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UTILIZATION OF THE SERIES RESONANT DC LINK CONVERTER AS A CONDITIONING SYSTEM FOR SMES

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ABSTRACT

In this paper a new Superconductive Magnetic Energy Storage (SMES) system utilizing a high frequency series resonant dc link power converter of high efficiency as the conditioning converter is presented. This system generates a high frequency (20kHz or more) resonant current in a series link and switching is done at zero current instants, reducing switching losses to a minimal value. Through the utilization of an adequate control strategy, input power factor can be fully adjusted during the charging, storing, and discharging modes of the SMES, improving the overall system efficiency. Different semiconductor devices are employed as the switching elements of the resonant converter and switching losses are established for each case. Experimental results from a monophase and three-phase system verified the results obtained from digital simulation.

INTRODUCTION

A Superconductive Magnetic Energy Storage (SMES) system consists basically of a large superconducting storage coil, its cooling system and an ac to dc power converter system, typically called the power conditioning system. SMES has recently draw attention not only as a potential means for load leveling but also as a power system stabilizer [1-2].

For utility load leveling a SMES system has two operational modes:

a) During low demand periods it absorbs surplus ac power as stored energy in the dc SMES coil
b) During high demand periods the energy stored into the superconducting coil is then delivered back to the utility network through the ac-dc converter.

The basic requirements for the power conditioning system that interfaces the utility system and the SMES coil are the following:

1) Ability to operate at very high currents or ability to operate with parallel devices or parallel bridges
2) Power transfer in both directions due to load leveling
3) High efficiency
4) Fast changes in power level or direction
5) Minimum reactive power consumption under normal operation and supplying or taking reactive power from the utility network as necessary at the same level of real power
6) Ability to independently control the real and reactive power

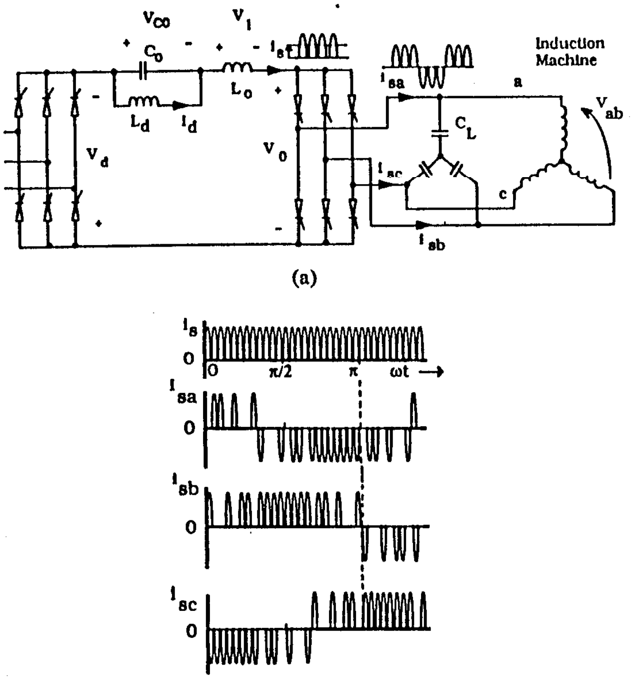
In [1] and [2] different power conditioning circuits have been studied for this purpose utilizing GTO converters. In contrast to these hard switched converters, high power density ac/ac converters utilizing resonant link schemes have been developed recently. These converters not only have high power density but also possess very low switching losses, since the switching of the devices is done at zero voltage or zero current instants.

In general, switching schemes for resonant converters can be classified according to their resonant ac link and resonant dc link modes of operation. The resonant ac circuits utilize a parallel or series resonant link, impressing both polarities of ac voltage and current on the link thus requiring bidirectional switches in the input and output converters [3-5]. The resonant dc circuits can also utilize a parallel [5] or series resonant link.

The series dc link circuits realize pulsating dc currents in the link by adding dc offsets to the ac resonant currents. A high frequency series resonant dc link, ac-to-ac power converter is proposed in [6] utilizing only 12 unidirectional switches.. As shown in Figure 1(a) the capacitor C_0 and inductor L_0 cause a resonant high frequency current i_s to flow from the input ac source to the load while the inductance L_d provides a dc bias current (I_d) to the resonant current i_s. The resonant pulses can then be distributed in the input phases by a Pulse Density Modulation control strategy, as shown in Fig. 1(b). The four thyristors conducting in the two bridges turn on and off at zero current instants, reducing switching losses significantly. In [7] a design methodology and a control strategy is established for the complete ac/ac drive system.

