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APPLICATION OF THREE-PHASE SERIES PARALLEL (SPRC) RESONANT CONVERTER FOR POWER QUALITY IMPROVEMENT

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ABSTRACT
In modern power systems, due to increase of non-linear loads, power quality has become a great concern. Non-linear loads, which were only 15% of total loads in 1987, have increased up to 60%-65% in 2006 and day-by-day it is still increasing. non-linear loads with power electronic interface that generate large harmonic current have been greatly increased in power system Next, the end-user equipments have become more sensitive to power quality than before. Harmonics in the distribution network have become an area of keen interest for utilities, power consumers and academic researchers due to its potentially disruptive impact on economy. This interest has lead to the development of large number technological solutions to meet the power quality specifications. In this paper, we discuss the power quality enhancement using power electronics equipment i.e. resonant converter in processing power.

KEY WORDS
Power quality, power electronics, resonant converter, digital signal processor; and zero voltage switching.

1. Introduction

In the recent years, power quality (PQ) has become a significant issue for both power suppliers and customers. There have been three important changes in relation to power quality. First of all, the characteristics of load have become so complex that the voltage and current of the power line connected with these loads are easy to be distorted. Non-linear loads with power electronic interface that generate large harmonic current have been greatly increased in power system and the end-user equipments have become more sensitive to power quality than before. Role of power electronics is rapidly increasing in all aspects of electric energy i.e., generation, transmission, distribution and end use. One of the major areas of growth in power electronics relates to the issue of Power Quality for Industrial and commercial customers. For increasing number of these customers, it is no longer an issue of buying a few un-interruptible power supplies (UPS) for control circuits. It is an issue that involves maintaining power for a variety of drives, processes, robotics and database systems. A voltage dip of a few cycles, a common occurrence in utility systems, can result in a considerable loss of production and business. However increasing number of customers needs front-end correction at feeder level, based on power electronics. This power electronics based technology offers a portfolio of products that combined with storage and stand by generators, enable value-added reliable power supply to industrial and commercial customers. The concept can be extended to serve industrial parks or even high tech cities. Regardless of the downstream or feeder-level Custom Power solutions, the distribution utilities serving the customers are invariably involved in finding the best solutions for their customers. Otherwise they stand to get a bad reputation and lose customers to competition. For most industrial and commercial customers, migration to the Custom Power concept of reliability, which accounts for voltage dips and not just long-term outage, is inevitable.

In the resonant converter, zero voltage switching (ZVS) and / or zero current switching (ZCS) makes the switching operation possible at high frequency, thus dynamic performance get improved. Also apart from sinusoidal power processing capability, resonant converter offers advantages like reduction in size, light-weight and utilization of non-idealities of the high frequency (HF) transformer, high conversion efficiency and low EMI generation. Thus, resonant converters are found to be more suitable for modern power electronic system.

Three phase converters are used for high power level. Also for the same power level, three phase resonant converter offers many advantages over single phase such as smaller size of high frequency transformer, better core utilization, higher power transfer for the same component stress level, better power conversion efficiency due to reduced inverter output current and very small filtering requirement owing to very high ripple frequency (six times the switching frequency) at the output. Out of many converter topologies of resonant converters, it has been shown with analytical as well as experimental support that series-parallel resonant converter (SPRC) is a strong candidate for high voltage dc-dc application as well as for ac input line power quality improvement [1]-[3]. It also has the lower inverter output current, lower voltage stress, low conduction loss and needs narrow variation in switching frequency for output voltage regulation. In single-phase resonant converter topologies, component stress increases with the increase in output power and this becomes its limitation in high power applications. Hence in this paper, power electronics for power quality using three-phase SPRC is proposed.

