

Review of Inductive Pulsed Power Generators for Railguns

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Abstract—This literature review addresses inductive pulsed power generators and their major components. Different inductive storage designs like solenoids, toroids and force-balanced coils are briefly presented and their advantages and disadvantages are mentioned. Special emphasis is given to inductive circuit topologies which have been investigated in railgun research such as the XRAM, meat grinder or pulse transformer topologies. One section deals with opening switches as they are indispensable for inductive storages and another one deals briefly with SMES for pulsed power applications. In the end, the most relevant inductor systems which were realized in respect to railgun research are summarized in a table, together with its main characteristics.

Index Terms—Railgun, Pulsed power, review.

I. INTRODUCTION

INDUCTIVE storages are used in pulsed power generators for railguns for several reasons. In combination with a homopolar generator (HPG) or a battery, inductors are used to generate the high voltage which is needed to inject current into a railgun at high armature velocities. They are used in capacitor banks to limit the maximum current amplitude and adjust the pulse length to the requirements of the railgun. Furthermore, they decouple several capacitor modules from each other and allow time-delayed switching and therefore pulse shaping. However, inductor research was not very evident within the electromagnetic launch community in the past as inductors were mostly part of HPG, capacitor bank, or battery system development. Thus, there is no comprehensive reference work about inductive storage systems for pulsed power generation. This paper aims at filling the gap as inductive pulsed power systems are becoming more relevant due to emerging technologies like Li-ion batteries, supercapacitors, and superconductors.

II. INDUCTIVE STORAGE

Charged inductors can be seen as current sources which can create any voltage, assuming a corresponding insulation. Thus, inductors represent an ideal power source for railguns. In an inductive storage, energy is stored by its magnetic field. The interaction between the magnetic field and the current in the windings creates Lorentz forces on the windings of the inductor. Therefore, a coil can be regarded as a pressure vessel with the magnetic field B as a pressurized medium. The corresponding pressure p is related by $p = \frac{1}{2\mu} B^2$ to the magnetic field B with the permeability μ . The energy density of the inductor is directly linked to the magnetic field and

therefore, its maximum depends on the tensile strength of the windings and the mechanical support. The upper limit for the energy density W/V follows from the virial theorem and can be expressed by

$$W/V = \lambda\sigma \quad (1)$$

where σ is the tensile strength of the coil material and λ is a coefficient related to the structural efficiency of the coil design [1], [2]. $\lambda = 1$ is the maximum value which is achievable by an ideal coil geometry. In the case of long and thin solenoidal coils or toroidal coils, λ gets close to $\frac{1}{3}$ [3], [4]. In practice, the best value for λ can be achieved with short solenoidal coils like the Brooks coil, where λ can be as high as $\frac{1}{2}$ [1], [4].

In superconducting coils, the mechanical stress is the major limitation of the energy density. In normal conducting coils, other limitations like resistive losses or heat dissipation might be more critical than the mechanical stress.

III. SUPERCONDUCTING MAGNETIC ENERGY STORAGE

Ohmic losses can be avoided by using superconducting coils. In this case, the current could be stored for very long time periods. Instead of electrical losses, thermal losses of the cooling system have to be considered. The maximum energy and power of a superconducting coil is limited by the maximum breakdown voltage, the operating conditions of the conductor material and its mechanical strength [5]. Both the mechanical support and the electrical isolation will increase the coil volume and mass. Additionally, the cooling system has to be considered. Therefore, superconducting coils for high-power applications are still very bulky. Nowadays, the realized superconducting magnetic energy storage (SMES) systems in the order of 1 MJ/1 MW have a volume exceeding 2 m³ (estimated from [6]). When the corresponding vacuum vessel, vacuum pumps and cooling equipment are taken into account, the volume can easily be multiplied by a factor of two or more. Therefore, a normal conducting coil seems presently more appropriate if a high energy density is desired.

However, several researchers applied superconducting coils in small scale demonstrators [7]–[10]. Some of them applied the superconductor itself as opening switch by letting it quench on purpose [11]–[13]. A 20 MJ/1 MA conceptual design for a high temperature superconducting coil pulsed power generator is presented in [14], [15].

IV. COIL DESIGN

The optimization of normal conducting coils with respect to the energy density and L/R is usually performed by optimizing the inductance per given piece of wire (GPW) [16]. The coil with the best inductance per GPW is known as the

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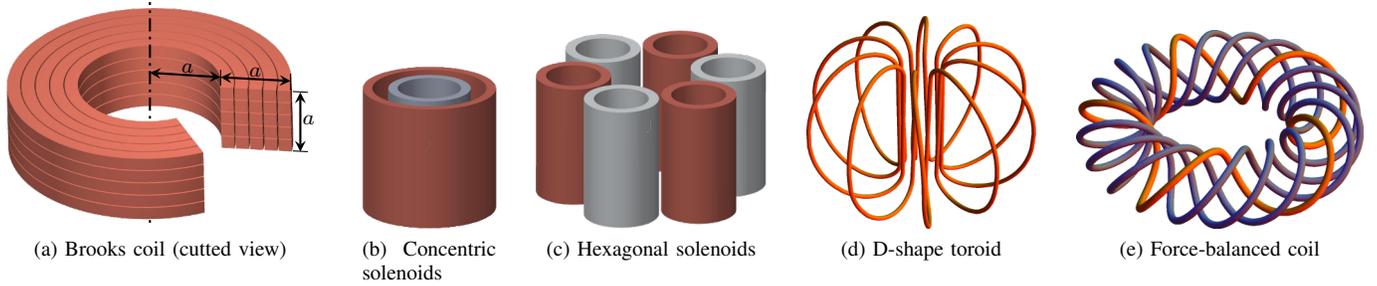


Fig. 1. Different coil geometries and arrangements

Brooks coil (see Fig. 1a) which is a solenoidal coil where the inner radius corresponds to half the outer radius and is equal to the height of the coil [16], [17]. Additionally, the number of windings in the radial and axial directions is the same.