This paper proposes the utilization of a series resonant dc link power converter as the conditioning system for SMES. The superconducting coil L_d provides the bias dc current for the resonant pulses. The system provides bidirectional power flow enabling three operational modes which are charging, storing, and discharging. Operation with extremely low switching losses (both at the instants of turn on and turn off of the devices), continuous operation from start up with unity fundamental input power factor (if desired), independent control of real and reactive power in all modes of operation, and low harmonic content make the system suitable to be utilized in high power applications such as a power conditioning circuit for SMES with excellent overall efficiency.

Different semiconductor device structures, like Gate Turn-off Thyristors (GTO) in the Gate Assisted Turn-off mode [8, 9 and 10] and Silicon Controlled Rectifiers (SCR), are utilized as the switching elements of the resonant converter. Switching losses are established and compared for



(a)

(b)

Fig. 1 AC/AC drive system utilizing the series resonant dc link

each case. Resonant frequencies up to 32kHz were obtained in the experimental monophase and three-phase models.

A control strategy utilizing sigma-delta modulators for continuous control of the active and reactive input/output power during the charging/discharging modes is proposed in this paper. Complete and continuous control of the input power factor and low harmonic content can be cited as advantages of this control scheme.

SYSTEM ANALYSIS

Figure 2 shows the three-phase resonant converter utilized as a power conditioning drive in a Superconductive Energy Storage system. The bias inductor L_d in the original system is substituted by the super conducting element. The resonant frequency of the system is determined by the capacitor C_0 and the inductor L_0. In the generation of the first resonant pulse the capacitor C_0 and the inductors L_0 and L_d are completely discharged. Through an adequate choice of the initial output of the switching matrix a positive voltage is applied to the link resulting in the generation of the first resonant pulse. When the resonant current i_s returns to zero, one or two switches of the three phase bridge are turned off. During this interval the bias current I_d flows into C_0 causing a linear discharge of this voltage resulting in the application of a controllable dV/dt over the switches. When an adequate positive voltage (V_{swt}) is observed over the switches they are triggered and a new pulse is generated. This positive bias voltage over the devices increases the system stability insuring that the resonant pulses reach zero in each cycle and the application of a negative voltage over the devices equals to V_{swt} at turn-off. It can be observed that no special operating mode or circuit is needed during start up, since from the instant of the first resonant pulse, the system is already in the charging mode.

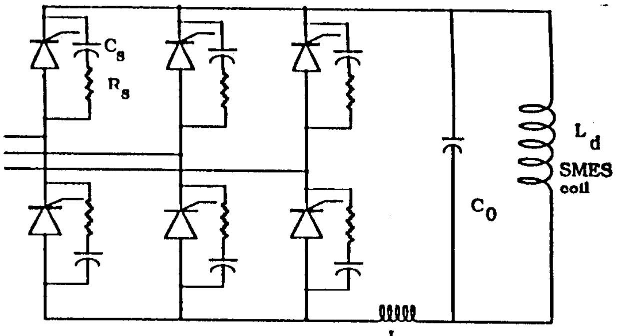


Fig. 2 Series resonant dc link converter utilized as a power conditioning system for a SMES

The resonant current and resonant capacitor voltage can be expressed as

$$i_s(t) = I_d - I_d \cos \omega_0 t + \left(\frac{V_{swt}}{Z_0}\right) \sin \omega_0 t \qquad (1)$$

$$v_c(t) = (V_d) - I_d Z_0 \sin \omega_0 t - (V_{swt}) \cos \omega_0 t \qquad (2)$$

where

$$Z_0 = \sqrt{\frac{L_0}{C_0}}, \; \omega_0 = \frac{1}{\sqrt{L_0 C_0}}, \quad V_{swt} = V_d - V_{c0} \qquad (3)$$

V_d is the output voltage of the resonant converter and V_{c0} represents the initial voltage over the resonant capacitor at the beginning of the current pulse. On the interval between pulses the offset bias current I_d circulates through the resonant capacitor C_0 which discharges linearly from $V_d + V_{swt}$ to $V_d - V_{swt}$ during a time interval equal to

$$2\, t_p = 2 \frac{V_{swt}\, C_0}{I_d} \qquad (4)$$

The resonant period (T_r) can be defined as

$$T_r = T_0 + 2\, t_p \qquad (5)$$

where

$$T_0 = \frac{1}{f_0} = \frac{2\pi}{w_0} \qquad (6)$$

SYSTEM CONTROL

It can be observed that the average value of the resonant pulses is approximately equal to the value of the bias current I_d. If I_d becomes bigger than the average value of i_s, the resonant pulses will not reach the zero crossing point and an unstable operational condition would occur. Regulation of this bias current is then necessary. Through an adequate switching sequence, regulation of I_d at the desired level is obtained during the three operational modes.

