Power Quality Enhancement of Three-Phase Front-End Rectifier of UPS System Using Current Injection Technique

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***Summary*: Power Quality, in terms of power factor and harmonics, is greatly hampered by a three-phase rectifier used as a front-end ac-to-dc converter in many systems including a UPS. This paper presents the high power factor operation of the converter with reduced total harmonic distortion up to 4%. The power quality up gradation is due to high-frequency current injection, at the input of the front-end rectifier. A small filter is required at the output for filtering the high-frequency content. Sinusoidal PWM technique is used for controlling the output voltage. DSP is used for generating the desired gate pulses. The converter has high efficiency, low EMI emissions, high power packing density and suitable for UPS system. A Simulation and experimentation is carried out on a 3 kW converter and experimental results are in good agreement with simulation results.**

Key words:
High-frequency-current-injection, High-power-factor, Soft-transition, Power-factor-correction circuit

1. INTRODUCTION

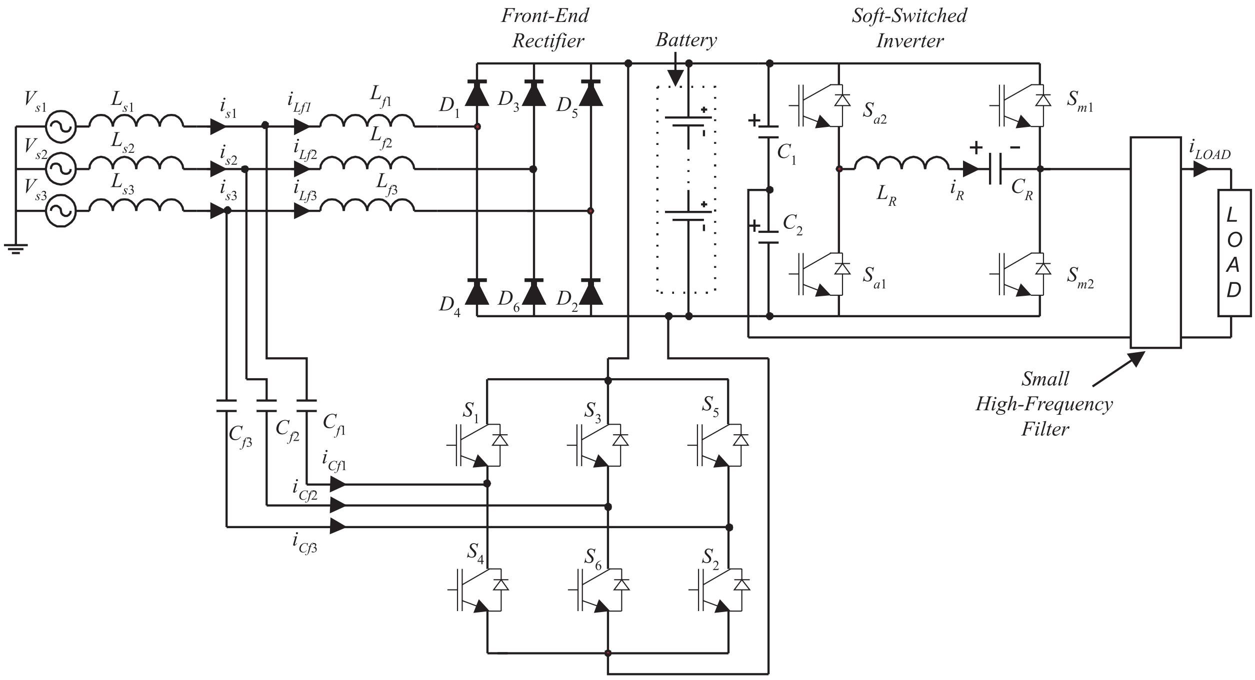
The increased use of power electronic equipments in the power system has a profound impact on power quality. The high power non linear loads (such as static power converter, arc furnace, adjustable speed drives etc) and low power loads (such as fax machine, computer, etc) produce voltage fluctuations, harmonic currents and an imbalance in network system which results into low power factor operation of the power system. There is a need of improved power factor and reduced harmonics content in input line currents as well as voltage regulation during power line over-voltage and under-voltage conditions. The uninterruptible power supplies (UPSs) have been extensively used for critical loads such as computers used for controlling important processes, some medical equipment, etc. The traditional UPS draws harmonic currents [1]. The uncontrolled diode bridge rectifier with capacitive filter is used as the basic block in many power electronic converters. Due to its non-linear nature, non-sinusoidal current is drawn from the utility and harmonics are injected into the utility lines. The total harmonic distortion (THD) factor increases to 70% [2]. The harmonics cause the malfunction of the equipments connected to the point of common coupling (PCC). They are not only responsible for increased losses but also cause excessive heating in the system [3]. Therefore regulations on line current harmonics have made power factor control, a basic requirement for power electronic equipments [4]. Several active power ac-to-dc converters are presented in [5–7]. Resonant converter based and high-frequency current injection methods for power-factor control are presented in [8–11]. Several soft-switching converters are presented in [12–16] In this paper, high power factor operation of ac-to-ac converter with zero voltage transition (ZVT) and zero current transition (ZCT) is presented. The ZCT reduces the switching losses in the system. The ZCT operation is accomplished by taking away the main device current prior to the switching transitions, by the resonant circuit. The proposed ac-to-ac converter is shown in Fig.1.It consists of three-phase input line bridge rectifier (D_1–D_6) with power factor correction (PFC) circuit, a half-bridge inverter with two main switches (S_{m1}–S_{m2}) and two auxiliary switches (S_{a1}–S_{a2}) and L_R–C_R resonant circuit. The PFC consists of three-phase bridge inverter (S_1–S_6) with feed back capacitors (C_{f1}–C_{f3}) and inductors (L_{f1}–L_{f3}). The L_{S1}–L_{S3} are the source inductors. The diodes of the rectifier, main and auxiliary switches of half-bridge inverter operate at ZVT and ZCT. The switches of three-phase inverter show ZVT, reducing switching losses considerably. Digital Signal Processor (DSP) TMS320F2812 is used for gating the inverters. The sinusoidal PWM is used for the output voltage control. Small low pass filter is used at the output to filter the high-frequency content in the voltage. Computer simulation and experimentation is carried out for 3 kW, operating at a switching frequency of 50 kHz.

