Design of an Active Power Factor Converter for UPS with Backup Proton Exchange Membrane Fuel Cell/Battery

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***Abstract*-- In this paper, a 300 W boost active power factor corrector (PFC) for single-phase high frequency uninterruptible power supply (UPS) with universal input and fixed output voltages is analysed and then designed for backup and emergency power applications. The UPS is supplied by a backup proton exchange membrane fuel cell (PEMFC) and battery hybrid power source, in addition to the main source. The principle and structure of the active PFC are introduced and discussed. Based on the idea of adopting mature technologies, key practical techniques of the design are presented, including the control technique of the active PFC and the design of the boost inductance, capacitances and external circuits. Experimental results show that the active PFC can achieve a fixed output voltage of ±380 VDC within a wide range of input voltage. It owns the advantages of high efficiency, high power factor as close to 1, and total harmonic distortion of less than 5%.**

***Index Terms*--Power factor correction (PFC); AC/DC converter; Proton Exchange Membrane Fuel Cell (PEMFC); Uninterruptible power supply (UPS); Backup and emergency Power applications**

I. Introduction

The high frequency uninterruptible power supply (UPS) systems have played a very important role for backup and emergency power applications, such as computers, medical/life support systems, communication systems, and industrial controls, in case of power failures. An ideal UPS should have the following features: regulated sinusoidal output voltage with low total harmonic distortion (THD) and independent from the changes in the input voltage or in the linear and nonlinear loads, on-line operation that means zero switching time from normal to backup mode and vice versa, low THD sinusoidal input current, unity power factor, high reliability, high efficiency, low electromagnetic interference (EMI) and acoustic noise, electric isolation, low maintenance, and low cost, weight and size [1]. Therefore, UPS systems that can keep the information and data from being destroyed have become very popular. Particularly, with the popularisation of personal computers and Internet, low capacity UPS products will take an increscent part in the industrial and domestic markets.

Most UPS systems are realised with load resonant DC/AC inverters and the traditional peak detection AC/DC converters, which commonly use the diode bridged rectifiers with large filters to achieve the input DC voltage source. The power factor (PF) is only 0.5-0.76, which causes much harmonic pollution to the electric power network. Furthermore, this circuit may cause a large and sharp input current when the input AC source voltage reaches its peak. The harmonics of the input current are harmful for the other electrical appliances. To handle this problem, the criterion of harmonics was amended by the Institute of Electrical Engineering, as in IEC 61 000-3-2 [2]. As the traditional rectifiers cannot meet the new criterion, new techniques like active PF corrector (PFC) have become strong research interest in the power supply industry. The active PFC rectifier based on a boost converter is one of the most popular single-phase topologies used in practice to fulfil the current standards on power factor and input current distortion of power supplies. For example, active PFC circuits using the boost converter configuration have been widely employed in the design of single-phase power supplies. Their advantages include wide work range of AC voltage, high voltage stability allowing the use of small capacitance to meet the need of holding time, PF improvement with a typical value of larger than 0.98, and reduction of the THD factor with a typical value of less than 5%. In large power equipments, three phase AC/DC converters with more complex topologies and controls are commonly used, as the harmonic pollution can be more serious [3]-[4].

In order to achieve low harmonic distortion of the input current, a current-mode control scheme such as average current-mode control (ACC) is generally used. From the control point of view, the main limitation of ACC-controlled PFC rectifiers is that the crossover frequency of the voltage loop is limited to be about 20 Hz in order to properly attenuate the contents of the second line harmonic at the control signals. Therefore, the response of the output voltage to load steps is generally slow. Several methods have been proposed to overcome this problem, such as the ripple compensation approach or the use of digital controllers allowing the implementation of notch filters.

