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INERTIAL AND INDUCTIVE ENERGY STORAGE FOR FUSION SYSTEMS*

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Energy storage is necessary for all proposed fusion reactor systems. The plasma physics for confinement and primarily the energy transfer time determine the nature of the storage system. Discharge times vary from 0.7 ms for theta-pinch reactors to one to two seconds for tokamak reactors. Three classes of devices are available for energy storage-- inductors, capacitors, and rotating machines. The transfer of the energy from the store imposes unusual switching requirements. The broad requirements for reactor energy stores and more specifically those for tokamak experimental power reactors (EPR) and for the Scyllac fusion test reactor (SFTR) will be presented. Assessments and comparisons of alternative energy storage and transfer systems for these devices are to be discussed. The state of the pulsed superconducting inductive energy storage coils and homopolar development programs will be emphasized. Plans for tokamak ohmic-heating systems will be discussed briefly.

INTRODUCTION

Large fusion devices will require advancement of technology to meet the demands for the delivery of pulsed energy. For high-β systems superconducting coils, inertial storage, or other moderately fast energy storage and transfer systems will be needed to replace more expensive, lower energy density capacitive systems.

Toroidal and linear theta pinches, liners, Z-pinches, glass lasers, and tokamaks all require large, fast energy delivery systems. In the pinches and liners, magnetic fields for plasma compression are driven by these large energy systems, while tokamaks and toroidal Z-pinches require pulsed supplies for ohmic heating. The flash lamp supplies for glass lasers require about 100 MJ on the 0.1 to 0.5-ms time scale.

The toroidal reference theta-pinch reactor (RTPR) requires about 60 GJ delivered in 30 ms,[1] the linear theta-pinch fusion/fission hybrid reactor needs about 25 GJ in 2 ms,[2] and a liner reactor may require about 10 GJ in 1 ms. The ohmic-heating coils in present U.S. designs of tokamak EPR's have about 1-2 GJ of stored energy, and the storage currents must be reversed in 0.5 to 2 s to induce plasma current.[3-5] Tokamak reactors require even larger ohmic-heating systems. Similar systems are needed for toroidal Z-pinches to ignite the plasma by ohmic heating.

The transition from capacitive storage to some alternative storage system was specified in the theta-pinch SFTR[6] by requiring a superconducting Magnetic Energy Transfer and Storage (METS)[7] system. In the RTPR, a METS system is required for staging between the implosion and compression fields.

Inertial storage has also been proposed for fusion systems, an early proposal being the NRL imploding liner system[8] with a self-excited, homopolar machine. More recently, the RTPR design has incorporated modules of homopolar machines to provide compressional field energy to bring the plasma to ignition. The energy is subsequently recovered at high efficiency, a necessary feature to achieve an energy balance in the reactor. Westinghouse, in a design study[9] for the Los Alamos Scientific Laboratory (LASL), identified the potential economic advantage of homopolar machines for the RTPR. A subsequent study[10] gave more detail to the machine and considered other system problems.

Over the past year, Westinghouse (W), the University of Texas (UT), and LASL have participated in a further design study, sponsored by the Electric Power Research Institute (EPRI), of the RTPR homopolar. The first phase of that study led to a fairly extensive conceptual engineering design[11] of the machine, which was used to determine the scale size model to construct for testing key features of the machine. That model, a 10-MJ, two-rotor machine, is now in final engineering design under the EPRI study. The construction of that machine, related component development, and its initial testing at W and LASL are the subject of a proposal[12] for a three year program.

Tokamak ohmic-heating systems and their energy sources have only recently begun to enjoy a more thorough analysis. The three EPR design studies[3-5] just begin to treat these power supplies. The Oak Ridge National Laboratory has examined[4] their EPR ohmic-heating system in more detail; and LASL, W, and UT are working on a joint ERDA study for a cost optimization of ac and dc machines in a number of circuits.

Nasar and Woodson[13] give information comparing pulsed power sources for energy density, transfer times, costs, and installation size and conclude that the pulsed-power technology is relatively advanced for fusion experimentation with needs for lower cost, higher power density supplies.