The power control scheme utilizes two commands:

1) Real power command, which determines the value of I_d current to be maintained in the superconductive coil
2) Reactive power command, which determines the phase shift between the input current and input voltage

For the determination of the proper switching matrix

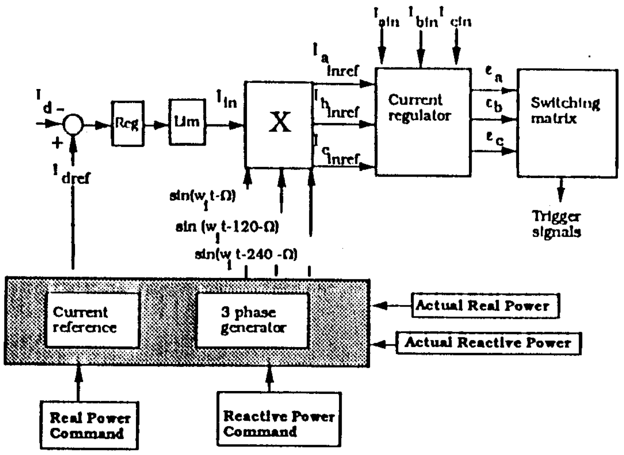


Fig. 3 Real and reactive power control in the SMES system

of the resonant converter the bias current I_d is initially compared with a reference current I_{dref}, which is determined from the real power command, which generates an error signal (ε). A proportional-integral regulator and a three phase sine multiplier are then utilized to produce current references for each phase which are at a certain angle (Ω) with respect to the input voltages determined by the reactive power command. The comparison of these three current references with the actual input currents through a sigma-delta modulator, generates three errors which are used to determine the phases to be triggered to generate the next resonant pulse. The sum of these three errors must satisfy the relation

$$\varepsilon_{ain} + \varepsilon_{bin} + \varepsilon_{cin} = 0. \tag{7}$$

which establishes the triggering principle based on the fact that the three errors can never have the same polarity. The triggering principle is then the following:

a) the thyristor in the phase having the larger error out of the two phases of the same polarity is chosen to be triggered

b) the phase corresponding to the error with the opposite polarity error is selected as the other triggering phase.

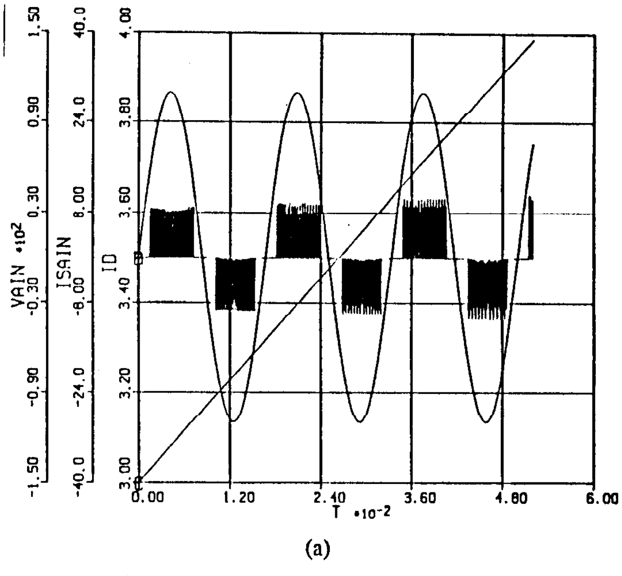
Actual values for the real and reactive powers are then compared with the real and reactive commands, generating errors which are utilized in an external compensation feedback loop with the purpose to correct the reference current I_d and the phase shift Ω to obtain the desired power levels.