2. The System Set up

The system setup is depicted in Figure 1**.** It consists of three principal parts, namely 1. The computer and the DSP-TMS320LF2402 (EVMmaster & slave) card, 2**.** Interface card, 3. Power converter, 4. Separately excited dc motor. Generally speaking, the computer serves as the central control unit in motion control and signal processing. Commands are sent to the DSP-TMS320LF2402 card through the computer, which in turn sends the control signal out to drive the separately excited dc motor. Signal is converted from digital form to analog form before it can be used to drive the motor by a built-in Analog Interface Controller (AIC) chip on the EVM card. The bipolar driver then sends the analog signal to power converter to drive the motor. The input supply to the converter is single-phase ac, which is rectified using an uncontrolled diode bridge rectifier, followed by a small DC link capacitor C_{in} (i.e. high frequency by pass) connected to three phase series parallel resonant converter (SPRC). The dc output from SPRC is applied to the armature of separately excited dc motor. Three-phase converters are used for high power level. Also for same power level, three-phase resonant converter offers many advantages. Hence in this paper, power electronics for power quality using three-phase SPRC is proposed.

DSP-TMS320LF2402 is used for generating six gating pulses for three-phase resonant inverter. A variable frequency, symmetrical, 180º gating control scheme is used. Typical triggering pulses for the practical three-phase series-parallel resonant converter operating with gating pulse width lesser than 180^0 (Typical value of the gating pulse width is 150^0) is achieved with DSP-TMS320LF2402 as shown in fig.2. Performance of a three-phase SPRC fed dc drive system is evaluated with variable frequency control for controlling the output voltage of the resonant converter for maintaining the motor speed constant at different load torques.

The defining equations of the dc motor are

Field circuit equation; $V_e = R_e \cdot i_e + L_e \dfrac{di_e}{dt}$ (1)

Armature circuit equation; $V_a = V_o = R_a \cdot i_a + L_a \dfrac{di_a}{dt} + e_a$ (2)

Mechanical system equation; $T_d = J\dfrac{d\omega}{dt} + B\omega + T_L$ (3)

per phase equivalent circuit model of three phase series parallel resonant converter (SPRC) feeding motor load obtained, all the components on the secondary side of the HF transformer are referred to its primary. The per phase ac equivalent impedance Z_{ac} replaces the three phase HF transformer, three phase diode bridge rectifier along with its *LC* filter and motor load (*R-L-E*). Output voltage of three-phase H.F. rectifier,

$$V_o = \frac{3\sqrt{3}}{\pi} V_m \tag{4}$$

where, V_m is the peak value of the input phase voltage to the three-phase diode bridge H.F.rectifier.

Voltage input to the motor is

$$V_o - E_b = \frac{3\sqrt{3}\sqrt{2}}{\pi} V_{Zac} \tag{5}$$

Assuming rectifier circuit and the HF transformer losses are negligible, the power balance equation is as under;