Among the recently developed new-type control strategies of active PFC rectifier are the single-period control technology [5], the space vector modulation [6], the non-deviation beat control [7], the sliding mode varying-structure control [8], the control based on Lyapunov's non-linear large signal method [9], and the dq0 transform control [10]. Moreover, a single-stage power factor correction AC/DC converter based on zero voltage switching (ZVS) full bridge topology with two series-connected transformers was proposed [11]. The basis of these techniques is that, if the ripple at the frequency of the second line harmonic is removed from the control signals, the voltage loop gain crossover frequency can be increased, keeping low distortion of the input current. As a result, the dynamic response of the rectifier is faster. The drawback of these techniques is the need for relatively complex control circuits, which use additional multipliers/dividers, analog/digital circuits, digital controllers, etc.

A new concept, introducing an ACC scheme with load-current injection (LI^2ACC) applied to PFC rectifiers was proposed in [12]. The idea of LI^2ACC is to generate the steady state value of the inductance current reference by means of an additional load-current control loop. By means of the load-current injection, the slow dynamic response of the voltage loop is not an obstacle for fast response of the output voltage to load steps.

Many companies, such as Unitrode, Motorola, Silicon and Genezal Siemens, have produced different kinds of specific chips for the active PFC including UC3852, UC3854, MC34261, ML4812, ML4819, TDA4814, TDA4815, CS3810, etc. Most of them have already been used in small power switch-mode power supply (SMPS), UPS, and other aspects. Among these products, the high power factor pre-regulator UC3854 has many advantages, and is widely used. It can make the input PF of AC/DC boost PWM converter be close to 1, restrict the input current's THD less than 5%, adopt the average current control and constant frequency control, and allow the frequency band of its current amplifier to be wide.

In this paper, a 300 W boost active PFC with universal input and fixed output voltages is analysed and then designed based on the idea of adopting mature technologies and using the high power factor pre-regulator UC3854. The developed active PFC has been applied in high frequency network UPS system with backup proton exchange membrane fuel cell (PEMFC)/battery hybrid power source. Experiment results show that the active PFC designed can achieve a fixed output voltage of ±380 VDC within the universal input voltage range of 160-275 VAC. If the main supply voltage is lower than 160 V, the UPS will be supplied by the backup PEMFC/battery hybrid power source. The active PFC has a full load efficiency of over 92% and a PF of over 0.98.

II. CONTROL SCHEME OF ACTIVE PFC

Fig. 1 illustrates schematically the structure of a single-phase high frequency 300 W UPS system with a backup 300 W PEMFC generating system and battery, which consists of AC/DC rectifier, AC/DC recharger, DC/AC inverter and DC/DC converter and their control subsystems. The UPS supplies the load with the required and uninterruptible AC power. The PEMFC stack operates on hydrogen and air. Because of the slow start-up of the PEMFC stack, which may take a few seconds, a small capacity battery is required for UPS applications. In the designed UPS system, in order to reduce the harmonics in the input current, a PFC circuit should be attached.

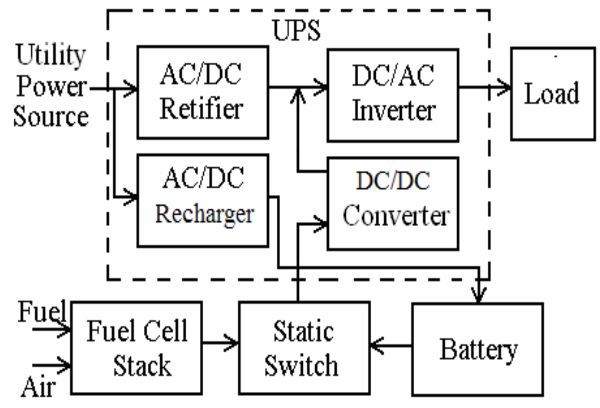


Fig. 1. UPS structure with backup PEMFC/battery

A. Circuit Topology and Working Pattern

Fig. 2 shows the single-phase high frequency active PFC AC/DC rectifier and its working pattern.