The control of the fundamental input power factor is obtained through adequate distribution of the resonant pulses in the three phases (PDM). Regulation of the current I_d at the desired level in the SMES coil is guaranteed in the three operational modes through the application of the appropriate voltage to the resonant link. Consequently the real and reactive powers of the SMES are fully controlled. During the storing process the superconducting element should be shorted, which can be accomplished by turning-on two switches connected to the same phase. No extra switches are then necessary for this mode. The complete control diagram is shown in Figure 3.

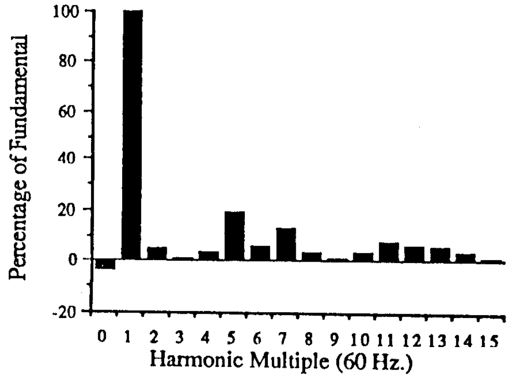
This control system represents a very flexible alternative for controlling a SMES system, since it can be adjusted to any requirements in terms of input power factor or input power. If a situation of maximum input power is desired during the charging process, the bias current reference (I_{dref}) would be set in its total final value. In this mode, the input phase selection would be determined by the most positive and negative phases in each instant. If an operational condition requires control of power factor and input power, idref should then slowly change during the charging process, determining the charging speed and consequently limiting i_d variation. The displacement angle (Ω) should then be zeroed in the control scheme.

If unity displacement power factor and low distortion factor without input power control is the desired feature for a SMES system, then a Geometric PDM control strategy can be utilized. In this simple open loop control structure, the pulses are distributed in each phase accordingly to the input voltage amplitude in a geometric way. This control strategy can be easily implemented, since no sigma-delta modulators or proportional-integral regulators are required.

Figure 4 and 5 show simulated results for the proposed system. Figure 4(a) shows the input current and voltage in phase *a* during the start up and charging process in the case of maximum input power requirement. Figure 5(a) shows the input current and voltage in phase "a" during the start up and charging process in the case of unity power factor requirement. Figures 4(b) and 5(b) present the spectral component for each case. Figure 5 shows the resonant

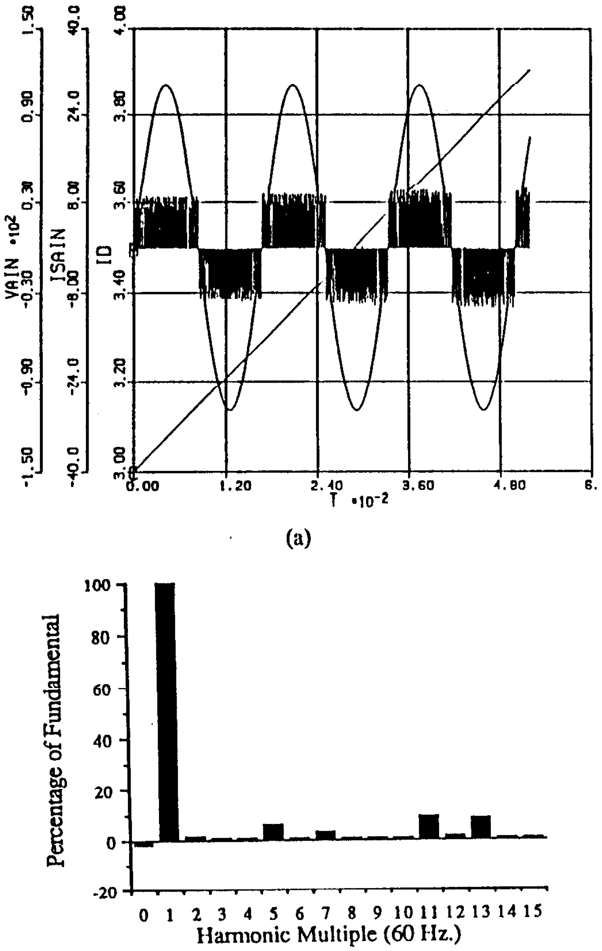


(a)



(b)

Fig. 4 Input voltage, current, charging current and spectrum of the input current for the maximum power control mode



(a)

(b)

Fig. 5 Input voltage, current, charging current and spectrum of the input current for the Geometric PDM control

current i_s and the charging current I_d during the storing process.