A significant drawback of solenoids is that very high fringe fields appear in the vicinity of the coil. A safety distance between the coil and the operator or sensitive electronics is necessary in most cases if magnetic shielding is not applied [18]. But even then, a certain distance between the coil and the shielding has to be kept in order not to saturate the shielding material [19]. Placing several solenoids in a concentric or hexagonal arrangement (see Fig. 1c & 1b) can help to reduce fringe fields [20], [21].

An alternative to the solenoidal coil is the **toroidal coil**. Here, the magnetic field is encased in the windings of the coil and, therefore, a fringe field, ideally, does not exist. In actual fact, a fringe field cannot be completely avoided but a toroid made of five or more solenoids has a fringe field at least ten times smaller than a solenoidal coil [22]. Thus, shielding or a safety distance might not be necessary. On the other hand, the encapsulation of the magnetic field is attained at the expense of the energy density. The inductance per GPW of a solenoidal filament coil is, for example, 2.6 times higher than that of a toroidal filament coil with a circular turn window and a totally filled coil center (toroidal counterpart of a Brooks coil) [16]. The inductance of toroids can be further increased by choosing the so-called *Shafraanov D-* or *Princeton D-* shape for the windings (see Fig. 1d) [16], [23], [24]. The D-shape is not only the optimum shape with respect to the energy density but also an optimum with respect to the mechanical stress distribution.

Recent optimizations with respect to the mechanical stresses performed in superconducting coils have led to the development of the **force-balanced coil** (see Fig. 1e). It is a combination of a solenoidal coil with a toroidal one realized by adapting an optimized pitch angle to the helical windings of a toroidal coil [2]. It offers a good compromise between storage efficiency and electromagnetic compatibility. A drawback is that producing it is very complex.

V. OPENING SWITCHES

In order to transfer the energy from an inductive storage inductor to a load, an opening switch is necessary which interrupts the charging circuit and commutates the current to the load. During the commutation process, a voltage V

depending on the self-inductance L of the circuit and the load current I is generated equally at the load and the opening switch according to $V = L \frac{dI}{dt}$. This voltage generation is desired when batteries or HPGs are used which are generally low voltage sources. But the same voltage is applied to the opening switch and in case of large railguns, the so called speed-voltage can easily amount to several kilovolts [25, p. 8]. Therefore, opening switches for high current applications are challenging and were often avoided by preferring capacitor based solutions with closing switches.

Three kinds of opening switches are basically available: mechanical switches, fuses, turn-off controlled semiconducting switches and hybrids of all of them [26]–[28]. For inductively powered railgun systems, heavy duty contactors [29], explosively driven switches [30]–[32] and counter-current switch-off techniques [33]–[36] were used. Today, considerations go toward semiconducting switches like GTOs or IGBTs which are now capable to operate for short time in the MW range [37], [38]. The recent availability of such improved components facilitates system designs, but in order to switch off currents in the kA range, arrays of such switches are still necessary, which is expensive, heavy and bulky [39]. Wide bandgap semiconductor switches based on materials like SiC, GaN or diamond promise better electrical properties but the state of the art is still far from required values. An applicable technique in an inductive pulsed power generator is the introduction of an inverse current to a thyristor, allowing the switch to turn-off safely at a low or zero current. Efforts at ISL in this direction resulted in the development of the so-called ICCOS switch which utilizes power thyristors in this respect [40], [41]. Such switch is avoiding the generation of high commutation voltages by applying the inverse current also to parasitic circuit inductances. A design study for a 1 MJ inductive generator clearly showed the advantages of this switch compared to other semiconductor switches [39] with respect to size, weight and costs. Researchers at Netherlands Organisation for Applied Scientific Research - Pulse Physics Laboratory (TNO) built and tested such kind of opening switch for currents up to 300 kA for their HPG system [42].

VI. PULSE GENERATION CIRCUITS USED FOR RAILGUNS

A. Single coil

Single coil setups have been built in combination with HPGs [43], [44] or huge battery banks [29], [45], [46]. They are needed for the generation of high voltages, as HPGs

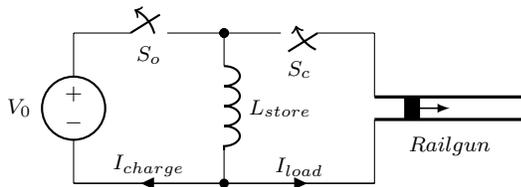


Fig. 2. Simplified circuit for a single coil pulsed power generator

and batteries are usually operated at a few hundred volts. Inductances are also widely used in capacitive pulsed-power generators [47], [48]. But in this case, the aim is to achieve pulse shaping in order to generate the required pulse length and to limit the maximum current. In contrast to other prime energy sources, opening switches are not required.

Fig. 2 displays a circuit diagram which shows how a railgun can be supplied by a single coil. First, the inductor L_{store} is charged by the voltage source V_0 . After charging, the current is commutated to the railgun by opening switch S_o and closing switch S_c at the same time.

In single coil setups, the amplitude of the load current directly correlates with the maximum current with which the inductance is charged. Current amplifying circuit topologies could be a better option, as they need a less powerful current source and opening switch. The following three basic circuit topologies are repeatedly suggested in the field of railgun applications.

B. Pulse transformer

Pulse transformers are based on the magnetic energy transfer between two coupled coils. Transformers are usually used for voltage amplification, but if the turns ratio between the secondary and primary windings is less than 1 ($N_2/N_1 < 1$), they can also be used for current amplification. But note that a transformer itself is not a power amplifier because the transformation ratios of current and voltage are inverses to each other. Pulses for railguns can be generated by discharging capacitors into the primary windings of the transformer [8], [49]–[51] or by applying pulse compression if a DC voltage source is used for charging the primary windings of the transformer as shown in Fig. 3. Pulse compression can be achieved by using an opening switch S_o to decrease the current in the primary windings rapidly, thus generating a high current in the secondary windings by magnetic coupling. An additional switch S_c connected to the secondary windings blocks the current in the load circuit during charging.

