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Regenerative magnet load power supply with utility friendly operation

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ABSTRACT **-In the present paper, a utility friendly regenerative magnet load power supply has been proposed which can tolerate supply voltage dips and long duration sags or under voltages and maintains unity input power factor under all operating conditions. The harmonics injected into the utility are very less and the total harmonic distortion (THD) complies with IEEE standards. Unity power factor at the input is maintained by using a synchronous link onverter (SLC) as the front-end ac to dc converter with regenerative capability. The two-quadrant chopper in the second stage operates in a constant frequency current control mode and takes care of the load current ripple. The performance evaluation of the magnet load power supply has been made using SABER simulator. A laboratory prototype has been fabricated and tested successfully. The real time control algorithm has been implemented using a PC with PCL-207 data acquisition card.**

I. INTRODUCTION

In the recent days, power quality has become a major issue and it has become necessary to control the injection of harmonics from various loads.

A magnet load power supply is a special type of power supply used in Physics research and medical institutions for particle beam excitation and control [1,2,3]. Two essential requirements of magnet load power supply are (1) Low harmonic content in the magnet current and (2) Fast dynamic response [1,3]. The typical cycle of operation for load current of Magnet power supply is trapezoidal in nature. It consists of two steady levels, a ramp up and a ramp-down period as shown in Fig. 1.

Additionally, with the increased use of high power inductive loads, it is very common to have voltage dips and long duration voltage sags in the absence of correcting measures. This necessitates the development of power supplies, which are able to sustain under voltages and take sinusoidal unity power factor current from the utility.

Phase controlled rectifiers are most often used ac-dc converters for controlling the power delivered to the magnet load [4, 5]. This topology results in high harmonic content in the current drawn from the utility in addition to voltage and current ripples in the converter output. To reduce the large harmonic content in the output voltage and current, passive filters are used which becomes bulky and make the system response slow. So as to overcome this problem, active filters are added to achieve faster dynamic response. In [2] a bank of transistors operating in linear region was used to realize an active filter. The efficiency was low due to operation in linear region.

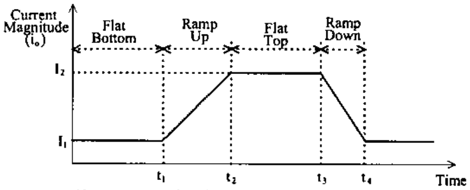

Fig. 1. Typical cycle of magnet load

Rong Liang and Shashi Diwan [6] replaced the linear regulator with switch mode ripple regulator (SMRR). A passive filter and a series active filter follow the phase-controlled rectifier. SMRR is a simple two-quadrant chopper connected in series and the main function is to cancel the harmonics of low order.

Due to the availability of high power switching devices, switch mode power supplies operating at high switching frequencies are designed [7]. But due to the limited switching capabilities the operation is limited to low and medium power range only.

For achieving large rating with high performance, a hybrid structure consisting of a phase-controlled rectifier in series with a high frequency PWM converter is proposed [3-5]. The main

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drawbacks of this system are the control of proper power sharing. As the PWM converter is fast in response compared to the phase controlled rectifier, the PWM converter supplies the major part during transient condition and this should be avoided with proper control.

The major problem encountered in series converter is that the switches need to carry the full current. Although this can be eliminated by connecting the PWM converter (active filter) in parallel to the phase controlled rectifier [5], the dynamic response suffers with this connection.

In all these power supplies, no care is taken to keep the power factor high and to reduce the harmonics that are injected into the utility. To shape the input current waveform and to reduce the supply current harmonics, a two-stage topology [8] is proposed for low and medium power applications. The drawback of this system is the inability to regeneration. The inductor-stored energy is wasted in the load resistance during load current ramp-down period.

Energy can be saved by feeding the inductor stored energy back to the source during the load current ramp-down period which improves the efficiency.

In view of the above aspects a new two stage topology is proposed with synchronous link converter as the front end converter and two quadrant chopper as the second stage. The SLC makes the input current sinusoidal with unity power factor, and the two quadrant chopper takes care of the load current ripple and makes the system dynamic response fast. As the system can operate in two quadrants, the inductor energy can be fed back to the source during the load current ramp-down period.