2. OPERATION OF THE CONVERTER

The proposed ac-to-ac converter is shown in Figure 1. It mainly consists of PFC circuit and a soft-switched inverter for zero voltage and zero current transitions.

2.1 Operation of PFC Circuit

The PFC circuit consists of three phase inverter, capacitors C_f and switched inductors L_f The inverter is switched with high frequency The high-frequency (HF) current is injected at the input of three-phase diode bridge rectifier through capacitor C_f causing modulation of input voltage of the diode bridge rectifier. This forces the diodes of the three-phase bridge rectifier to turn-on and turn-off at the switching frequency over the complete cycle of the input supply voltage. In a switching cycle, the input current is the sum of average values of injected current i_{Cf1} and i_{Lf1}, as shown in Figure 2. Average value of i_{Cf1} over a switching cycle is zero and peak value of i_{Lf1} follows an envelope of the input supply phase voltage. In each switching cycle this current is reset to zero. Therefore average value of i_{Lf1} also follows the envelope of input voltage. When none of the diodes conducts then supply current flows through C_{f1}. Thus L_S operates in continuous conduction mode (CCM).therefore the input current is always in phase with the input supply phase voltage, v_{S1}. Hence the converter operates at high-power-factor. For



Fg. 1. A proposed ac-to-ac converter

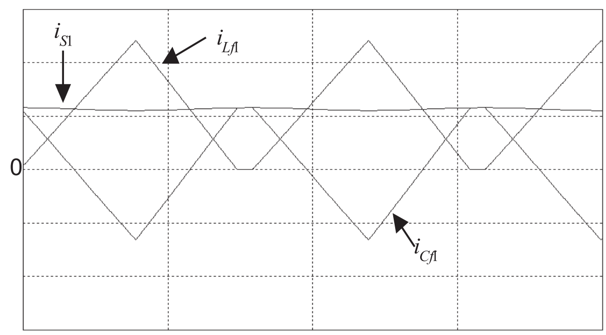


Fig. 2. Input current, capacitor current and inductor current. Scale: 5A/div, 20μs/div

