}(ds) \ . \quad (17)$$

We see that the cost of the energy transfer system for ac operation is the cheapest because Eqs. (16) and (17) are always positive. To estimate the cost savings $P_{OH,dw}$, the relative change in the OH magnetic energy during the dwell time has to be calculated:

$$P_{OH,dw} = \frac{d}{dt}\left(\frac{1}{2} L_{OH} I_{OH}^2\right) = \phi(t) \frac{d(NI_{OH})}{dt} \ , \quad (18)$$

where

$\phi(t) = L_{OH} I_{OH}(t)/N$ = OH transformer flux

N = number of turns in the OH coils

L_{OH} = inductance of the OH coil.

For a monotonic change in I_{OH} and ϕ during the dwell time (t_{dw}), Eq. (18) gives

$$P_{OH,dw} = \Delta\phi \frac{\Delta(NI_{OH})}{t_{dw}} \ . \quad (19)$$

Equations (16) and (17) can now be described by one equation,

$$\Delta C_{ETS} = \$0.1 \times \Delta\phi \frac{\Delta(NI_{OH})}{t_{dw}} + \$3.7 \times 10^6 t_{dw} \ , \quad (20)$$

which has a minimum value at $d(\Delta C_{ETS})/d(t_{dw}) = 0$, yielding the optimum dwell time

$$t_{dw,opt} = \left[\frac{\$0.1 \times \Delta\phi\Delta(NI_{OH})}{\$3.7 \times 10^6}\right]^{1/2} \ . \quad (21)$$

At the optimum dwell time, the minimum cost difference is given by

$$\Delta C_{ETS,min} = \$1.22 \times 10^3 [\Delta\phi\Delta(NI_{OH})]^{1/2} \ . \quad (22)$$

If the dwell time is longer than $t_{dw,opt}$, the cost difference increases due to the thermal storage unit. When the dwell time is shorter, the cost difference increases due to the increase in the recharging power.

For single-swing operation, shown in Fig. 7a with case I and $R = 10$ m, the OH flux variation during the dwell time indicated by B and C is given by $\phi_{BC} = \Delta\phi = \phi_t - \phi_L = 1005 - 230 = 775$ (V·s). The change in the OH coil current, $\Delta(NI_{OH})$, during the dwell time (recharging time) is given by

$$\Delta(NI_{OH})_{BC} = (\phi_{BC}/\phi_t) \times 2\Delta(NI_{OH})_{max} \ , \quad (23)$$

where

$\Delta(NI_{OH}) = B_{OH}^{max} l/\mu_0$ is calculated by Ampere's theorem

l = length of the OH solenoid

μ_0 = magnetic permeability

B_{OH}^{max} = maximum flux density in the OH solenoid.

For $l = 15$ m and $B_{OH}^{max} = 10$ T, we obtain

$$\Delta(NI_{OH})_{BC} = 2(775/1005) \times 119 \times 10^6 = 183.5 \times 10^6 (AT) \ ,$$

$$t_{dw,opt} = 62 \text{ s} \ ,$$

and

$$\Delta C_{ETS,min} = \$460 \times 10^6 \ .$$

For double-swing operation, shown in Fig. 7b, the flux variation during the dwell time is smaller and we obtain

$$t_{dw,opt} = 18.4 \text{ s} ,$$
$$\Delta C_{ETS,min} = \$136.5 \times 10^6$$
$$\text{for } \phi_{BC} = \Delta\phi = \phi_L = 230 \text{ (V·s)} ,$$

and

$$\Delta(NI_{OH})_{BC} = 2(230/1005) \times 119 \times 10^6 = 54.46 \times 10^6 (AT) .$$

Thus, we find that the cost of the energy transfer system for single-swing operation is the most expensive, the one for double-swing operation is the next expensive, and the one for ac operation is the cheapest.

Cost savings in the energy transfer system for ac operation are offset to some extent by the increase in cost of the TF coil support and the vacuum tank needed to overcome mechanical fatigue problems. We try to estimate this factor by utilizing results in Fig. 5-24 of Ref. 6, where the total costs of the TF coil versus the number of fusion cycles N_f are shown for an $R = 7$ m reactor. The number of fusion cycles for ac operation $N_{f,\text{ac}}$ can be calculated by inversion of Eq. (11):

$$\frac{N_{f,\text{ac}}}{N_{f,ss}} = \frac{\phi_t - \phi_L}{\phi_t - 2\phi_L} , \tag{24}$$

where $N_{f,ss}$ is the number of fusion cycles for single-swing operation. We notice from Figs. 7a and 7b that the number of fusion cycles for double-swing operation $N_{f,ds}$ is almost identical to $N_{f,ss}$. Hence, we obtain $N_{f,\text{ac}} = 1.42 N_{f,ds}$ for case I with $\phi_L/\phi_t = 0.2288$. The number of fusion cycles for ac operation is larger than that for double-swing operation. The increased cost of the TF coil may be inferred by shifting a constant slope cost line for double-swing operation to the lower N_f side (by a factor of 1/1.42). The cost difference between ac and double-swing operation is $\Delta C_{BT}(\text{ac-}ds) = \$27.3 \times 10^6$. Taking into account an increase in size from $R = 7$ to 10 m, the cost increase may be $\Delta_{BT}(\text{ac-}ds) = \$27.3 \times 10^6 \, (10/7)^3 = \$79.6 \times 10^6$. (These rough estimations should be refined in the future.) The cost increase in the TF coil ($\$79.6 \times 10^6$) due to the increase in the number of cycles for ac operation is found to be smaller than the cost saving ($\$136.5 \times 10^6$) in the energy transfer system with respect to the double-swing operation. Thus, ac operation is cheaper than double-swing operation for case I by $\$56.9 \times 10^6$. It is to be noted that these results are highly dependent on the ϕ_L/ϕ_t ratio.