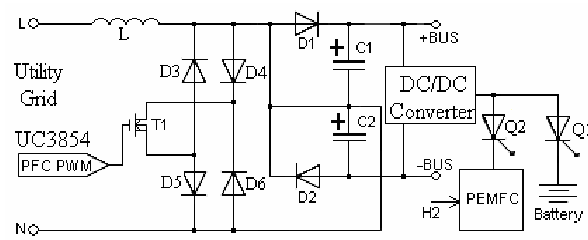


Fig. 2. Schematic diagram of an active PFC AC/DC rectifier

Under the state of main supply (160-275V), the silicon-controlled rectifier (SCR) Q_1 and Q_2 are switched off. The active PFC MOSFET T_1 is in the "off" state, and the positive and negative BUS voltages are built with filtering through the inductance L and capacitances C_1 and C_2. Because the inductance value is small here, the BUS output voltage can be estimated by:

$$U_{BUS} = \sqrt{2}U_{in} \tag{1}$$

where U_{in}.is the input voltage of the utility grid.

When the UPS operates, T_1 turns on or off, for chopping the wave. The positive and negative BUS voltages increase to the typical steady values of about ±380 VDC.

When T_1 is switched on, the current flows through the inductance in which magnetic energy is stored. As the capacitances have a DC voltage of about 340 V for the rated input AC voltage of 240 V, the diodes are cut off. While T_1 is switched off, the inductances charge the capacitances through the diodes, and release the stored magnetic field energy. Because the switching frequency of the active PFC IGBT is as high as 100 kHz, the changing rate of the current will be tremendous, which can bring out a high over-voltage (Ldi/dt) across the capacitances.

When the main supply voltage is less than 160 V, Q_1 is switched on at first and the battery works as the power supply of the UPS. At the same time, the PEMFC stack starts up. When the output voltage of the PEMFC stack reaches the rated value, Q_2 is switched on and Q_1 is switched off, and the PEMFC stack works as the power supply of the UPS system.

B. Control Techniques of the active PFC

Fig. 3 illustrates the schematic diagram of the boost active PFC controlled by UC3854 in a single-phase UPS system with backup PEMFC/battery hybrid power source, where CA is a current error amplifier, VA is a voltage error amplifier, and M is a multiplier [13]-[14]. With the action of the initiative switch (PFC MOSFET), it can modify input current to sine wave, which follows and changes with the input voltage (U_{in}), so it can achieve the goal of unity PF.

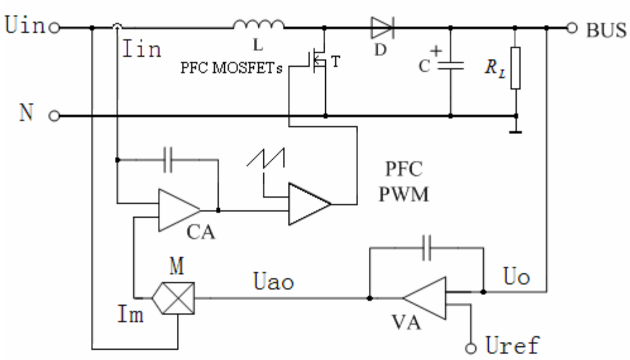


Fig. 3. Schematic principle diagram of Boost active PFC

The output signal I_m of analog multiplier M is the standard current, which can be calculated by

$$I_m = I_{AC}(V_{ao} - 1.5) / V_{rms}^2 \tag{2}$$

where I_{AC} is the multiplier's input current which is about 250 μA and comes from the input voltage U_{in}, V_{ao} is the output voltage of the voltage error amplifier, and V_{rms} is the feed-forward voltage which is about 1.50-4.77 V and is provided with the partition of the active PFC input voltage U_{in}.

III. DEVELOPMENT OF APFC AC/DC CONVERTER

The 300 W boost active PFC rectifier based on UC3854 adopts a fixed switching frequency, f=100 kHz, which is controlled by the average current mode. When the AC input voltage is 160-275 V, the DC output voltage U_{BUS} is ±380 V, and the maximal output power $P_{o,max}$ is 500 W.

A. Design of Boost Inductance

It is very important to design the boost inductance and choose its magnetic cores as they affect the characteristics, efficiency and functions of the correction circuits.