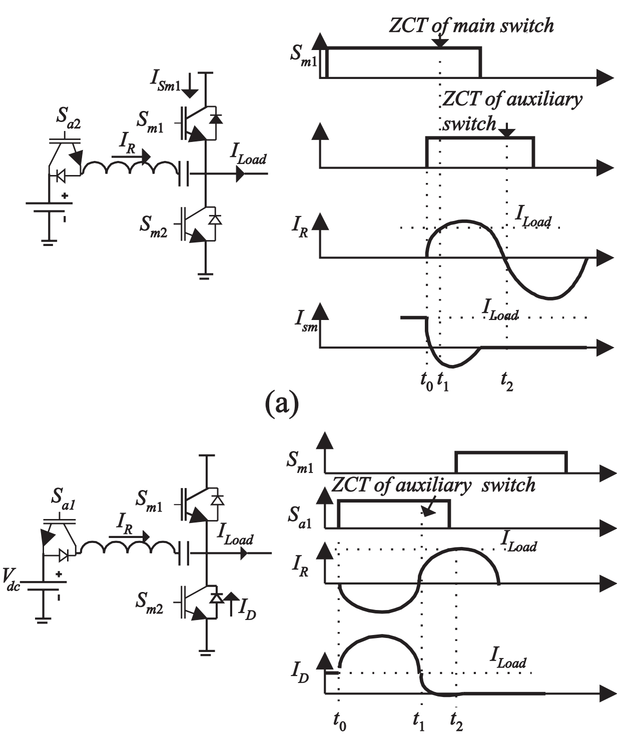


Fig. 3. Simplified circuit. a) Turn-off transition of S_{m1} b) Turn-on transition of S_{m1}

CCM the output voltage of the rectifier should be twice the peak value of input phase voltage (2).

2.2 ZV and ZC Transitions

A zero current transition (ZCT) and zero voltage transition (ZVT) are accomplished by a circuit consisting of a half-bridge inverter (S_{m1}-S_{m2}), two auxiliary switches and a resonant network (L_R-C_R) [16].The basic concept is explained by a simplified circuit shown in Fig. 3a and 3b., the auxiliary switches, (S_{a1}-S_{a2}) are switched alternately in a definite pattern (Fig. 4).To assist the top main switch S_{m1} for turn-off, an auxiliary switch S_{a2} is turned on. The L-C resonant circuit starts resonating and resonating current i_R starts to build up and the current in S_{m1} starts to decrease and i_R reaches I_{Load} at t_1. Thus the current in S_{m1} falls to zero and the body diode across S_{m1} starts to conduct surplus current. The gate driver signal can be removed at the zero current condition without causing turn off loss. The same concept is applicable for turn on transition also. As shown in Fig. 3(b), I_{Load} initially flows through body diode of S_{m2}. During turn on topological stage, the direction of S_{a1} is equivalently changed. Prior to turning on S_{m1}, S_{a1} is turned on for short duration. The current i_R starts to build up in negative direction and reverses its direction at t_1. The current through body diode of S_{m2} decreases due to increasing i_R in positive direction and surplus current passes through body diode of S_{m1} and it can be turned on at t_1. If S_{m1} is gated at this moment then zero voltage switching can be achieved. Moreover i_R flows through body diode of S_{a1}, at this moment the auxiliary switch S_{a1} can be turned off at zero-current. The same principle is also applicable to turn on and turn off of S_{m2}. Prior to turn on off S_{m2}, auxiliary switch S_{a2} is gated for short duration. Required gating pattern is generated using digital signal processor (DSP) TMS320F2812.The battery is charged from dc link voltage. Digital sinusoidal

PWM technique is used for output voltage wave shaping and magnitude control. A small output filter is used to filter HF content in the output voltage.

3. DESIGN PROCEDURE

3.1 PFC circuit

The total three phase input power is given by:

$$P_i = 3 \cdot \frac{1}{2\pi} \int_0^{2\pi} V_s \cdot I_s \cdot d(\omega t) \qquad (1)$$

The value of the switched inductor is given by [2]:

$$L_f = \frac{3}{4} \cdot \frac{V_m^2 \cdot d}{f_s \cdot P_i} \qquad (2)$$

If, P_0 is the output power of the converter, then:

$$L_f = \frac{3}{4} \cdot \frac{V_m^2 \cdot d \cdot \eta}{f_s \cdot P_0} \qquad (3)$$

where,
V_s — supply phase voltage
V_m — peak value of phase voltage
d — duty cycle of the inverter
η — efficiency of the converter
f_s — switching frequency

3.2 Soft-transition circuit

If V_{dc} is dc link voltage, I_{Load} is load current, Z_0 is resonant tank impedance, then:

$$I_{Rp} = \frac{V_{dc}}{Z_0}, \quad Z_0 = \sqrt{L_R / C_R} \qquad (4)$$

For the design of resonant components, a ratio M is defined as:

$$M = \frac{I_R}{I_{Load}}$$

Therefore from (4)

$$Z_0 = \frac{V_{dc}}{(M \cdot I_{Load})} \qquad (5)$$

M should be at least 1.1.