VII. DISCUSSION

We have considered a large fusion reactor with a corresponding large transformer flux to investigate ac operation with long pulses from the flux consumption viewpoint. Careful optimization of the fusion parameters have not been attempted in these analyses. In fact, although we assumed a density of $\bar{n} = 1 \times 10^{20}$ m^{-3} in ac operation, it slightly exceeds the density limit given by the Murakami coefficient,[16] $\bar{n}_{lim} \lesssim 3 \times B_t\,(\text{T})/q_a R\,(\text{m}) \times 10^{20}\,(\text{m}^{-3}) \simeq 7.2 \times 10^{19}\,(\text{m}^{-3})$ for auxiliary-heated plasmas. The Troyon-Gruber critical β value,[17] given by $\beta_{crit} = 0.04 I_p\,(\text{MA})/a\,(\text{m}) \times B_t\,(\text{T}) \simeq 3.3\%$ for case I, is slightly smaller than the beta value, $\beta_T = 4.46\%$, at the operating point employed here, but larger than $\beta_T = 3.2\%$ for $\bar{n} = 7.2 \times 10^{19}$ m^{-3}. Even if we lower the operating density to 7.2×10^{19} m^{-3}, the effects on these analyses are rather small and the discharge length is shortened by only 0.9% through the resistivity.

The advantage of the large fusion reactor proposed here is that it may access the ignition regime even with the Goldston L-mode scaling law[18] since the large current ($I_p \sim 10$ MA) and large aspect ratio provide a higher confinement time. This possibility has been discussed in Refs. 19 and 20 for case I.

It may seem desirable, considering thermal fatigue problems, to maintain a hot plasma in the current reversal phase. Multipole and multiquadrupole systems may be capable of confining a hot plasma in this interval.[21] However, as demonstrated already, a reduction of the plasma temperature in the reversal phase is needed for optimum use of the transformer flux, leading to smooth ac operation with long and nearly equal pulse lengths. This is especially important for a smaller machine.

The most important condition required for attaining ac operation in a tokamak is to reduce the electron density in the current rampdown phase. Otherwise, the plasma will disrupt due to an excessive density, as determined by the Hugill diagram. The decay of the electron density depends on wall conditioning and on the use of a divertor or pump limiter. If the current rampdown time is long, the density would decrease similarly. However, if the density reduction needs to be controlled, pumping out the plasma and neutrals with a divertor or pump limiter might be necessary. Another possible method for reducing the density is decompression by the poloidal electric field E_p induced by a decrease in the toroidal magnetic field B_t during the current rampdown phase.[22] In this case, plasma particles experience an $E_p \times B_t$ outward drift in the radial direction, which leads to a decrease in the density. Reducing the toroidal magnetic field in the current rampdown phase is equivalent to constant q_a operation. Sawtoothing in the $q < 1$ region near the plasma center may enhance diffusion of the plasma energy and cause a decrease in the electron temperature. These scenarios are only speculative at present, and experimental verification is necessary in a large tokamak.

Impurity injection may be able to increase the plasma resistance in the current rampdown phase. (Care must be taken not to induce disruptions.) However, the effect of impurity injection on the subsequent discharge is not known. Experimental checks on these problems are necessary. Neutral particle injection by gas puffing[23] in the final stage of the current rampdown phase or just before the current reversal may be used to cool down the plasma and increase the resistivity, and also to ensure the evolution of the next discharge by refueling with neutral particles.

Finally, in order to accomplish ac operation, complete control of the plasma position is also important in the current rampdown phase.

VIII. CONCLUSIONS

The main conclusions are summarized as follows:

1. Alternating current operation is possible with appropriate management of the transformer flux.

2. A simple criterion ($L_p/R_p < T_{d,ss}$) for achieving continuous ac operation and the relationship of the discharge lengths in the ac and standard pulse scenarios were obtained, assuming constant plasma parameters while maximizing the available transformer flux.

3. Since a fusion reactor with large major radius ($\sim$10 m) can satisfy this condition in the reactor parameter range, ac operation with long pulses is capable of providing continuous electric energy output. On the other hand, it is difficult for a smaller machine operating at the same current to satisfy the above condition because of a shorter discharge length. In this case, reducing the plasma current increases the discharge length, making ac operation possible.

4. If a plasma resistance enhancement technique, such as impurity injection, could be used to help the plasma current decay, ac operation would become more attractive in a smaller tokamak. The condition in conclusion 2 is no longer required in this case.

5. The SMES system could be an attractive power supply for continuous ac tokamak operation. The number of energy transfers between the power supply and the OH transformer in ac operation becomes less than that required in a conventional pulsed operation scheme for the case $\phi_L/\phi_t < \frac{1}{3}$.

6. An ac tokamak is less costly than one utilizing double-swing operation.

ACKNOWLEDGMENTS

One of the authors (O.M.) gratefully acknowledges encouragement from President Y. Nakayama and all faculty members in the Department of Electrical Engineering at Kumamoto Institute of Technology. We are grateful to one of the referees for pointing out the relationship [Eq. (11)] between the durations of the ac and the standard operation.

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