The magnetic core of the inductance is commonly a kind of soft magnetic material used for low magnetic field, requiring high permeability, low coercive force and high resistivity. Although many soft magnetic materials can be used as the cores, in the condition of high frequency, only three kinds of material are suitable for the active PFC inductances, including the ferrite magnetic core, the magnetic powder core, and the noncrystal material magnetic core. Each of them has its own merits and can be adopted to design the boost inductance.

For the ferrite magnetic core, the open air gap forms the vortex flow on its surface and causes the local temperature to increase. When the temperature exceeds the Curie point, the permeability of the core falls rapidly, causing damage of the PFC MOSFET. On the other hand, the noncrystal material magnetic core is expensive. Therefore, in this design, the boost inductances are manufactured by magnetic powder cores (FeSiAl), whose saturation flux density can reach around 1.0 T. Under the action of strong magnetic field, namely working in heavy current, the magnetic core would be saturated immediately.

The boost active PFC inductance does not need an open air gap, so it would not generate electromagnetic interference (EMI) to the circuit. Furthermore, the dynamic performances of DC excitation are very well, so the inductance value under the rated current can be accurately controlled by careful design. If the size of the magnetic core and the number of turns of excitation coils are properly chosen, the magnetic core loss will be small.

The critical inductance can be obtained by

$$L \geq \frac{\sqrt{2}U_{i(ac)\min} T_{on}}{\Delta I} = \frac{\sqrt{2}U_{i(ac)\min} T_{on}}{0.2 I_i} \tag{3}$$

$$T_{on} = \frac{U_o - \sqrt{2}U_{i(ac)\min}}{U_o f} \tag{4}$$

$$I_i = \sqrt{2}\,\frac{P_{o,\max}}{\eta U_{i(ac)\min}} \tag{5}$$

where $P_{o,max}$ is the maximum output power, $U_{i(ac)min}$ the minimum value of input AC voltage, η the efficiency, U_o the output DC voltage, and T the working period.

As an example, a boost inductance is designed with the following main parameters: $P_{o,max}$=500 W, U_o=400 V, η=95%, f=100 kHz and $U_{i(ac)min}$=90 V. According to (3), (4), and (5), the inductance L is computed as no less than 524 μH.

To determine the dimensions of magnetic core, the operational point of the magnetic circuit should be known. From the B (flux density) – H (field strength) curve of the material and the required excitation current in ampere-turns, the permeability of the magnetic circuit at the operational point can be obtained. The dimensions of the inductance can then be acquired by using the conventional equivalent magnetic circuit method and inductance formula.

B. Design of Output Filter Capacitance

According to the filtering value of the preset maximal output voltage, the output filter capacitances C_1 and C_2 are decided by

$$C > \frac{P_o}{(\Delta U_{pk})_{\max} \omega U_o} \tag{6}$$

In the design, by choosing P_o=500 W, $(\Delta U_{pk})_{\max}=5\%U_o$, and $\omega=100\pi$, then C is computed as greater than 199 μF.

C. Design of Active PFC External Circuits

As shown in Fig. 4, the active PFC external circuits contain the measuring circuits of the output voltage u_o, the input current i_{in}, and the input voltage u_{in}. Each of them has a divider resistance or sampling operational amplifier which can modulate circuits.