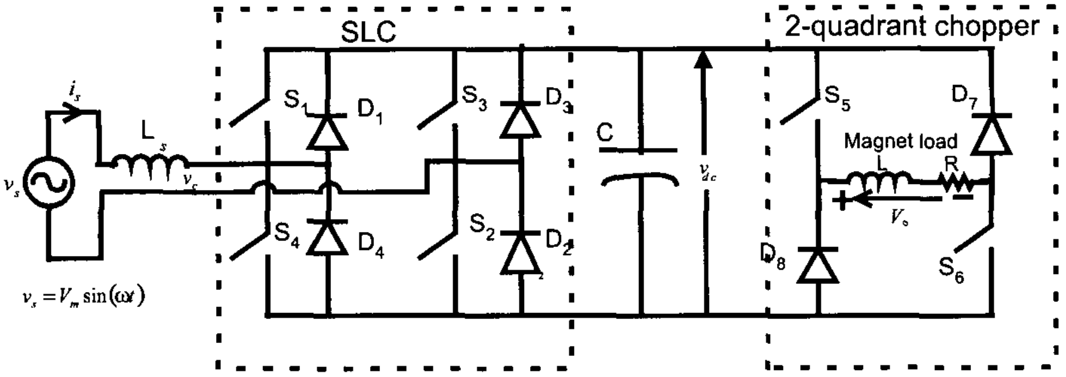


Fig. 2. Proposed magnet load power supply

This paper presents the development of a utility friendly regenerative magnet load power supply. The proposed system is simulated using SABER simulator and the results are verified using a laboratory proto-type model.

II. SYSTEM CONFIGURATION AND OPERATION

The power circuit of the proposed regenerative magnet load power supply is shown in Fig.2. All the protection circuits are omitted for simplicity. The system consists of a synchronous link converter (SLC), a two quadrant chopper and magnet load. The two-quadrant chopper operates at 20kHz and takes care of the load current ripple. SLC takes care of the source current ripple and maintains unity power factor under all conditions.

During load current ramp-down period, the chopper operates in regenerative mode and pumps the inductor-stored energy into the dc link. With the result the dc link voltage exceeds the reference value and the SLC starts working in the regenerative mode feeding the energy to the utility.

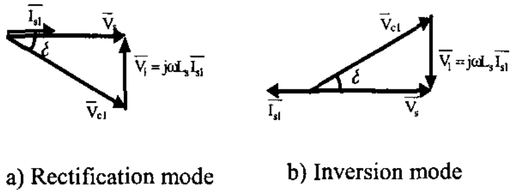
In the first stage, the switches S_1, S_2, S_3 and S_4 are self-commutating switches such as IGBTs. This circuit resembles that of a voltage source inverter. When the switches are operated with a known pulse width modulation technique, the converter produces a voltage v_c at the converter-input terminal [9]. If the dc link voltage is maintained constant, the magnitude of v_c can be varied by adjusting the modulation index of the converter. The phase of the converter input voltage v_c with reference to supply voltage v_s can be altered by changing the phase of switching pulses with respect to v_s.

Let I_{s1} be the fundamental component of source current phasor and V_{c1} be the fundamental component of v_c, under UPF condition. It is assumed that the source voltage v_s, is sinusoidal without any harmonics. Fig. 3 shows the phasor diagram taking $\overline{V}_s$ as the reference.

$$\overline{V}_s = \overline{V}_{cl} + \overline{V}_l \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

$$\overline{V}_l = j\omega L_s \overline{I}_{sl} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Real power transferred to from the source to converter, $P = V_s I_{sl}$



a) Rectification mode b) Inversion mode

Fig. 3. Phasor diagrams of synchronous link converter

From the phasor diagram

$$I_{sl} X_s = V_l = V_{cl} \sin\delta \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

$$V_s = V_{cl} \cos\delta \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

$$P = \frac{V_s V_{cl} \sin\delta}{X_s} \ldots\ldots\ldots\ldots\ldots(5)$$

From this we can see that for a given supply voltage V_s and a chosen value of L_s one can obtain the magnitude and phase of the converter input V_{cl} for unity power factor operation (UPF).

The phasor diagram for UPF operation under forward and reverse power flows are shown in Fig. 3.

In SLC, it is required to regulate the dc link voltage for matching the input power to the converter with the power demand from the dc link. The converter is operated at UPF for either direction of power flow.

In indirect current control scheme, the ac input is indirectly controlled by a suitable PWM, which modulates the fundamental component of voltage at the converter-input terminals.