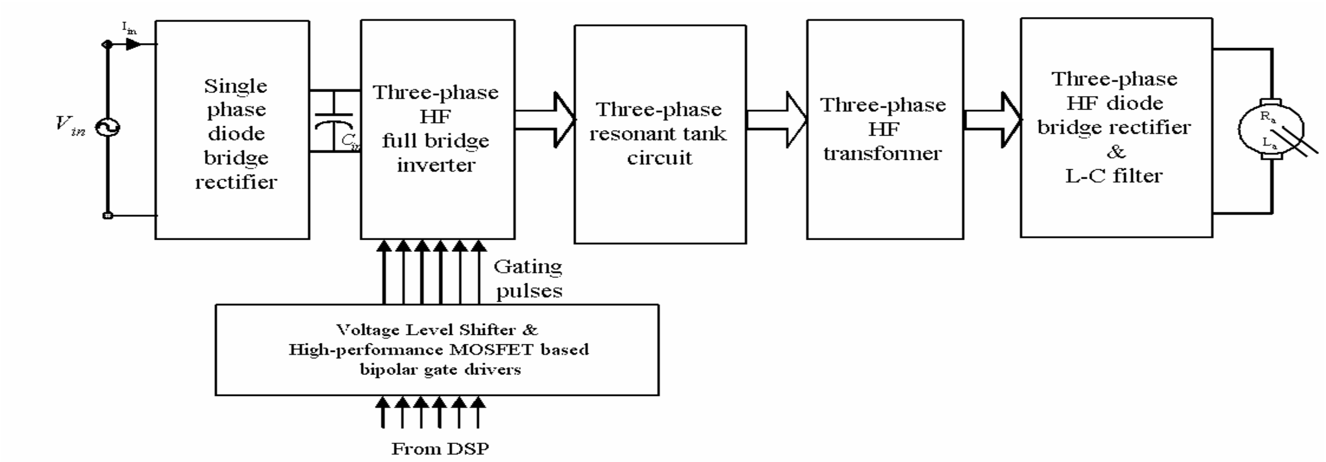


Figure 1. Block schematic of proposed AC-DC resonant converter fed dc motor

$$\frac{(V_o - E_b)^2}{Z_L} = \frac{3\left(\frac{\pi}{3\sqrt{6}}.V_o\right)^2}{Z_{ac}} \tag{6}$$

where, $Z_L = R_a$

$$Z_{ac} = \frac{\pi^2}{18}\frac{V_o^{\,2}}{(V_o - E_b)^2}R_a \tag{7}$$

The per phase equivalent impedance Z_{eq} calculated as follows

$$Z_{eq} = \left[(jX_{L1} - jX_{C1}) + \frac{-jX_{CP}Z_{ac}}{Z_{ac} - jX_{CP}}\right] \tag{8}$$

Thus, the current through the resonant tank circuit I_{L1} is

$$I_{L1} = \frac{4V_{dcin}\big/\sqrt{2}\pi}{Z_{eq}} = \frac{4V_{dcin}\big/\sqrt{2}\pi}{\left[(jX_{L1} - jX_{C1}) + \frac{-jX_{CP}Z_{ac}}{Z_{ac} - jX_{CP}}\right]} \tag{9}$$

$$I_{L1} = \frac{4V_{dcin}\big/\sqrt{2}\pi}{\left[(jX_{L1} - jX_{C1}) + \frac{-jX_{CP}\frac{\pi^2}{18}\frac{V_o^{\,2}}{(V_o - E_b)^2}R_a}{\frac{\pi^2}{18}\frac{V_o^{\,2}}{(V_o - E_b)^2}R_a - jX_{CP}}\right]} \tag{10}$$

3. Design of Resonant Converter

A resonant converter is designed for 2.5KW, 230V, and 1500-rpm dc motor. The converter is operated at 150 KHz switching frequency on full load condition to increase the power packing density. The proposed converter fed dc drive system operates in lagging power factor (pf) mode for the entire load range ensuring ZVS operation for all of the inverter switches.

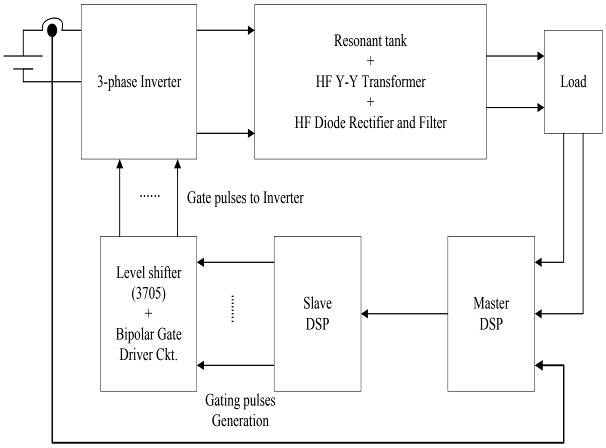


Figure 2. Block diagram of control scheme of proposed converter

The converter specifications are as follows:

Input voltage: V_{in} = 230 V (RMS)
Supply frequency: f_{in} = 50 Hz
Output Voltage: V_O = 230 V
Output Power: P_O = 2500 W
Resonant frequency: f_r = 140 KHz
Minimum switching frequency : f_s = 150 KHz

Design of converter is based on sine wave approximation for the waveforms, in which only fundamental components are considered. This approximation is valid since the resonant tank circuit acts as a tuned low pass filter allowing only the fundamental frequency component of current to pass through the tank circuit.