With respect to pulse transformer, several researchers applied superconducting coils as primary transformer windings and simultaneously as opening switches [7], [11], [12]. The current in the primary windings was rapidly reduced by forcing the superconductor into the normal-conducting state by an intended temperature increase. Amplification factors of more than 20 were reported. Nonetheless, the use of a pulse transformer as power supply for a railgun system was first reported by the Texas Tech University (TTU). Their railgun facility HERA comprised a pulse transformer which was connected to a 500 kJ capacitive pulse forming network (PFN) which can

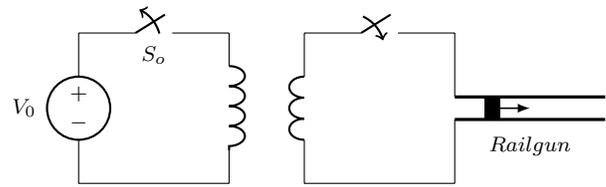


Fig. 3. Simplified pulse transformer circuit

deliver a maximum current of 100 kA [49], [50]. The turns ratio of the transformer is at maximum 20:1, but it is operated with a turns ratio of 5:1. Pulse compression is not applied in this system. Another system was very recently built at the GEDI Lab for the supply of a brush railgun [52]. Here, a modular 14 MJ double layer capacitor bank is supplying a pulse transformer with a maximum current of 70 kA which is then amplified by the transformer with a winding ratio of 20:1. The transfer to the load and pulse compression is initiated by a pneumatically driven opening switch. Higher amplification factors can be expected by combining a pulse transformer circuit in an XRAM-like topology as done in [53]. Here a transformer with superconducting primary windings and IGBT switches were used. Single stage experiments show that a seed current of 100 A was amplified to 4.7 kA [8]. Based on this small scale experiment and simulation results, it was estimated that several stages can amplify a current of 500 A to more than 120 kA.

C. Meat Grinder

In the meat grinder concept, several coupled coils are charged in series by a common current source (see Fig. 4). Opening switches are used to subsequently disconnect the coils from the circuit until one coil is left which is connected to the load. In the first step, S_1 is opened and S_2 is closed simultaneously. The switches of the following stages are switched likewise in subsequent steps (S_2 opens when S_3 closes and so on). During each switching process, the energy of the disconnected coil is transferred to the remaining coils by magnetic field coupling. Thus the load current can be increased or decreased [54], [55].

The meat grinder has been under consideration as railgun power source for more than 30 years. In this respect, a single step meat grinder was tested with a 1 m-long railgun as load by Lindner et al. [56]. Experiments with primary energies of up to 42 kJ and current amplitudes of 150 kA were conducted but did not meet the predicted current amplification as the fuse opening switch did not open in time. Twenty years later, Sitzman et al. improved the concept by adding a storage capacitor and called it the STRETCH meat grinder [57]. They reported successful railgun experiments with a corresponding demonstrator which was realized by a multi-section Brooks coil, GTOs as opening switches and batteries as primary energy source [58], [59]. It was claimed that with 30 kJ of inductively stored energy, an output current amplitude of 172 kA could be achieved [59], [60] but only preliminary experimental results with a current amplification from 2 kA to 21 kA were published. Recently, Wu et al. realized a meat

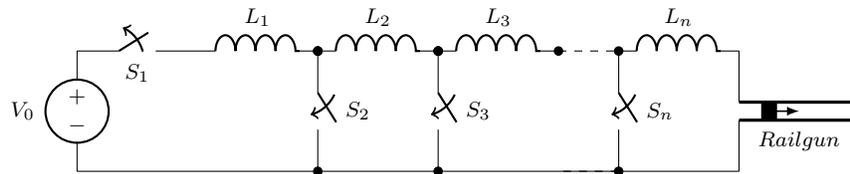


Fig. 4. Basic meat grinder circuit

grinder with a superconducting coil and IGBTs [10], [61]. They amplified a charging current of 100 A to 4.29 kA at a resistive dummy load. X. Yu et al. are investigating the STRETCH meat grinder with the ICCOS switch as developed at the ISL [62]–[66]. Most of their work is still conceptual but the increasing number of papers and involved personnel is indicating growing efforts.

D. XRAM generator

In the XRAM circuit, inductors energized in series from a current source (battery, rotating machines, or others) are switched by corresponding opening and closing switches to discharge in parallel, producing an output current which is the sum of the individual inductor currents. In Fig. 5, the source current is amplified by 2 after switching all switches synchronously. A higher amplification is possible with more than 2 stages. In high-energy pulsed-power systems, this multiplier technique simplifies the primary power design at the expense of more complex switching. The term XRAM generator originates from the well-known Marx generator where capacitors are charged in series and discharged in parallel to generate high voltages. By reversing the letters, the term XRAM indicates that the generator is the inductive counterpart to the Marx generator and its goal is to generate high currents. First proposed by Koch in 1967 [67], this topology was investigated several times as a power source for railguns [20], [68]–[72]. However, the largest devices of such kind were built in Russia for other applications: a 12.5 MJ-system within the X-ray test facility BAIKAL at TRINITI [73], and an XRAM system with a 20 MJ inductive storage at ESRI (see Tab. I). Currently, XRAM generators for railguns are under investigation in Japan, China and France [9], [62], [74], [75]. The XRAM concept was already proven to be applicable to superconducting coils [5], [20], [76]. It is also promising together with an augmented railgun, then also known as XRAM-gun [9], [68], [77].