The second stage is a two-quadrant chopper having two IGBT switches and two diodes as shown in Fig 4. When the switches are ON the DC link voltage (V_{dc}) is connected to the load and when the switches are OFF the diodes get forward biased and the load is connected to $-V_{dc}$.

III. CONTROL STRATEGY

The control block diagram of the proposed system is given in Fig. 4. SLC is controlled by

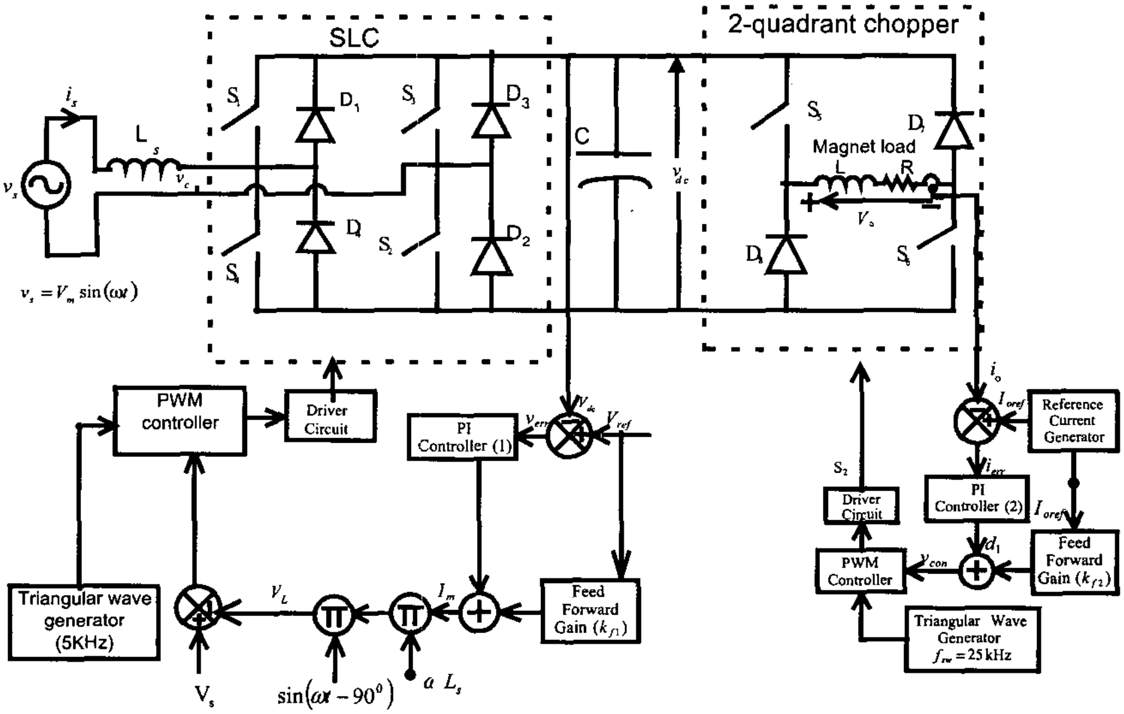


Fig. 4. Control block diagram of proposed magnet load power supply

indirect current control and the two quadrant chopper by constant frequency current controlled PWM control.

In the indirect current control scheme of SLC, the DC link voltage is compared with the reference voltage and the error is then passed through a PI controller which gives the peak of required source current.

The in phase and quadrature components of the current are resolved and the reference voltage for the converter is generated. The reference voltage is then compared with the triangular wave and the pulses are generated for the SLC.

The two-quadrant chopper is controlled by a current controlled PWM at constant switching frequency. It consists of feedback and feed forward loops. The feedback loop maintains the steady state accuracy and low current ripple whereas the feed-forward loop improves the transient response. The reference current is compared with actual current and the error is then passed through a PI controller. The signal is then compared with the constant frequency triangular wave and the pulses are generated for the chopper.

The two controls are independent of each other.

IV. SIMULATION AND EXPERIMENTAL REALIZATION

The complete system is simulated using SABER simulator and a laboratory proto type is developed in the laboratory. IGBTs are used for realizing the power switches.

The control circuit is realized partially with analog hardware and partly with digital computer Pentium-S operating at 200 MHz. A data acquisition card, PCL-207, has been used to interface the PC with the external hardware.