The major design issues are choice of C_1/C_p ratio and selection of quality factor-*Q* of the resonant tank circuit. For C_1/C_p ratio greater than 1, the frequency variation required for output voltage regulation is large [5]. The peak current through the inverter switching devices does not decrease with the load current for smaller ratios of C_1/C_p. It is therefore necessary to choose compromised value of C_1/C_p to be equal to 1 . The KVA rating of the resonant tank circuit decreases as the quality factor-*Q* decreases for a given f_s/f_r ratio. This dictates the lower value choice for quality factor-*Q*. But it is observed that as the value of full load *Q* is increased, there is a decrease in the peak inverter output current with a larger decrease in load current. However, this decrease is small for the values of quality factor - *Q* greater than 4. Quality factor (*Q*) of the resonant tank circuit is $Q = \frac{\omega_r L_1}{Z_L'}$. Where, $\omega_r = \frac{1}{\sqrt{L_1\,C_1}}$ and Z_L' = Equivalent Load resistance referred to primary of the transformer. Considering the limitations, following compromised design values [5]-[6] are chosen for capacitor ratio C_1/C_p and full load quality factor Q, as $C_1/C_p = 1$ and $Q = 4$. At full load condition the converter operated with switching frequency (f_s) of 150 KHz. For this condition component value of resonant tank circuit are calculated as below:

L_1 =106.66 µH, C_1 = 0.0121µf, C_p = 0.0121µf, $C_{p'} = n_t^2\, C_p$ = 0.0133µf

Where, n_t is turn ratio of HF Transformer primary to secondary.

The PID (Proportional, Integral, plus Derivative action) controller is very widely used by industry. Its popularity stems from the fact that the control engineer essentially only has to determine the best settings for the Proportional, Integral, and Derivative action terms needed to achieve a desired closed-loop performance[4].

The PID controller is usually implemented using following Equation

$$u_c = k_p[e(t) + \frac{1}{\tau_i}\int_0^t e(t)dt + \tau_d \frac{de(t)}{dt}] \qquad (11)$$

$$e(t) = yr(t) - y(t)$$

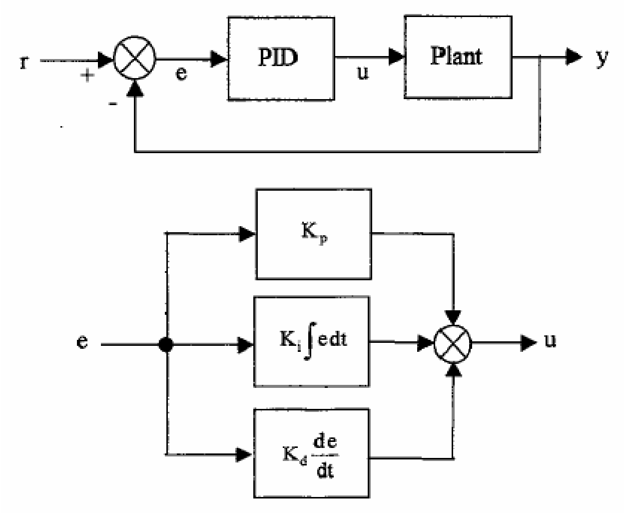
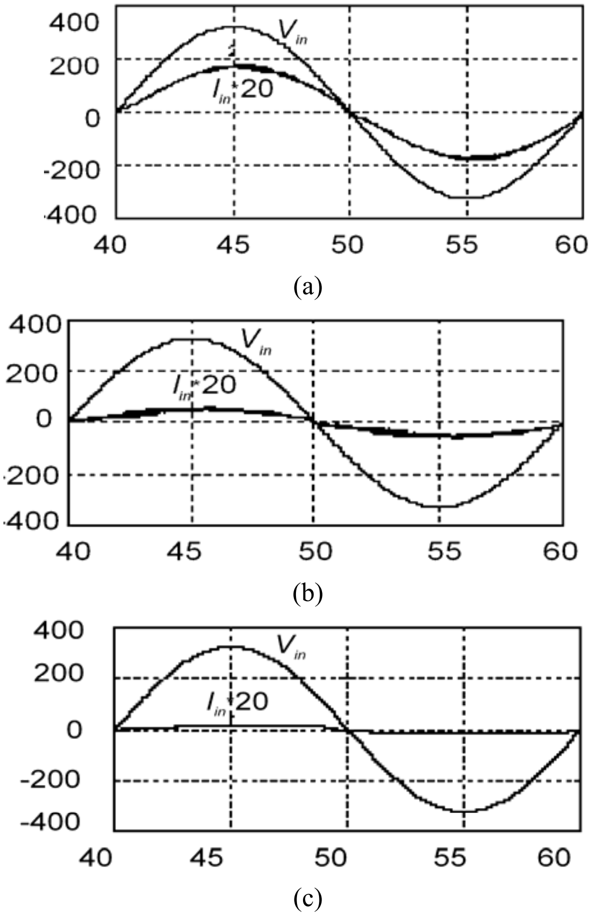