VII. CONCLUSION

Inductive storage systems are applied to nearly all pulsed power generators, in some cases for voltage generation (HPGs, batteries) and in other cases for pulse shaping (capacitors, FCGs). They are theoretically more compact than capacitors but less compact than flywheels. As they need to be operated with a primary energy storage which can deliver a high current to the coil, the complete system compactness has to be considered. Flywheels, batteries and double-layer capacitors are available options in this respect. The latest research tends toward batteries as there are huge advances in the field of

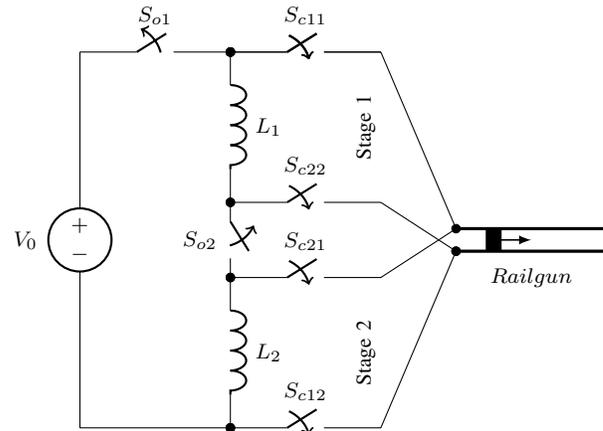


Fig. 5. Schematic for an XRAM generator with 2 stages

battery technology due to a large interest from the automotive industry.

A challenge regarding inductive storages are still the opening switches for currents in the range of megaamperes. Recent developments show that opening switches based on semiconducting switches will be possible but were not yet tested at an energy and power which is required for large railgun systems. Several inductive circuit topologies like the meat grinder or XRAM topologies are possible means of reducing the stress on opening switches by current amplifying properties. Table I summarizes some of the most considerable inductive generators which were developed with respect to electromagnetic launch.

Generators based on inductive storage are an attractive alternative to capacitors, due to their higher energy density. This can be an asset when mobile platforms are concerned but not for stationary applications. It is especially interesting when the inductive storage can be integrated into the railgun itself, augmenting the driving magnetic field and thus improving the energy efficiency. If the railgun system is installed on an electromobile platform, one can expect that an energy storage system such as a battery or a flywheel is already available. In this case, an inductive pulsed power generator is the most convenient choice as it does not require an additional energy converter. The compactness of an inductive pulsed power generator should be even more pronounced compared to capacitors if bursts of repetitive discharges are envisaged.

REFERENCES

- [1] L. Gredin, P. Mongeau, and H. Kolm, "Modular storage inductor," in *5th IEEE Int. Pulsed Power Conf. (PPPS)*, Dig. Techn. Pap., Arlington, US-VA, 1985, p. 594.

TABLE I
EXAMPLES OF REALIZED PULSED POWER GENERATORS APPLYING INDUCTIVE STORAGES

Feeding power supply	Switches	Inductively stored energy	Load	Max. load current	Size	Operator	Year	Ref.
Single coil topology								
Battery	Fuse	1.5 MJ	Resistor	28.5 kA	0.4 m ³	ELR, UK	1985	[1]
HPG	N/A	3.1 MJ	Railgun	1000 kA	1 m ³ ^a	CEM-UT, USA	1985	[78]
HPG	Exp. switch	10 MJ	Railgun	2000 kA	3 m ³ ^a	Westinghouse, USA	1986	[44]
Capacitors	Thyristor/Diodes	40 kJ	Railgun	52 kA	N/A	ISL, FR	1995	[79]
Capacitors	Ignitrons	0.7 MJ	Railgun	250 kA	0.5 m ³	IAT, USA	1995	[80]
Capacitors	Thyristor/Diode	60 kJ	n/a	68 kA	> 6 dm ³	ESRI, RU	2009	[81]
Pulse transformer topology								
Battery	SCR/GTO	16 kJ	short-circuit	150 kA	N/A	TNO, NL	1989	[82]
PFN	Ignitrons/Diode	550 kJ *	Railgun	500 kA	1 m ³	TTU/USA	1993	[49], [50]
DC supply	Quenched SC	500 J	N/A	23.3 kA	3 m ³ ^a	IGE/CREEBEL, FR	1999	[11]
DC supply	IGBT/Diode	69 J	Resistor	4.26 kA	12 dm ³ *	SJU, CN	2012	[8]
Meat grinder topology								
Capacitors	Fuse/Varistor	19.1 kJ	Railgun	135 kA	N/A	ECR, USA	1987	[56]
Li-ion batteries	GTOs	30 kJ	Railgun	172 kA	~ 1/8 m ³ *	IAT, USA	2007	[58]–[60]
DC supply	IGBT	78 J	Resistor	4.29 kA	0.003 m ³	SJU, CN	2013	[10], [61]
XRAM topology								
HPG	Exp. switch	20 MJ	N/A	6000 kA	316 m ³	ESRI, RU	1977-1992	[83]
Generator	Exp. switches	12.5 MJ	X-ray system	1500 kA	N/A	TRINITI, RU	2001	[73]
Battery	GTO/Varistor	25 kJ	Resistance	10 kA	N/A	SNRC, Israel	1993	[71], [84]
Capacitors	ICCOs	4725 J	Cable	60 kA	0.2 m ³	ISL, FR	2011	[85]
Capacitors	ICCOs	200 kJ	Railgun	40 kA	0.4 m ³	ISL, FR	2013	[75]
Capacitors	Spark gap/Diode	93 kJ	Aug. Railgun	200 kA	integrated	ISL, FR	2014	[77]
Supercaps	IGBTs	25 kJ	Cable*	24 kA	< 1 m ³	NIFS/JSW, Japan	2014	[74]
* capacitively stored ^a just coil								
ELR - Electromagnetic Launch Research, Inc.; CEM-UT - Center for Electromechanics, The University of Texas at Austin; IAT - Institute of Advanced Tech.; ESRI - Efremov Scientific Research Institute; TNO - Netherlands Organisation for Applied Scientific Research - Pulse Physics Laboratory; TTU - Texas Tech Univ.; IGE - Energy Eng. Institute; CREEBEL - Belfort Research Center in Electrical Eng.; SJU - Southwest Jiaotong Univ.;								
ECR - Energy Compression Research Corp.; SNRC - Soreq Nuclear Research Center; NIFS - National Institute for Fusion Science; JSW - Japan Steel Works, Ltd.								