Schmitter[14] concludes that inductive energy storage units will only have a chance of competing with capacitive storage units if their higher energy densities can be utilized. He suggests subdividing inductive units and connecting them in parallel. For transfer times less than 1 ms he indicates that modules must be smaller than 1 MJ in size to be competitive.

Robson and coworkers[15] in discussing their homopolar machine used to implode liners point to the associated current switching problems and the need for a systems approach.

Most of the reviews[13,16-20] dealing with energy storage bear heavily on the technical aspects of a variety of systems and treat more lightly or not at all the importance of need for system optimization.

Toroidal Theta-Pinch Energy Supply

In the RTPR,[1] 63 GJ is transferred to the compression coils in 30 msec, the coil is crowbarred during the burn by the closing of S_2, and then the energy is returned to the homopolar. The circuit in Fig. 1 illustrates the process, with the capacitor C being the machine. The energy is supplied by 50 machines, each rated at 1.3 GJ, 11 kV, and

FIGURE 1. Simplified circuit and voltage - current curves for homopolar energy transfer for the RTPR.

12.25 MA. To achieve an energy balance, the energy must be recovered with a high efficiency, and the machine must have a 95% energy recovery in a full cycle. The estimated future cost is 0.6¢/J, giving a system cost of $300/kW of plant output.

The machine is to have eight rotors, operate at a surface speed of 277 m/sec, and use superconducting field coils.[11] The current collection system will use solid copper-graphite brushes at a current density of 1550 A/cm^2. These features--high speed, high field, and high current density--are necessary characteristics of all machines needed for fusion applications. Discharge times vary according to the rotor inertia, but from a technological viewpoint this discharge time is not as important and fundamental a characteristic as are field, speed, and current density. The design selected for RTPR is illustrated in Fig. 2 (2 of the 8 counter-rotating drums are shown), and the machine characteristics are listed in Table I. The superconducting coils are

FIGURE 2. An eight-rotor, superconducting field coil excited homopolar machine for the RTPR (courtesy Westinghouse).

TABLE I. Principal Homopolar Characteristics

Capacity	1290 MJ
Voltage (max)	11 kV
Current (max)	12.25 MA
Discharge time	30 ms
No. rotor modules	8
Rotor diameter	2.17 m
Collector length	25 cm
Brush current density	1550 A/cm^2
Brush packing factor	0.5

enclosed in an iron shield and the return conductor is a cylindrical sleeve just outside the rotors. Rotor current flows axially and continues between rotors through brushes rubbing on sliprings on the inner surface of the extended rotor.

Theta-pinch systems are characterized by a fast heating cycle capacitive driven implosion shock heating or beam injection,

followed by adiabatic compression by fast rising magnetic fields. For the RTPR the 30-ms homopolar discharge time is too slow and the field must be held up after the heating cycle with a bridging circuit and compression field with 500-MJ pulsed energy capacity. The superconducting METS system being developed for the SFIR very nearly meets this requirement.

Scyllac Fusion Test Reactor Energy Supply

The SFTR[6] is a high-ß, 40-m radius toroidal theta-pinch device. Energy for driving the compression coils for the adiabatic heating of the theta-pinch plasma is to be supplied from a superconducting METS system. The system has 128 cylindrical plastic dewars outside the plasma toroid, each dewar containing 10 energy-storage coils. The energy, to be pulsed into the compression coils in a 0.7-ms transfer period, is charged from a dc, low voltage power supply into a series-connected, modularized, superconducting inductive energy store.

Basic to the SFTR module concept are the high voltage and high current limits of 60 kV and 26 kA established for the superconducting energy-storage coils with a 2.5-T magnetic field to supply a 5.5-T compression field.

The total stored energy in the 1280 superconducting coils around the torus is 488 MJ.

The transfer capacitor for the L.-C-L resonant circuit for the superconducting METS system is sized to store approximately half the energy during transfer.

The SFTR circuit is shown in Fig. 3, and the METS storage coil parameters and superconductor characteristics are given in Table II.

Tokamak Ohmic-Heating System Energy Supply

Plasma heating in tokamak systems is accomplished by transformer coupling of energy from pulsed ohmic-heating coil systems. The

FIGURE 3. METS-SFTR circuit diagram.