REDUCED SWITCHING FREQUENCY STRATEGY

With the objective of reducing the switching frequency when GTO's are utilized as the main switching devices in the resonant converter without altering the resonant frequency, an improved switching strategy can be utilized. When the end of the resonant pulse is reached the new switching requirement obtained from the control scheme is compared with respect to the previous one. If both switches are required to be turned on in the next pulse, only one switch is turned off and then back on in the beginning of the following pulse. If again both switches need to be on in the following pulse the device that did not suffer any commutation in the previous pulse is turned off and then back on. If two different switches needed to be utilized in the next pulse then both switches are turned-off . In this case the maximum switching frequency that a device could be subjected to is always half of the resonant frequency.

DESIGN METHODOLOGY

A complete design methodology and total loss calculation for a resonant dc current link system was presented in [7]. The same design methodology can be utilized for the resonant converter utilized as the conditioning system for the SMES element. Since L_d can be considered an lossless ideal element, the reduction of the initial voltage over the resonant capacitor at the beginning of each resonant pulse caused by the equivalent series resistance (ESR) of the bias inductor will not be present any more. Consequently no external exciters circuits or compensators are necessary for this purpose, even in high power applications, and a negative voltage naturally occurs across the switches at the end of the resonant pulse.

The same selection criteria for L_0 ,C_0 and V_{swt} ,as in [7] can be applied. Considering a resonant frequency of approximately 30kHz and a bias current of 15A resulting in

$$Z_0 = \frac{V_{swt}}{I_d} = 10 \tag{8}$$

$$V_{swt} \geq \left[\frac{I_d \, t_{rr}}{C_0} + \frac{2\sqrt{3}\pi}{f_r} \left(V_{inpk} \, f_i \right) \right] \frac{1}{K_r} = 35V \tag{9}$$

where K_r represents the resonant pulse peak reduction due to the ESR of the resonant inductor and t_{rr} the reverse recovery time of the switching device. The resonant elements can be chosen as

$$C_0 = 0.5\ \mu F \quad \text{and} \quad L_0 = 60\mu H$$

The peak resonant current and voltage over the resonant capacitor can be calculated utilizing the results in [7], resulting in

$$i_{speak} = I_d + \sqrt{I_d{}^2 + \left(\frac{V_{swt}}{Z_0}\right)^2} = 36.21A \tag{10}$$

$$v_{cpeak} = V_d + Z_0 \sqrt{I_d{}^2 + \left(\frac{V_{swt}}{Z_0}\right)^2} = 330V \tag{11}$$

$$\Delta v_{cmax} = 2\,V_d + 2\,Z_0 \sqrt{I_d{}^2 + \left(\frac{V_{swt}}{Z_0}\right)} = 660V \tag{12}$$

The reverse recovery time available is $t_p = 5\mu s$.

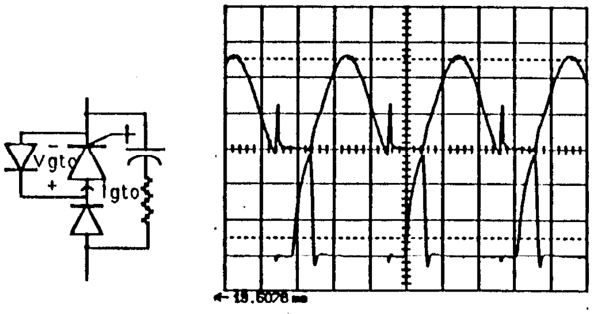
Device Selection

The dc current link resonant system requires the utilization of unidirectional current switches naturally commutated, since the current pulse drops naturally to zero due to the resonant scheme utilized. Since switching losses are extremely reduced, commutation delays, and most importantly turn off time, are parameters to be considered in the selection of the devices.

Initially GTO's in the gate assisted turn-off mode (GATT) were utilized as the main switches of the resonant converter. The utilization of the turn-off ability of the gate circuit (GATT), acting as an additional recovery mechanism, improves the commutation process efficiency and time, requiring the utilization of small snubbers.

In an attempt to improve the switching characteristics of a gate assisted turn-off GTO, a series and anti-parallel diodes were incorporated to the basic device in order to avoid the reverse and forward recovery processes reducing significantly the turn-off losses and time. Reverse voltage stress over the GTO's are reduced to practically zero in this structure.