- [2] S. Nomura, N. Watanabe, C. Suzuki, H. Ajikawa, M. Uyama, S. Kajita, Y. Ohata, H. Tsutsui, S. Tsuji-Iio, and R. Shimada, "Advanced configuration of superconducting magnetic energy storage," *Energy*, vol. 30, no. 1112, pp. 2115–2127, 2005.
- [3] F. C. Moon, "The virial theorem and scaling laws for superconducting magnet systems," *J. Appl. Phys.*, vol. 53, no. 12, pp. 9112–9121, 1982.
- [4] Y. Eyssa and R. Boom, "Considerations of a large force balanced magnetic energy storage system," *IEEE Trans. Magn.*, vol. 17, no. 1, pp. 460–462, Jan. 1981.
- [5] A. Badel, "Superconducting magnetic energy storage using high temperature superconductor for pulse power supply," Ph.D. dissertation, INPG, Université de Grenoble, Sep. 2010. [Online]. Available: <http://tel.archives-ouvertes.fr/tel-00654844>
- [6] T. Mito, H. Chikaraishi, A. Kawagoe, R. Maekawa, R. Abe, T. Baba, K. Okumura, A. Kuge, M. Iwakuma, and F. Sumiyoshi, "Summary of a 1 MJ conduction-cooled LTS pulse coil developed for 1 MW, 1 s UPS-SMES," *IEEE Trans. Appl. Supercond.*, vol. 19, no. 3, pp. 1999–2003, 2009.
- [7] S. Singh, C. Heyne, D. Hackworth, E. Shestak, P. Eckels, and J. Rogers, "Designs of pulsed power cryogenic transformers," *IEEE Trans. Magn.*, vol. 24, no. 2, pp. 1504–1507, Mar. 1988.
- [8] H. Li, Y. Wang, Y. Zhu, R. Wu, L. Dong, and K. Dou, "Design and testing of a high-temperature superconducting pulsed-power transformer," *IEEE Trans. Appl. Supercond.*, vol. 22, no. 2, pp. 5 500 205–5 500 205, 2012.
- [9] A. Badel, P. Tixador, and M. Arriet, "Optimized use of superconducting magnetic energy storage for electromagnetic rail launcher powering," *Superconductor Science and Technology*, vol. 25, no. 1, p. 014006, 2012. [Online]. Available: <http://stacks.iop.org/0953-2048/25/i=1/a=014006>
- [10] R. Wu, Y. Wang, Z. Yan, Z. He, and L. Wang, "Design and testing of a novel inductive pulsed power supply consisting of HTS pulse power transformer and ZnO-based nonlinear resistor," *IEEE Trans. Plasma Sci.*, vol. 41, no. 7, pp. 1781–1786, 2013.
- [11] E. Floch, P. Hiebel, Y. Laumond, and A. Lacaze, "Modelization and test of a 500J superconducting pulsed power transformer," *IEEE Trans. Appl. Supercond.*, vol. 9, no. 2, pp. 1289–1292, Jun. 1999.
- [12] M. Hilal and E. Leung, "Energy compression and transfer using hybrid pulse power transformer (HPPT)," in *6th IEEE Int. Pulsed Power Conf. (PPPS). Dig. Techn. Pap.*, Arlington, US-VA, 1987.
- [13] W. Weck, P. Ehrhart, A. Muller, H. Scholderle, and E. Sturm, "Demonstration of a superconducting inductive pulsed power supply at simulated load conditions," *IEEE Trans. Magn.*, vol. 35, no. 1, pp. 383–387, Jan. 1999.
- [14] Y. Aso and S. Yamada, "Current multiplier by inductive storage (CMIS) cooled by LN₂ and design of mega-ampere CMIS," *IEEE Trans. Plasma Sci.*, vol. 39, no. 1, pp. 247–250, Jan. 2011.
- [15] S. Yamada, Y. Hishinuma, and Y. Aso, "Multi-functional current multiplier by high temperature superconducting magnet energy storage," *Physics Procedia*, vol. 36, pp. 741–746, 2012. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S1875389212019736>
- [16] P. N. Murgatroyd, "The optimal form for coreless inductors," *IEEE Trans. Magn.*, vol. 25, no. 3, pp. 2670–2677, 1989.
- [17] F. Grover, *Inductance Calculations: Working Formulas and Tables*, ser. Dover phoenix editions. Dover Publications, 1946.
- [18] C. Polk, R. Boom, and Y. Eyssa, "Superconductive magnetic energy storage (SMES) external fields and safety considerations," *IEEE Trans. Magn.*, vol. 28, no. 1, pp. 478–481, Jan. 1992.
- [19] A. Pokryvailo, I. Ziv, and M. Shapira, "Repetitive inductive storage supply for an ETC tank gun," *IEEE Trans. Magn.*, vol. 39, no. 1, pp. 257–261, Jan. 2003.
- [20] W. Weck, P. Ehrhart, A. Muller, and G. Reiner, "Superconducting inductive pulsed power supply for electromagnetic launchers: Design aspects and experimental investigation of laboratory set-up," *IEEE Trans. Magn.*, vol. 33, no. 1, pp. 524–527, 1997.
- [21] G. Schonwetter, C. Magele, K. Preis, C. Paul, W. Renhart, and K. Richter, "Optimization of SMES solenoids with regard to their stray fields," *IEEE Trans. Magn.*, vol. 31, no. 3, pp. 1940–1943, May 1995.
- [22] M. Kanter, A. Pokryvailo, N. Shaked, and Z. Kaplan, "Factors in inductive storage system design," in *10th IEEE Int. Pulsed Power Conf. (PPPS). Dig. Techn. Pap.*, vol. 1, Albuquerque, US-NM, Jul. 1995, pp. 186–191.
- [23] V. Shafranov, "Optimum shape of a toroidal solenoid," *Soviet Physics - Technical Physics (Engl. Transl.)*, vol. 17, no. 9, pp. 1433–1437, 1973.
- [24] P. Birkner, "Toroide mit idealem Feld," *Electrical Engineering (Archiv für Elektrotechnik)*, vol. 74, no. 4, pp. 275–287, 1991.
- [25] R. A. Marshall and W. Ying, *Railguns: Their science and technology*. 22 Baiwanzhuang Road, Beijing 100037 China: China Machine Press, 2004, ISBN 7-111-14013-3.