In the actual experimental set up, the SLC is controlled by a software program. The dc link voltage, which is to be maintained constant, is sensed using a Hall effect sensor and fed to the computer through the data acquisition card. The processing of error and the multiplication with the reactance (synchronous link inductor) is done inside the computer and sent to the external hardware through D/A channel. The signal is then filtered and multiplied with phase shifted sine wave using analog multiplier ICL8013 and added with the input signal to get the reference waveform. The two-quadrant chopper control circuit is realized by analog hardware. Adder, PI controller and comparator are realized with op amp TL081.

The following parameters are used in the experimental work:

Supply voltage	: 13 V, 50 Hz a.c Single Phase
Synchronous Link Inductor	: 12.7 mH
DC Link Capacitor	: 2200 uF
Load	: 30 mH, 0.1 Ohm
Switching Frequency of SLC	: 5 kHz
Switching Frequency of Chopper	: 20 kHz
DC Link Voltage	: 30 V

V. EXPERIMENTAL RESULTS

The magnet load power supply is implemented in the laboratory and the experimental results along with the corresponding simulation results are presented in this section. Fig. 5 presents the simulation and experimental results of the proposed magnet load power supply during ramp-up period. Fig. 6 gives the simulation and experimental results when the load current changes from higher value to lower value. Regeneration is observed in this period. Fig. 7 gives the results for the complete cycle of magnet load.

The dc link voltage and source current are shown in Fig. 8 for complete cycle. Fig. 9 gives the source voltage and source current waveforms under steady state.

Figs. 10-11 compare the harmonic spectrum of source current of the proposed magnet power supply with the source current when a diode bridge is used as the front end converter.

VI. CONCLUSION

A two stage converter topology using a Synchronous Link Converter as the first stage and a two quadrant chopper as the second stage is proposed for low and medium load magnet power supplies. The first stage takes care of the source current harmonics and maintains unity power factor at the input. The second stage converter meets the requirements of magnet load such as low ripple and fast dynamic response. As the complete system has regenerative ability, it returns energy to the utility during the load current ramp-down period. The proposed power supply can sustain voltage dips and long duration voltage sags or under voltage. Indirect current control is used for the Synchronous Link Converter while the dc-dc chopper employs current controlled PWM with constant switching frequency. Unity input power factor under all conditions and regenerative operation are the main merits of the proposed system.

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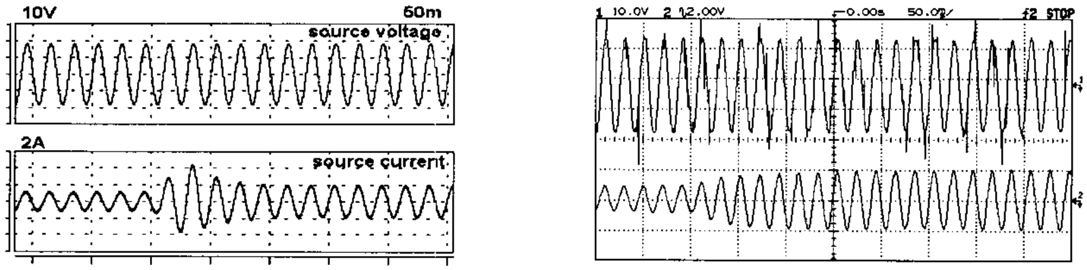
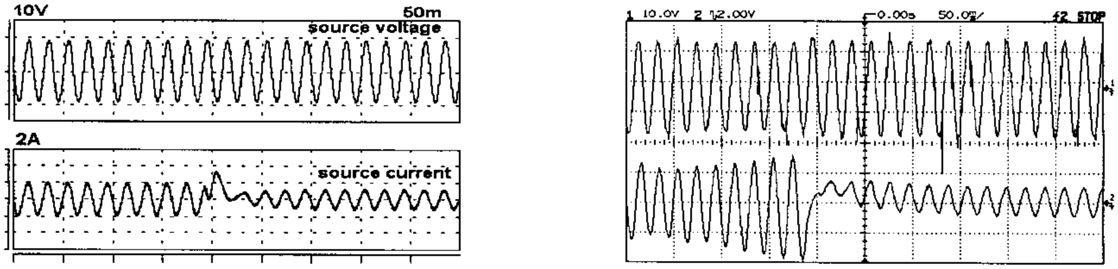