Figure 6 shows the GTO being utilized in the gate assisted turn-off mode, employing a series and an anti-parallel diode. In the turn-on process a gate current consisting of a large front-porch and a continuous back-porch is required. An improved turn-on gate pulse, and a very small energy discharge of the snubber capacitor reduce the on time restriction of the device. Since controllable and reduced current slopes are a natural characteristic of the resonant current pulse reduced turn-on and turn-off times are obtained.



10A/div, 50v/div,10µs/div

Fig. 6 Current and voltage over the GTO in the resonant link converter

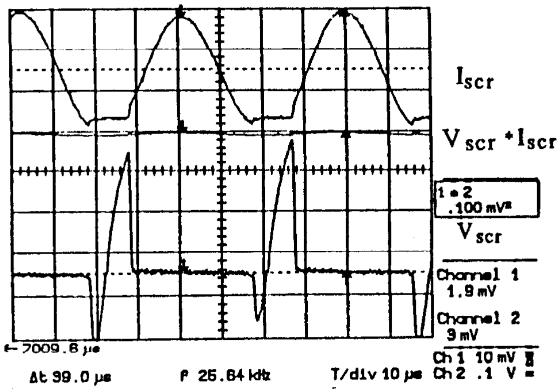
The fast-recovery diode and the anti-parallel diode in the GATT structure play an important role on the device turn-off process. The series diode reduces the reverse anode current and counterpolarization minimizing the GTO recovery process. In order to provide a path for the gate current to perform the depletion of the GTO central junction, reducing the forward recovery current, the anti-parallel diode is utilized. Turn-off losses due to reverse recovery and forward recovery losses are extremely reduced.

A perfect synchronization of the gate turn-off pulse with the current zero-crossing is of extreme importance in order to decrease the turn-off losses and turn-off time. After the anode voltage starts to rise during the turn off process a small anode current (tail current) is still maintained as carriers are removed from the central region of the device.

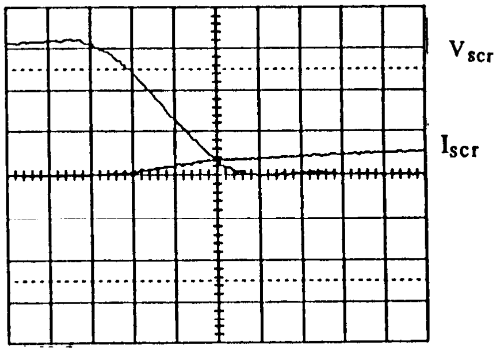
The dv/dt of the reapplied anode voltage is basically controlled by the resonant capacitor and the dc bias current level during the turn-off process. The reapplied voltage slope is very low, consequently not requiring snubber action for its limitation. The snubber circuit is only utilized with the purpose to produce an alternative discharge path for the reverse recovery current of the fast recovery series diode and a very small snubber resistor and capacitor are needed. Typical hard switching minimum off time (approximately 35µs) are reduced due to the zero current soft switching process to approximately 5 to 8%. Tail times are one of the most limiting factors for an increase in switching frequencies.

Switching frequencies of the order of 32kHz, for peak currents of 45 A were obtained utilizing this switching structure. Typical waveforms with turn-on and turn-off times are shown in Fig. 6. The total switching losses (considering turn-on, conduction and turn-off losses) for the GTO were 24W (considering a 6.40kW system). Turn-off times of 3 to 5 µs were measured .

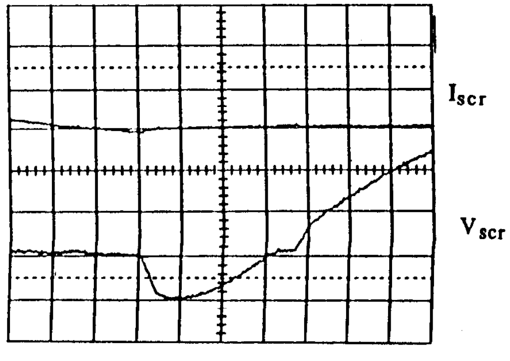
Since the resonant pulse drops naturally to zero with a controllable di/dt, SCR's would constitute a natural choice for the switching devices. Switching frequencies of the order of 27kHz, for peak currents of 45 A were obtained utilizing this switching structure. Current and voltage over the SCR during the charging mode and during turn-on and turn-off instants are shown in Fig. 7. Since switching losses were extremely small, as can be seen in Fig. 7(a) (the result of the multiplication of V_{scr} by I_{scr} is shown in the central line), they could not be accurately measured. The reduction in the switching losses is mainly due to a much faster turn-on process, reduction on the conduction losses and tail current.