- [26] A. Pokryvailo, V. Maron, and D. Melnik, "Review of opening switches for long-charge fieldable inductive storage systems," in *12th IEEE Int. Pulsed Power Conf. (PPPS). Dig. Techn. Pap.*, vol. 2, Monterey, US-CA, 1999, pp. 1341–1344.
- [27] K. H. Schoenbach, M. Kristiansen, and G. Schaefer, "A review of opening switch technology for inductive energy storage," *Proceedings of the IEEE*, vol. 72, pp. 1019–1040, 1984.
- [28] H. Bluhm, *Pulsed power systems: Principles and applications*, ser. Power systems. Springer, 2006. [Online]. Available: <http://books.google.de/books?id=kEliQgAACAAJ>
- [29] J. Sterrett, J. Lippert, M. Palmer, N. Johnson, and M. Altstatt, "Design of a battery power supply for the electromagnetic gun experimental research facility," in *6th IEEE Int. Pulsed Power Conf. (PPPS). Dig. Techn. Pap.*, vol. 29, Arlington, US-VA, 1987, pp. 42–45.
- [30] E. Aivaliotis and M. Peterhans, "Explosive opening switch work at Westinghouse," *IEEE Trans. Magn.*, vol. 25, no. 1, pp. 40–45, Jan. 1989.
- [31] D. Peterson, J. Price, J. Upshaw, W. Weldon, J. Zowarka, R.C., J. Gully, and M. Spann, "Heavy-duty explosively operated pulsed opening and closing switches: reducing cost and turnaround time [railgun power supplies]," *IEEE Trans. Magn.*, vol. 27, no. 1, pp. 369–373, Jan. 1991.
- [32] R. Klug, R. Ford, D. Jenkins, and W. Lupton, "Ten megacoulomb switching operation for the air force battery powered inductive storage launcher research facility," *IEEE Trans. Magn.*, vol. 27, no. 1, pp. 380–383, Jan. 1991.
- [33] E. Van Dijk and P. Van Gelder, "A resonant series counterpulse technique for high current opening switches," *IEEE Trans. Magn.*, vol. 31, no. 1, pp. 84–89, Jan. 1995.
- [34] E. Leung, R. Bailey, and P. Michels, "Using a small hybrid pulse power transformer unit as component of a high-current opening switch for a railgun," *IEEE Trans. Magn.*, vol. 25, no. 2, pp. 1779–1782, Mar. 1989.
- [35] T. Ding, J. Wang, H. Ding, L. Li, B. Liu, and Y. Pan, "A 35 kA disc-shaped thyristor DC switch for batteries power supply of flat-top pulsed magnetic field," *IEEE Trans. Appl. Supercond.*, vol. 22, no. 3, Jun. 2012.
- [36] B. Fridman, R. Enikeev, K. Kharcheva, N. Kovrizhnykh, and R. Serebrov, "Counter pulse capacitor bank for 70 kA, 10 kV commutation system," in *19th IEEE Int. Pulsed Power Conf. (PPPS). Dig. Techn. Pap.*, Jun. 2013, pp. 1–6.
- [37] S. Scharnholz, R. Schneider, E. Spahn, A. Welleman, and S. Gekenidis, "Investigation of IGBT-devices for pulsed power applications," in *14th IEEE Int. Pulsed Power Conf. (PPPS). Dig. Techn. Pap.*, vol. 1, Dallas, US-TX, Jun. 15-18, 2003, pp. 349–352.
- [38] A. Sitzman, D. Surls, J. Mallick, and E. Dierks, "Operational limits of a commercial gate turn-off thyristor for inductive-store systems," *IEEE Trans. Plasma Sci.*, vol. 39, no. 1, pp. 316–321, Jan. 2011.
- [39] O. Liebfried, V. Brommer, and S. Scharnholz, "Development of XRAM generators as inductive power sources for very high current pulses," in *19th IEEE Int. Pulsed Power Conf. (PPPS). Dig. Techn. Pap.*, San Francisco, US-CA, Jun. 16-21, 2013, pp. 646–651.
- [40] P. Dedie, V. Brommer, and S. Scharnholz, "ICCOS countercurrent-thyristor high-power opening switch for currents up to 28 kA," *IEEE Trans. Magn.*, vol. 45, no. 1, pp. 536–539, Jan. 2009.
- [41] V. Brommer and E. Spahn, "XRAM generator with an opening switch," US patent US7495357 B2, Saint-Louis, France, Feb. 2009.
- [42] E. van Dijk, "Experimental results obtained with the 1 ma resonant series counterpulse opening switch system, developed at tno," in *11th IEEE Int. Pulsed Power Conf. (PPPS). Dig. Techn. Pap.*, vol. 1, June 1997, pp. 287–292.
- [43] J. Gully, S. Pretap, and M. Spann, "Design of a compact inductor matched to a homopolar generator," in *4th IEEE Int. Pulsed Power Conf. (PPPS). Dig. Techn. Pap.*, Albuquerque, NM, USA, 1983.
- [44] D. Hackworth, D. Deis, P. Eckels, and D. Marschik, "A 10 MJ cryogenic inductor," *IEEE Trans. Magn.*, vol. 22, no. 6, pp. 1495–1498, Nov. 1986.
- [45] A. Pokryvailo, M. Kanter, Z. Kaplan, and V. Maron, "Design and testing of a 5 MW battery-based inductive power supply," *IEEE Trans. Plasma Sci.*, vol. 26, no. 5, pp. 1444–1453, 1998.
- [46] A. Pokryvailo, "Development of long-charge inductive storage systems at Soreq NRC," in *15th IEEE Int. Pulsed Power Conf. (PPPS). Dig. Techn. Pap.*, Monterey, US-CA, 2005, pp. 100–103.
- [47] E. Spahn, M. Lichtenberger, and F. Hatterer, "Pulse forming network for the 10 MJ-railgun PEGASUS," in *Proc. 5th Europ. Symp. Electromagn. Launch Techn.*, Toulouse, France, Apr.10-13 1995.
- [48] T. Wolfe, P. Riedy, J. Drake, F. MacDougal, and J. Bernardes, "Preliminary design of a 200 MJ pulsed power system for a naval railgun proof of concept facility," in *Proc. 12th Symp. Electromagn. Launch Techn.*, May 2004, pp. 490–494.