The resonant time period T_o is given by:

$$T_0 = 2\pi \sqrt{L_R C_R} \qquad (6)$$

From (5) and (6), the tank constants are as:

$$L_R = Z_0 \frac{T_0}{2\pi}, \quad C_R = \frac{L_R}{Z_0^2} \qquad (7)$$

Using procedure for design outlined above, the converter specifications and components values are as follows:
— Input: Three-phase, 400 V, 50 Hz
— Output: Single-phase, 220 V, 50 Hz, 3kW

Inverter switching frequency, f_S=50 kHz, Source inductors, L_S=5mH, Feedback inductors L_f=250 μH, Feedback capacitors, C_f=2μF, Split capacitors, C_1=C_2=1000 μF, Resonant components, L_R=20 μH, C_R=10 ηF.

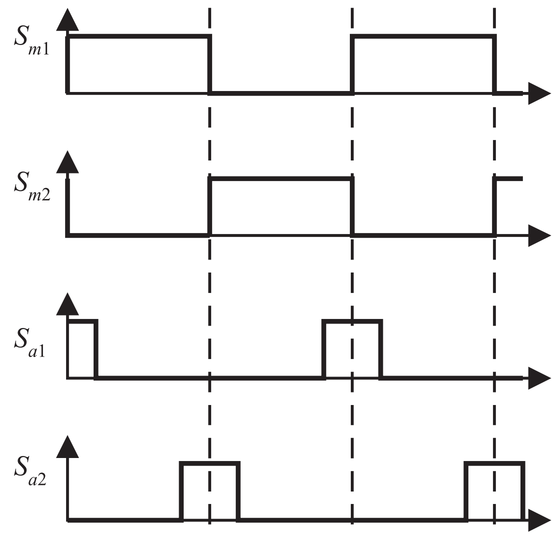


Fig. 4. Pulse pattern for turn-on and turn-off transitions

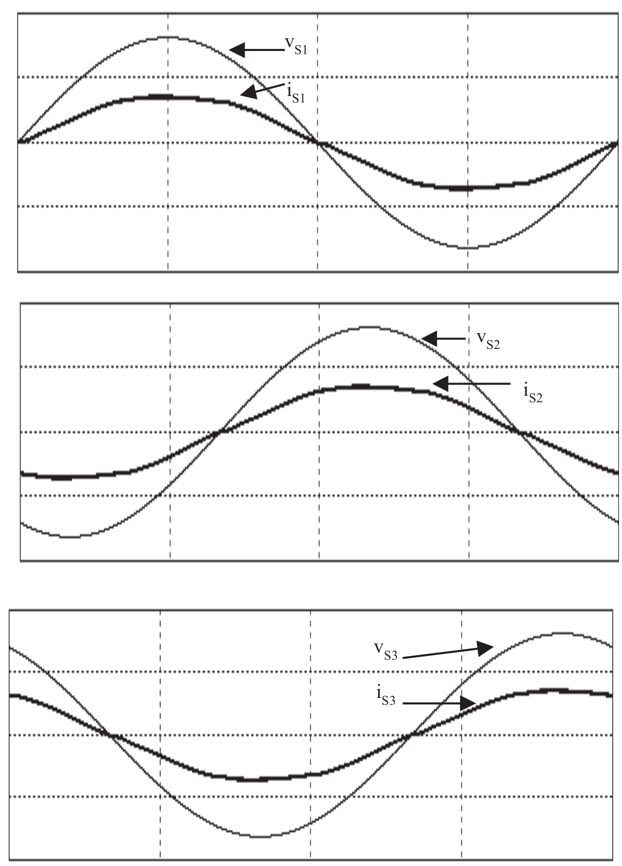


Fig. 5a. Simulated waveforms of supply voltage and current.Scale: 200 V/div, 10 A/div, 5 ms/div.