Figure 3. The PID Controller

Master DSP is used to realize the output voltage regulation and overload protection function under closed loop operation, while the slave DSP does the critical function of generating gating pulse pattern for HF inverter. Changing the content of the T1PR register can vary switching frequency.

4. Simulation and Experimental Results

The converter designed in section 3 is simulated using PSIM. The behavior of the converter feeding motor load is studied at different load conditions. Fig. 4 & Fig. 5 shows the simulation and experimental results at full load, 50% of full load and 25% of full load conditions respectively. It seems from the results that input line current maintains very high power factor, the converter operates in ZVS mode at all loads.



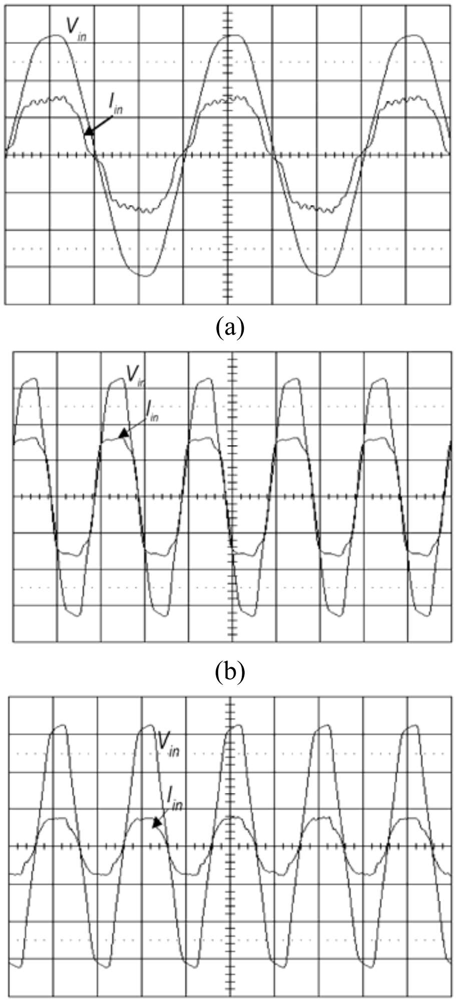
(a)

(b)

(c)

Figure 4 Simulation results for the converter input voltage (V_{in}) and input line current (I_{in}) (a) at full load condition (b) at 50% load condition (c) at 25% load condition

The resonant tank inductor L_1 of 107.23 µH is wound on P-43x30 ferrite core with 18 turns. The HF transformer built on E55x28x20 core sections, made up of N87ferrite material[8]. Fig.6, show the experimental performance of the converter at various load conditions. It is seen from Fig.6, waveforms for input voltage and input line current that maintains very high power factor through out the entire loading conditions with very low input current THD (3.1% at full load, 3.8% at 50% of full load and 7.2% at 25% of full load). Fig.6 shows waveform for phase voltage and phase current for three phase HF inverter revels that the converter operates in ZVS mode at all loads, eliminating the turn on losses.