TABLE 2. Energy-Storage Coil Parameters

Energy	381 kJ
Transport current	26 kA
Maximum operating voltage	60 kV
Maximum magnetic field	2.5 T
Inductance	1.13 mH
Radius (mean)	33.64 cm
Length	60.0 cm
Transport current	26 kA
Operating current density	$1.41(10)^5 A/cm^2$
Short sample critical current	$2.22(10)^5 A/cm^2$
Cable cross-sectional area	$2.83\ cm^2$
Cable thickness	1.08 cm
Insulation thickness, each face	0.076 mm
Strand filling factor	0.33
Matrix to superconductor ratio	4.0

requirement to supply 1 to 2 GJ in 0.5 to 2 s is well met by the capacitive nature of the homopolar machine for resonating energy

out of and back into the ohmic-heating coils.
The situation for tokamak EPR's is different
than for the high-β SFTR. With the longer
transfer period ac machines might well be
more economical energy sources to drive the
ohmic-heating systems. AC machines operated
in a variable speed mode into a rectifier,
much as a homopolar, appear as a capacitor
in the ohmic-heating circuits.

To synthesize circuits for the more de-
tailed studies required to establish an
appropriate energy supply, Weldon[21] has
reviewed the EPR design studies and calcu-
lated coupling coefficients for the ohmic-
heating, equilibrium, shield, and decoupling
coils and the plasma. These, together with
coil characteristics maximum energy, cur-
rent, and fields, are given in Tables III,
IV, and V.

Of the several component arrangements
that can be evolved, the joint study has ar-
rived at a comparison of ac and dc machine
energy systems to be made for the equiva-
lent series circuits of Fig. 4 and also the
Inall[22] dc circuit.

Figure 4 is used in the study to deter-
mine the necessary startup energy, transfer
times, and ohmic-heating coil requirements.
The ohmic-heating system, its transformer
coupling to the plasma and other coils, and
the plasma inductance are represented by
the inductor. Variable plasma resistance
is included in the analysis. A zero-dimen-
sion code is used to describe plasma build-
up and incorporates resistive heating, im-
purity effects, bremsstrahlung, line radia-
tion, charge exchange, plasma transport,
etc. The steady state power supply charges
the ohmic-heating coil with the "blip" re-
sistor and pulsed rotating machine bypassed.
Upon completion of charging the ohmic-heat-
ing coil the steady state supply is turned

TABLE III. Argonne OH and Equilibrium Coils

Parameter	Value
OH coil inductance per turn	$L'_{OH} = 0.933 \ \mu H$
EQ coil inductance per turn	$L'_{EQ} = 4.33 \ \mu H$
Plasma inductance	$L'_{P} = 11.16 \ \mu H$
No. turns OH coil	$N_{OH} = (1080)$ turns [a]
No. turns EQ coil	$N_{EQ} = (345)$ turns [b]
Inductance OH coil	$L_{OH} = 1.1036 \ H$
Inductance E coil	$L_{EQ} = (0.5) \ H$
Coupling OH and EQ	$k_{OH,EQ} = -0.05$
Coupling OH and plasma	$k_{OH,P} = 0.25$
Coupling EQ and plasma	$k_{EQ,P} = 0.2,5$
Max. energy EQ coil	$W_{EQ} = 0.9 \ GJ$ [c]
Max. energy OH coil	$W_{OH} = 0.883 \ GJ$ [d]
Max. OH current	$I_{OH} = 40 \ kA$
Max. EQ current	$I_{EQ} = 60 \ kA$
OH startup time	$\tau_{OH} = 1 \ s$
Burn time	$\tau_{B} = 20\text{-}50 \ s$
Peak field OH coil	$B_{OH} = 3.2 \ T$
Peak field EQ coil	$B_{EQ} = 3.7 \ T$

(a) The number of turns calculated is dif-
ferent depending upon whether it is calcu-
lated from the inductance per single turn
(1080), tabulated ampere turns (1135), or
the tabulated turns per coil (1182).

(b) The number of turns is equal to that
given in ANL/CTR-75-2, page IV-33 except the
number has been divided by 4 to reflect the
change from 15 kA to 60 kA.