(a)10A/div, 50V/div,10µs/div



(b) during turn-on, 10A/div, 50V/div, 0.2 µs/div



(c) during turn-off, 10A/div, 50V/div, 1 µs/div

Fig. 7 Current and voltage over the SCR in the resonant link converter

Turn-off times of 3 to 4 μs were observed for this operating condition. If a larger reverse recovery time is necessary at higher currents, Vswt could be increased accordingly. Consequently SCR's constitute the best and most simple alternative for the switches in the series resonant link converter and enables very high power ratings

EXPERIMENTAL RESULTS

A monophase and three-phase model were assembled, where different switch alternatives were investigated, as shown in Fig. 8(a) and (b). Fig. 9(a) shows the complete charging, storing and discharging process of a SMES element and Fig. 9(b) shows the dc current through the superconducting coil.

Figure 10 shows the three-phase system where maximum input power is required. A Motorola DSP56000 microprocessor is utilized as the controlling element for the SMES system. Driver circuits to be utilized with GTO's and SCR's at switching frequencies of 35kHz were developed for this specific application. For the resonant elements ceramic capacitors and litz wire wound inductors were utilized, in an effort to reduce ESR losses. The switching devices utilized in the experimental model are the following:

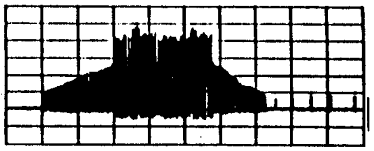
GTO:	IR 81RDT
Series diode:	IR R18CGF10A
Anti-parallel diode:	IR 40HFL100SO5
SCR:	IR 81RM80

Considering that the switching losses are dramatically reduced, the capacitor C_0 plays a minor role in the overall losses, L_d can be considered an ideal inductor the losses for the overall system consist of

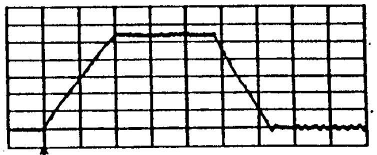
a) conduction losses which can be calculated as

$$P_{cond} = V_{on}\left[I_d T_0 + \frac{4}{\omega_0}\left(\frac{V_{swt}}{Z_0} - I_d\right)\right]\frac{1}{T_r} = 17.55 \text{ W} \qquad (13)$$

b) losses due to the snubber elements, which are very small considering that their function is only to provide a path for the discharge of the reverse recovery current of the SCR and at turn-on the di/dt of the resonant current is relatively small ($R_s = 100\Omega$, $C_s = 0.022\mu F$)



(a) Charging, storing and discharging process
10A/div, 5ms/div



(b) Current in the superconducting element
2A/div,5ms/div

Fig. 9 Charging, storing and discharging process of a SMES system

c) lossses due to the resistive element of the input ac capacitors

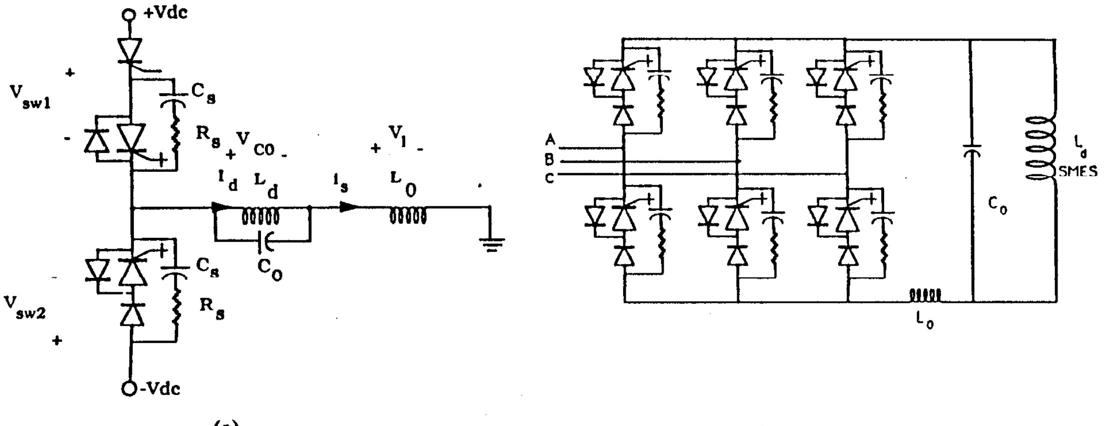
d) loss caused by the ESR element (R_{L0}) of the resonant inductor, which can be calculated as

$$P_{RL0} = \frac{R_{L0}}{2}\left[3I_d^2 + \frac{V_{swt}^2}{Z_0^2}\right]\frac{T_0}{T_r} = 175.51 \text{ W} \qquad (14)$$

The estimated efficiency of the overall three-phase system is approximately 95%.