(a) Simulated waveform

(b) Experimental waveform

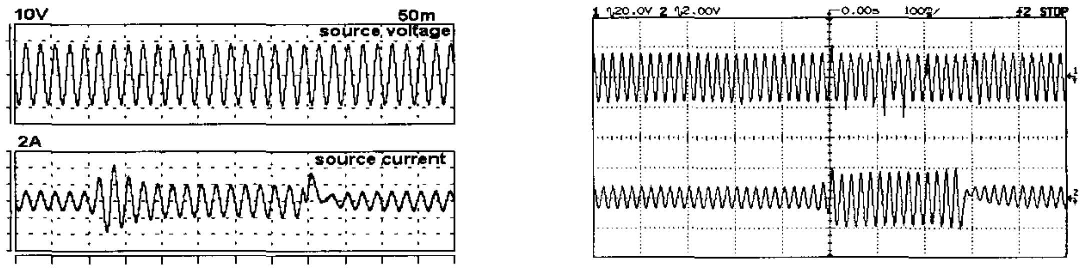
Fig. 5 Source voltage and source current during ramp-up period



(a) Simulated waveform

(b) Experimental waveform

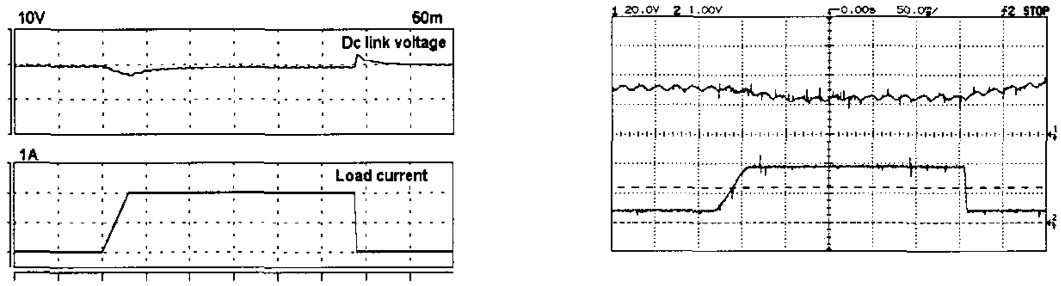
Fig. 6 Source voltage and source current during ramp-down period



(a) Simulated waveform

(b) Experimental waveform

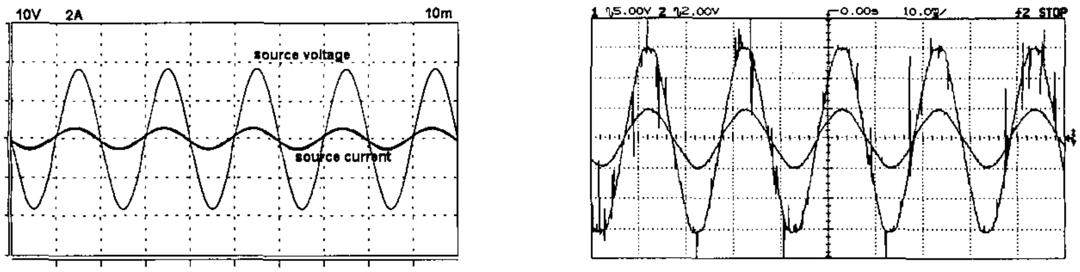
Fig. 7 Source voltage and source current over a complete cycle of magnet load



(a) Simulated waveform

(b) Experimental waveform

Fig. 8 DC link voltage and load current over a complete cycle of magnet load



(a) Simulated waveform

(b) Experimental waveform

Fig. 9. Source voltage and source current under steady state

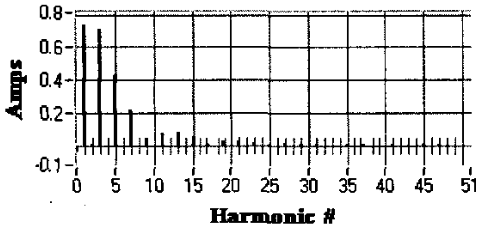


Fig. 10 Harmonic spectra of source current with diode-bridge as the front end converter

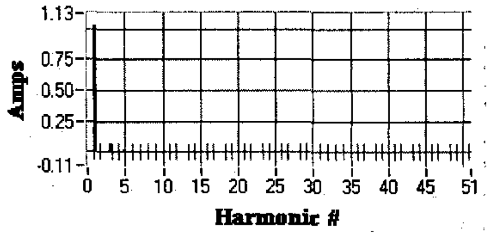


Fig. 11 Harmonic spectra of source current with the proposed magnet load power supply