(a)

(b)

(c)

Figure 5. Experimental waveforms for input voltage and input line current for the converter, Voltage Scale: 100V/division
(a) Full load - current scale: 20A/division : time 5ms/div
(b) 50% load - current scale: 10A/division : time 10ms/div
(c) 25% load - current scale: 10A/division : time 10 ms/div

The converter designed, is fabricated for verifying its performance, Three-phase IGBT bridge module BSM25GD120DN2 (EUPEC make),HF diodes DESI 60-12A, L_1=107.23µH, C_1=0.01μf, C_p = 0.01μf, L_F = 4.07µH. The control scheme is implemented using digital signal processor (DSP) TMS320LF2402.Variable frequency control is used for controlling the output voltage of the resonant converter for maintaining the motor speed constant at different load conditions. The overall experimental performance of the ac-to-dc converter using three-phase SPRC feeding dc-motor drive under variable load condition for variable frequency control is given in Table 1.

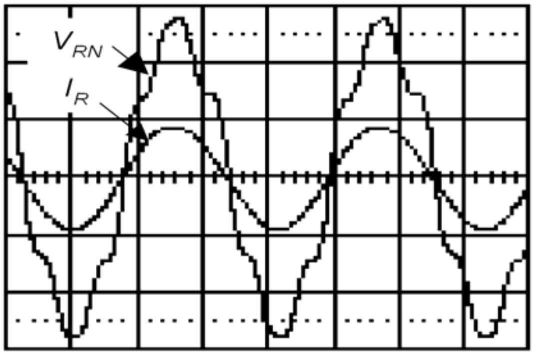


Figure 6. Experimental waveforms for phase voltage and phase current for three phase HF inverter at full load Scales: time 2 µs /division, voltage: 100V/division, current: 20A/division

Table 1
The overall experimental performance of the ac-to-dc converter fed drive

Parameter	Full load	50% Load	25% Load
Power Factor	1.00	1.00	0.99
THD (%)	3.1	3.8	7.2
Efficiency (%)	91.5	94.8	85

5. Conclusion

In present scenario, there is a need to enhance performance of existing dc drives in many industrial applications including machine tool drive, paper mills, waste water treatment and steel plants. The conventional dc motor drive continues to take considerable share of the variable speed drive market.

A three-phase series parallel (SPRC) resonant converter is a popular choice for medium to high power levels variable speed dc-motor drives, due to the improved power quality converter, the input power factor unity over a wide operating speed range. This drive system is most appropriate solution to preserve the present separately excited dc-motors in industry compared with use of variable frequency ac drive technology.

Application of this converter in dc drive has been investigated in this paper. Design of three phase SPRC that inherently operates at very high power factor with low THD has been outlined load as a separately excited dc-motor is modeled using dynamic equation. Simulations have been carried out using PSIM for variable torque condition of dc motor to investigate the control to output characteristic of three phase SPRC.

References

[1] R.L.Steigerwald, A Comparison of Half-Bridge Resonant Converter Topologies, *IEEE Transactions on Power Electronics, 3(.2)* 1988., 174-182.

[2] M.K.Kazimierczuk and D.Czarkowski, *Resonant Power Converters*, (John Wiley & Sons, Inc, New York: 1995).

[3] H.M.Suryawanshi, S. S. Tanavade, and M.R. Ramteke, Design and dynamic performance of modified series-parallel resonant converter, *EPE journal*, 15(2), 2005, 10-18.

[4] H.M.Suryawanshi, K.LThakre, S.G.Tarnekar, D.P Kothari, and A.G.Kothari, Power factor improvement and closed loop control of an ac-to-dc resonant converter, *IEE Proc.- Electric Power Applications*, *149 (2),* 2002,101-110.

[5] A.K.S. Bhat and R.L Zheng, A three-phase series-parallel resonant converter- Analysis, Design, Simulation and Experimental results, *IEEE transactions on Industry applications, 32 (4),* 1996, 951-960.

[6] R.W. De Doncker, D.M. Divan,and M.H.Kheraluwala, A three-phase soft-switched high power density DC/DC converter for high power applications, *Conference Record of the 1988 IEEE Industry Applications Society Annual Meeting*, 1988, 796 – 805.

[7] V. Pickert, and, C. M. Johnson, Three-phase resonant converters: An overview, *IEE colloquium on update on new power electronic techniques*, 1997/091, 1997,2/1-2/5.

[8] Siemens Matsushita components data book, ‘*Ferrites and Accessories*’, 1999.