CONCLUSION

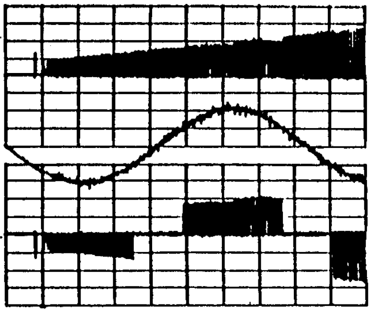
A series resonant dc current link converter to be utilized as a power conditioning rectifier in a SMES system is proposed. A control strategy allowing complete control of the input active and reactive power, and continuous adjustment of the input power factor is presented. Since the switches are commutated at zero current, extremely reduced switching losses, practically elimination of snubber losses,



(a)

(b)

Fig. 8 Experimental monophase and three-phase models



5A/div, 50V/div, 2ms/div

Fig. 10 Resonant current, input voltage and input current in the three-phase model utilizing maximum power mode control

improved harmonic content, bidirectional operation, high efficiency and the natural ability of shorting the storage element can be cited as advantages of the resonant converter in this application. Since the resonant current naturally decays to zero and a negative reverse voltage is present, SCR's constitute the ideal element to be utilized as the switching devices enabling very high power ratings. Resonant frequencies of 27kHz with current peaks of 45A, and efficiencies around 95% were obtained for the system.

The series resonant link is a very flexible structure. Figure 11(a) and (b) show the utilization of the resonant dc current link converter as a drive system for a dc machine. Figure 11(b) shows an improved link topology for this system. Research on these dc motor drive topologies are in progress and will be reported in a forthcoming paper.

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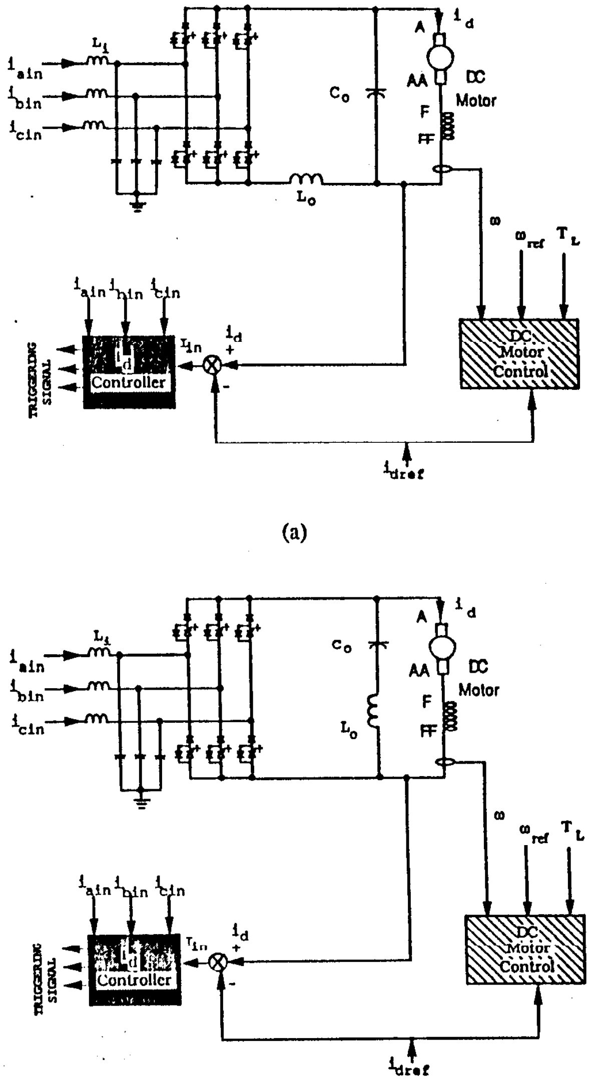

(a)

(b)

Fig. 11 Series resonant converter utilized as a drive system for dc machines