(c) Calculated from the total energy and a
current of 60 kA.

(d) The energy given here is the energy of
the self inductance at peak current.

off and the rotating machine and blip re-
sistor are switched into the circuit. A
fast rising current or energy blip develops
to ionize and heat the plasma. The resis-
tor is crowbarred and the homopolar capaci-
tor completes the energy transfer on the
several second time scale and is bypassed
during the burn. The circuit is sufficient
for establishing the initial rate of change
of current (10-50 MA/s), stored energy
(1-2 GJ), the coil primary circuit parame-
ters (peak voltages of about 30-60 kV, peak
currents of about 150-300 kA, and volt-sec-
onds of about 100-200) for typical tokamak
EPR's.

TABLE IV. GA E and F Coils

Parameter	Value
E coil inductance per turn	$L'_E = 0.514$ μH
F coil inductance per turn	$L'_F = 5.85$ μH
Plasma inductance	$L'_P = 6.22$ μH
No. turns E coil	$N_E = 157$
No. turns F coil	$N_F = 155$
Inductance E coil	$L_E = 12.8$ mH
Inductance F coil	$L_F = 140.0$ mH [b]
Resistance F coil	$R_F = 8.73$ mΩ
Coupling E and F coils	$k_{E,F} = 0.304$
Coupling E coil and plasma	$k_{E,P} = 0.292$
Coupling F coil and plasma	$k_{F,P} = 0.771$
Max. energy E coil	$W_E = 1.28$ GJ
Max. energy plasma	$W_P = 408$ MJ
Max. energy F coil	$W_F = 373$ MJ
Max. energy F coil-plasma system	$W_{FP} = 295$ MJ
Max. E coil current	$I_E = 448$ kA
Max. plasma current	$I_P = 114$ MA
Max. F coil current [a]	$I_F = 71.82$ kA
OH startup time	$\tau_{OH} = 2$ s
Burn time	$\tau_B = 77.5 - 115$ s
Peak field E coil	$B_E = (6T)$

(a) F coil current is approximately equal to the plasma current divided by the number of F coil turns.

(b) The lumped inductance of the F coil is best calculated from the stored energy in the F coil system with correct current for plasma equilibrium in each F subcoil.

TABLE V. ORNL OH and Shield Coils

Parameter	Value
OH coil inductance per turn	$L'_{OH} = 0.774$ μH
Shield coil inductance per turn	$L'_S = 12.25$ μH
Plasma inductance	$L'_P = 12.53$ μH
Decoupling coil inductance per turn	$L'_D = 11.59$ μH
No. turns OH coil	$N_{OH} = 400$ turns
No. turns shield coil	$N_S = 16$ turns
No. turns decoupling coil	$N_D = 16$ turns
Inductance OH coil	$L_{OH} = 0.124$ H
Inductance shield coil	$L_S = 3.14$ mH
Inductance decoupling coil	$L_D = 0.297$ mH
Coupling OH and shield coils	$k_{OH,S} = 0.185$
Coupling OH coil and plasma	$k_{OH,P} = 0.204$
Coupling OH and decoupling coils	$k_{OH,D} = 0.859$
Coupling shield coil and plasma	$k_{S,P} = 0.735$
Coupling shield and decoupling coils	$k_{S,D} = 0.207$
Coupling plasma and decoupling coil	$k_{P,D} = 0.226$
Max. energy OH coil	$W_{OH} = 1.90$ GJ
Max. energy shield coil	$W_S = 318$ MJ
Max. energy shield coil and plasma	$W_{S,P} = 171$ MJ
Max. energy plasma	$W_P = 325$ MJ
Max. OH current	$I_{OH} = 175$ kA
Max. shield current	$I_S = 450$ kA
Max. plasma current	$I_P = 7.2$ MA
OH startup time	$\tau_{OH} = 2$ s
Burn time	$\tau_B = 100$ s
Peak field OH coil	$B_{OH} = 6.5$ T

The series circuit keeps the charging power supply connected and it does not see the high voltage developed across the ohmic-heating coil; however, a high voltage-high current commutation circuit must be in parallel with the "blip" resistor. The Inall circuit avoids the high voltage-high current commutation circuit by using an L-R blip element and a very large parallel connected capacitor across the ohmic-heating coil, the homopolar energy source, and the steady state power supply. The power supply is commuted out of the circuit by backing off its voltage until the current is transferred to the capacitor with the SCR's in series with the supply ceasing to conduct. These SCR's interrupt at low voltage and no current but must withstand the full ohmic-heating coil voltage at a later time.