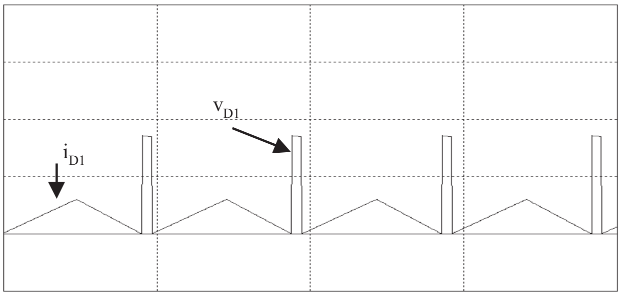


Fig. 5b. Simulated waveforms: Rectifier voltage and current. Scale: 200 V/div, 20 A/div, 20μs/div

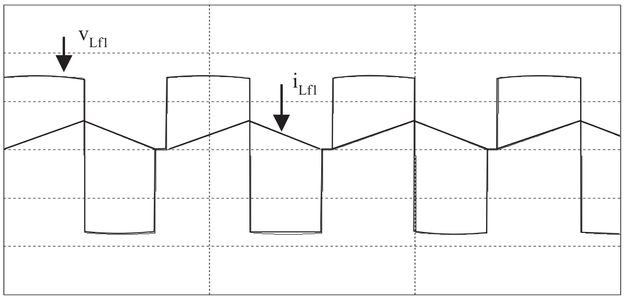


Fig. 5c. Simulated waveforms: Current through and voltage across inductor Lf. Scale: 20 A/div., 200 V/div

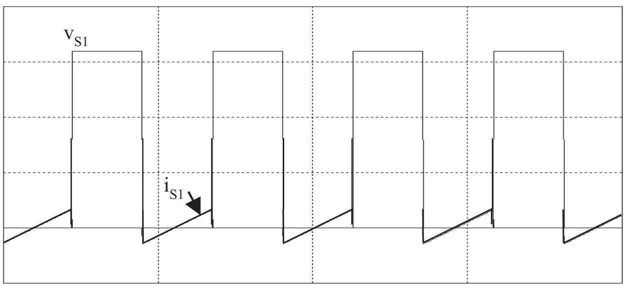


Fig. 5d. Simulated waveforms: Current through and voltage across inverter switch S1. Scale: 20 A/div., 200 V/div

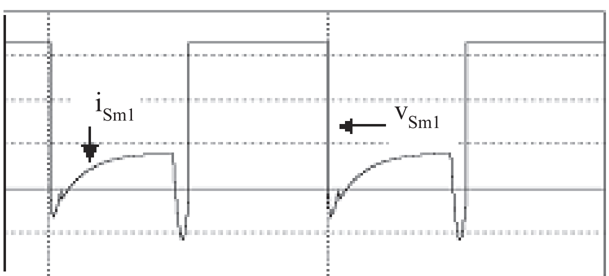


Fig. 5e. Simulated waveforms: Current through and voltage across main switch Sm1 of a half-bridge.Scale: 20 A/div., 200 V/div

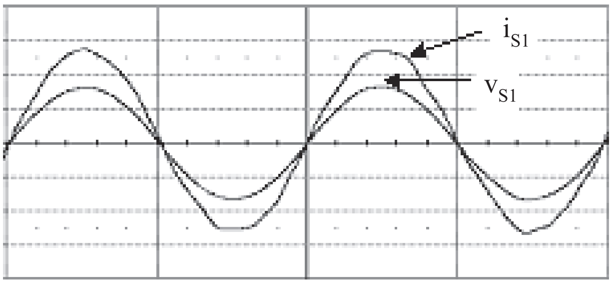


Fig. 5f. Experimental waveforms of supply voltage and current. Scale: 200 V/div, 2 A/div, 10 ms/div

4. RESULTS

The computer simulation of proposed converter designed as per the procedure in section III is carried out and simulation waveforms are shown in Fig. 5 (a)–(e). A laboratory prototype of 3 kW is designed and tested with a switching frequency of 50 kHz. Experimental waveform is depicted in Fig. 5 (f). The THD of supply current is found to be greatly improved and it is less than 4%.

5. CONCLUSION

A high-power-factor operation with soft-switching transition, three-phase ac-to-ac converter is proposed. The soft-switching of main and auxiliary switches are achievedthereby greatly reducing the switching losses and EMI emissions. The switches have lower stresses and can be used with high switching frequency. The proposed converter has many advantages such as high packing density, small filter requirement, high efficiency and high power factor. Better output voltage control is obtained with the flexible programming using DSP.

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