- [49] M. Wofford, M. Baker, and M. Day, "Design, simulation, and testing of a pulse forming network- transformer power supply for the Texas Tech railgun," in *8th IEEE Int. Pulsed Power Conf. (PPPS). Dig. Techn. Pap.*, San Diego, US-CA, Jun. 1991, pp. 138–140.
- [50] M. Day, M. Baker, and G. Grant, "HERA railgun facility at Texas Tech University," *IEEE Trans. Magn.*, vol. 29, no. 1, pp. 787–791, Jan. 1993.
- [51] R. Wu, Y. Wang, Z. Yan, W. Luo, and Z. Gui, "Design and experimental realization of a new pulsed power supply based on the energy transfer between two capacitors and an HTS air-core pulsed transformer," *IEEE Trans. Plasma Sci.*, vol. 41, no. 4, pp. 993–998, Apr. 2013.
- [52] Y. A. Dreizin, D. Rebrov, and A. Recksiedler, "Figure-8 inductive store for EM brushgun," in *20th IEEE Int. Pulsed Power Conf. (PPPS). Dig. Techn. Pap.*, Austin, US-TX, May 31 - Jun. 4 2015, pp. 122–125.
- [53] H. Li, Y. Wang, W. Chen, W. Luo, Z. Yan, and L. Wang, "Inductive pulsed power supply consisting of superconducting pulsed power transformers with Marx generator methodology," *IEEE Trans. Appl. Supercond.*, vol. 22, no. 5, 2012.
- [54] O. Zucker and J. Long, "The Meatgrinder: A reversible inductive storage and transfer system," in *4th IEEE Int. Pulsed Power Conf. (PPPS). Dig. Techn. Pap.*, Albuquerque, US-NM, 1983, pp. 375–379.
- [55] R. Kratz and P. Wyder, *Principles of Pulsed Magnet Design*, ser. Engineering Materials and Processes. Springer, 2002.
- [56] K. Lindner, J. Long, H. Helava, and O. Zucker, "Enhanced energy transfer to an EM gun," in *6th IEEE Int. Pulsed Power Conf. (PPPS). Dig. Techn. Pap.*, Arlington, US-VA, 1987, pp. 749–752.
- [57] A. Sitzman, D. Surls, and J. Mallick, "Stretch meat grinder: A novel circuit topology for reducing opening switch voltage stress," in *15th IEEE Int. Pulsed Power Conf. (PPPS). Dig. Techn. Pap.*, Monterey, US-CA, 2005, pp. 493–496.
- [58] —, "Design, construction, and testing of an inductive pulsed-power supply for a small railgun," *IEEE Trans. Magn.*, vol. 43, no. 1, pp. 270–274, Jan. 2007.
- [59] —, "Modification and testing of a battery-inductor repetitive pulsed power supply for a small railgun," in *16th IEEE Int. Pulsed Power Conf. (PPPS). Dig. Techn. Pap.*, vol. 2, Albuquerque, US-NM, 2007, pp. 1793–1798.
- [60] I. McNab, "Pulsed power options for large EM launchers," *IEEE Trans. Plasma Sci.*, vol. 43, no. 5, pp. 1352–1357, May 2015.
- [61] R. Wu, Y. Wang, Z. Yan, Z. He, and L. Wang, "Simulation and experimental investigation of an inductive pulsed power supply based on the head-to-tail series model of an HTS air-core pulsed transformer," *IEEE Trans. Appl. Supercond.*, vol. 23, no. 4, pp. 5 701 305–5 701 305, 2013.
- [62] X. Yu and X. Chu, "Comparisons of three inductive pulse power supplies," *IEEE Trans. Plasma Sci.*, vol. 41, no. 5, pp. 1340–1345, May 2013.
- [63] —, "STRETCH meat grinder with ICCOS," *IEEE Trans. Plasma Sci.*, vol. 41, no. 5, pp. 1346–1351, May 2013.
- [64] X. Yu, S. Ma, and Z. Li, "System implementation and testing of the STRETCH meat grinder with ICCOS," *IEEE Trans. Plasma Sci.*, vol. PP, no. 99, pp. 1–1, 2015.
- [65] X. Yu, H. Liu, J. Li, Z. Li, and P. Liu, "Discussion on the discharging effects of two STRETCH meat grinder modules with different triggering delays," *IEEE Trans. Plasma Sci.*, vol. PP, no. 99, pp. 1–1, 2015.
- [66] —, "Study on the collaborative triggering of multiple STRETCH meat grinder with ICCOS modules," *IEEE Trans. Plasma Sci.*, vol. PP, no. 99, pp. 1–1, 2015.
- [67] W. Koch, "Ein induktiver Stoßstromgenerator für Hochstromexperimente," German Federal Ministry for Scientific Research [Bundesministerium für wiss. Forschung], Tech. Rep. BMwF-FB K 67-35, 1967.
- [68] J. G. H. Salge, M. J. Loeffler, and U. E. Braunsberger, "Integrated magnetic acceleration - and energy storage system," in *5th IEEE Int. Pulsed Power Conf. (PPPS). Dig. Techn. Pap.*, Arlington, US-VA, 1985, pp. p.548–551.