Early results of the study indicate that both turbogenerators and salient pole generators of nearly state-of-the-art design can meet the tokamak ohmic-heating requirements by operating between half and full speed.

Homopolar Machine Development

Most of the fusion systems require high pulsed currents. Homopolars are being developed in several places to satisfy these needs.

FIGURE 4. AC and dc series tokamak ohmic-heating circuits (courtesy Westinghouse).

Robson and coworkers[15,23] have described the homopolar shown in Fig. 5, which is a self exciting machine for imploding liners. Five megajoules of energy are stored in each of two constant stress, counter-rotating beryllium-copper rotors. The maximum rotor speed is 18,000 rpm. Copper-graphite brushes are used on the inner slipring and copper plated carbon fibers contact the periphery.

The limitations of very fast discharge homopolars have been presented by UT,[24,25] and a small 0.36-MJ, 1-ms machine is being constructed. Figure 6 shows the two counter-rotating aluminum rotors which will discharge 2.8 MA in 1.3 ms from 14,000 rpm into a short circuit or 1 MA in 3 ms into a 0.25-μH, 60-μohm load from 28,000 rpm. The machine capacity is 16.6 F and has a 25-nH, 15-μohm internal impedance. The oil hydrostatic journal bearing supported rotors are driven by air turbines. The field coil is pulse excited with an energy store of about 1.2 MJ having a 4-T average field between brushes.

FIGURE 5. Layout of the NRL 10-MJ homopolar (courtesy A. E. Robson).

FIGURE 6. One-ms discharge period homopolar (courtesy J. Gully, UT).

UT[26] has also reported on a conceptual design study of a 50-MJ homopolar (TEXT) system as energy storage for both the toroidal and ohmic-heating coils of an experimental tokamak device. The machine is to have ferromagnetic rotors and normal field

coils and will deliver 200 kA at 125 V in 3 s from 268 rad/s. Several machines connected in series are planned to store 100 to 200 MJ.

The joint LASL-UT-W[11] study has led to a 1.3-GJ homopolar design as characterized in Table VI. The proposed[12] model machine is scaled one-third each in length, diameter, and drum thickness and wi 1 have two counter-rotating rotors. Thus with a NbTi excitation coil and a reduced average field of 30 kG on the drum the energy stored will be 10 MJ.

TABLE VI. 1.3-GJ, 30-ms Discharge SFTR Homopolar

    Rotors - 8
    Voltage - 11,100 V
    Current - 12.25 x 10^6 A
    Rotor diameter - 2.16/ m (85.3 in.)
    Drum length - 2.06 m (81 in.)
    Iron shield flux density - 18 kG
    Average gap density - 29 kG
    Average axial density - 50 kG
    Peak field - 80 kG
    Average radial field - 15 kG
    Average axial field - 55.4 kG

The 1.3-GJ machine losses are estimated at 5% and as high as 12.5% in the 10-MJ model because of indirect scaling of some of the losses. The model machine will simulate some of the rotor design and stress problems and most of the current collection problems of the large machine with a maximum slipring velocity of 277 m/s and 15.5 MA/m^2 brush current density. The peak current will be 1.5 MA delivered at 719 V into an 8.3 µH load. The model machine was originally designed to have an intrinsically stable superconducting field coil storing 8 MJ and is undergoing redesign to use a cryostable coil. The machine can be made to operate with a 1-s discharge period and a 46-kA peak current into a 9.5-mH load.

Superconducting Inductive Energy Storage

Early reactor designs and studies[1,27-29] clearly indicate that to achieve overall power balance will require superconducting systems. Design of superconducting ohmic-heating coil systems for tokamaks is in the formative stage being concerned more with solving the magnetics and the system electrical circuit requirements, i.e. parallel versus series connected coils, high current versus high voltage across the coils, and interspersed blip forming resistors connected between series connected coils. Some small scale tests are underway to develop and characterize superconductor.

The SFTR-METS pulsed superconducting coils have reached a more advanced stage of development. An engineering system study[30] was performed to minimize costs for the METS system. This study, together with the high refrigeration l _d associated with the use of dissipative superconducting switches, led to the abandonment of the superconducting switches and the adoption of the simple resonant L-C-L, capacitive transfer circuit with a HVDC vacuum interrupter to initiate the transfer. The SFTR design study[6] established goals for the present work at LASL. Four different 300-kJ coils, one by LASL and three by industry, have been built as part of a development toward these goals.

A monolithic conductor, 2700 filament, 6 Cu to NbTi, 300-kJ, edge wound single layer coil was built and successfully tested by LASL. The coil was operated at 12.5 kA with a stored energy of 386 kJ. Pulsed energy transfers were made for periods as short as 1 ms and peak voltages as high as 35 kV with 10-kA current.[31]

The three industrial coils are to operate at 10 kA, 2.3 T, 40-kV peak transfer voltage, and 2-ms transfer period. They are designed to operate at 67% along the load line, and

the coils made by Intermagnetics General
Corporation (IGC) and Magnetic Corporation
of America (MCA) have less than 0.3% energy
loss during the charge-discharge cycle.

The IGC coil uses a single layer, edge
wound cable of 319 multistrand, 0.39-mm
diameter CuNi-Cu matrix, NbTi multifilament
wires. The coil is vacuum impregnated with
epoxy resin. Testing has reached currents
up to 3.2 kA with normal transitions occur-
ring on a random basis. The coil has been
disassembled for redesign of the terminal
supports to prevent lead conductor motion as
a possible solution to the limited operation.
The coil is shown in Fig. 7.

The MCA coil uses a single layer, edge
wound, 1224 multistrand braid made of
0.127-mm diameter, 1.58 Cu to NbTi monofila-
ment wires. The coil structure is open with
the braid epoxy resin potted onto a helical
tray with spacers to form the winding. Pulsed
and hysteretic energy losses for the coil
were well below the specified requirement.
The coil operated to 4.8 kA but was limited
in performance from heating damage which may
have occurred at a lower current level dur-
ing a normalcy when operating without a
quench detection circuit.

The Westinghouse coil is made with a four
layer winding composed of 72 active strands
of 0.81-mm diameter Cu matrix, NbTi multi·
filament wires in twelve bundles to form a
cable wrapped around an insulated metal
strap. The structure is open for ℓHe cool-
ing. The cable lies in grooves and is fur-
ther stabilized by tension and an overwrap
of fiberglass and epoxy resin with care ex-
ercised to prevent the resin from direct
contact with the conductor strands. The
coil has not been tested to date.

Pulsed superconducting energy storage
coils of a similar nature using supercon-
ducting to normal transition switches for

FIGURE 7. Intermagnetics General Corpora-
tion 300-kJ coil.

discharges of more than 50 kV are reported
by Komarek and Ulbricht.[32]

CONCLUSIONS

Technology development for inertial and
inductive energy storage systems to supply

pulsed power for fusion devices is well underway. Conceptual studies are beginning to become more formalized into optimized engineering concepts and some hardware modeling is beginning to take place. Because of the large amounts of energy required for fusion reactors and the smaller EPR's, large extrapolations from these model experiments will remain for developments still later in time. Examples of the problem are apparent in the SFTR work with one coil to be tested in the near future at 400 kJ, 2.5 T, 60 kV, and 25 kA compared with 1280 of these to supply nearly 500 MJ to a compression field. Similarly, tokamak EPR's ohmic-heating coils will require several hundred kiloamperes current and 1 to 2 GJ pulsed energy in 1 to 2 seconds. Conventional turbogenerators rated at 1500 MVA[33] exist today; however, it remains to be determined whether such machines can be adapted to the tokamak ohmic-heating systems and modified to withstand pulsed loads. The largest efficient homopolar machines being considered for the near future will deliver only ten's of MJ's.

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