- [69] M. J. Löffler, "Über die Einkopplung elektromagnetischer Energie in lineare Hochleistungspulsbeschleuniger," Ph.D. dissertation, Technische Universität Braunschweig, 1988.
- [70] R. Ford, R. Hudson, and R. Klug, "Novel hybrid XRAM current multiplier," *IEEE Trans. Magn.*, vol. 29, no. 1, pp. 949–953, Jan. 1993.
- [71] M. Kanter, R. Cerny, N. Shaked, and Z. Kaplan, "Repetitive operation of an XRAM circuit," in *9th IEEE Int. Pulsed Power Conf. (PPPS). Dig. Techn. Pap.*, vol. 1, Albuquerque, US-NM, Jun. 1993, pp. 92–.
- [72] C. Stallings, F. Warren, and J. Naff, "A novel energy storage device," in *13th IEEE Int. Pulsed Power Conf. (PPPS). Dig. Techn. Pap.*, vol. 1, Las Vegas, US-NV, Jun. 2001, pp. 624–627 vol.1.
- [73] E. Grabovsky, E. Azizov, S. Alikhanov, A. Gribov, A. Jitlukhin, S. Levashov, A. Lotocky, S. Nedoseev, V. Pismenniy, E. Velikhov, G. Dolgachev, J. Kalinin, A. Kingcep, V. Smirnov, V. Chetvertkov, V. Glukhikh, V. Kuchinsky, O. Pechersky, A. Kormilitcin, V. Kovalev, and G. Rikovanov, "Development of X-ray facility "Baikal" based on 900 MJ inductive store and related problems," in *13th IEEE Int. Pulsed Power Conf. (PPPS). Dig. Techn. Pap.*, vol. 1, Las Vegas, Jun. 2001, pp. 773–776 vol.1.
- [74] S. Yamada, H. Nakayama, and Y. Aso, "Switching properties of liquid nitrogen cooled IGBTs and 24 kA demonstration of current multiplier by inductive storage," *Journal of Physics: Conf. Series*, vol. 507, no. 3, 2014. [Online]. Available: <http://stacks.iop.org/1742-6596/507/i=3/a=032059>
- [75] O. Liebfried and V. Brommer, "A four-stage XRAM generator as inductive pulsed power supply for a small-caliber railgun," *IEEE Trans. Plasma Sci.*, vol. 41, no. 10, pp. 2805–2809, Oct. 2013.
- [76] P. Dedie, V. Brommer, A. Badel, and P. Tixador, "Three-stage superconducting XRAM generator," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 18, no. 4, pp. 1189–1193, Aug. 2011.
- [77] O. Liebfried and M. Roch, "Augmented railgun with integrated XRAM current multiplication," in *Proc. IEEE Int. Power Modulator and High Voltage Conf. (IPMHVC)*, Santa Fe, US-NM, Jun. 1-4, 2014, pp. 279–282.
- [78] M. Driga, K. Nalty, R. Zowarka, T. Aanstoos, A. Wu, and W. Weldon, "Homopolar generator charged inductors," in *5th IEEE Int. Pulsed Power Conf. (PPPS). Dig. Techn. Pap.*, Arlington, US-VA, 1985, p. 606.
- [79] E. Spahn, G. Buderer, and F. Hatterer, "Compact 50 kJ pulse forming unit, switched by semiconductors," *IEEE Trans. Magn.*, vol. 31, no. 1, pp. 78–83, Jan. 1995.
- [80] J. Parker, D. Berry, and P. Snowden, "The IAT electromagnetic launch research facility," *IEEE Trans. Magn.*, vol. 33, no. 1, pp. 129–133, Jan. 1997.
- [81] N. Kovrizhnykh, A. Drozdov, R. Enikeev, B. Fridman, A. Konstantinov, Y. Krukov, and A. Malkov, "Inductive storage - inductor for a capacitor cell," in *17th IEEE Int. Pulsed Power Conf. (PPPS). Dig. Techn. Pap.*, Washington, DC, Jun. 2009, pp. 646–651.
- [82] E. Tuinman, "Characterization and optimization of the Kapitza facility at PML-Pulse Physics," in *7th IEEE Int. Pulsed Power Conf. (PPPS). Dig. Techn. Pap.*, Arlington, US-VA, 1989, pp. 134–139.
- [83] A. Druzhinin, V. Kuchinsky, B. Larionov, A. Roshal, V. Silin, and V. Soikin, "Pulse power systems using inductive energy storage," *IEEE Trans. Magn.*, vol. 28, no. 1, pp. 410–413, Jan. 1992.
- [84] M. Kanter, R. Cerny, Z. Kaplan, and J. Ashkenazy, "Capillary discharge response to XRAM inductive generator," in *8th IEEE Int. Pulsed Power Conf. (PPPS). Dig. Techn. Pap.*, San Diego, US-CA, Jun. 1991, pp. 792–794.
- [85] P. Dedie and V. Brommer, and S. Scharnholz, "Twenty-stage toroidal XRAM generator switched by countercurrent thyristors," *IEEE Trans. Plasma Sci.*, vol. 39, no. 1, pp. 263–267, Jan. 2011.



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