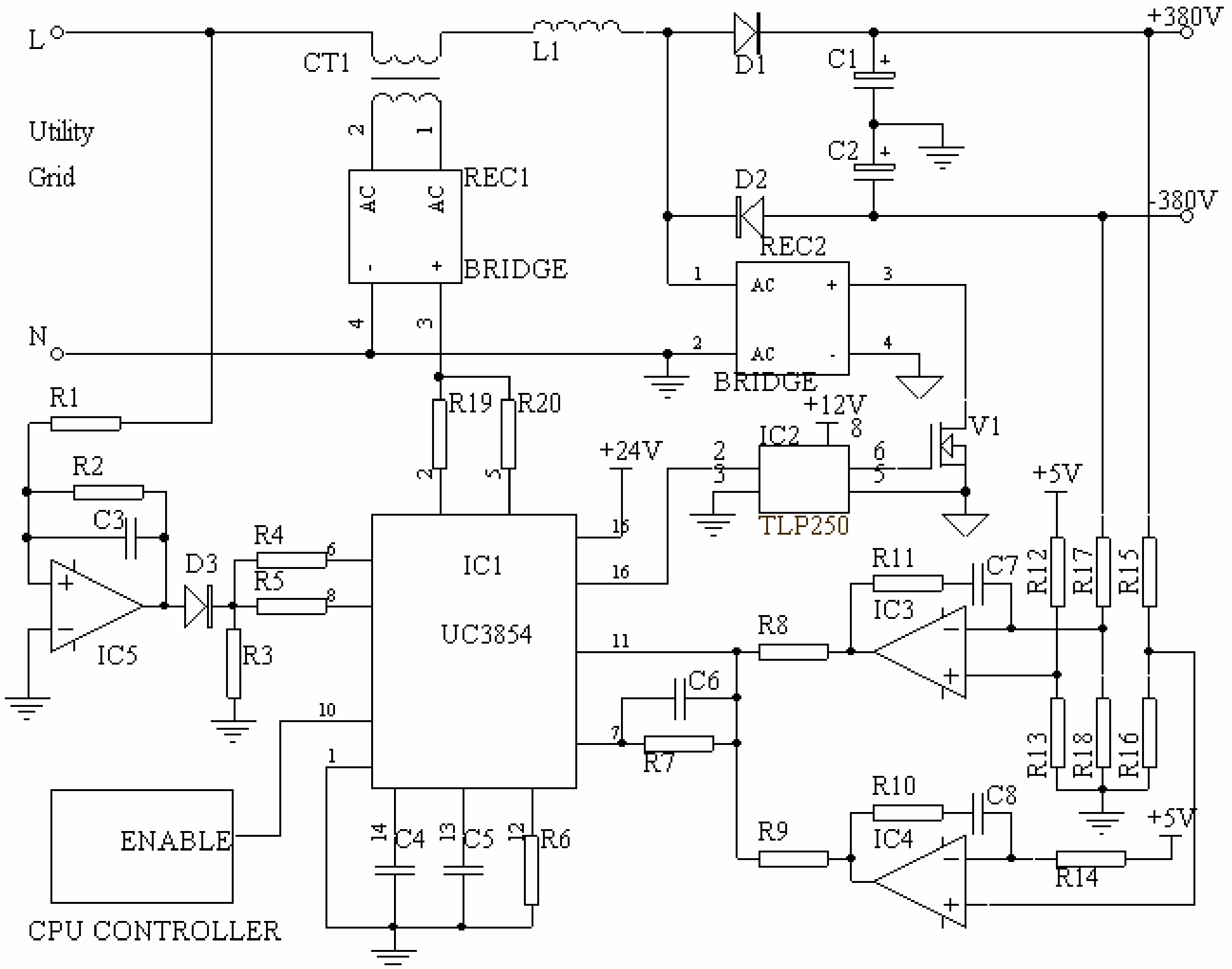


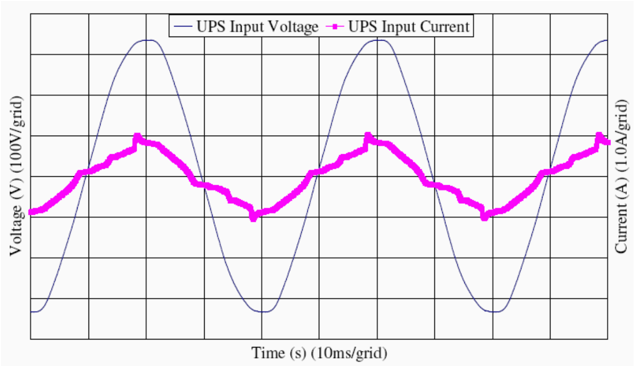
Fig. 4. Schematic diagram of the external circuits of Boost active PFC

IV. Experimental Results

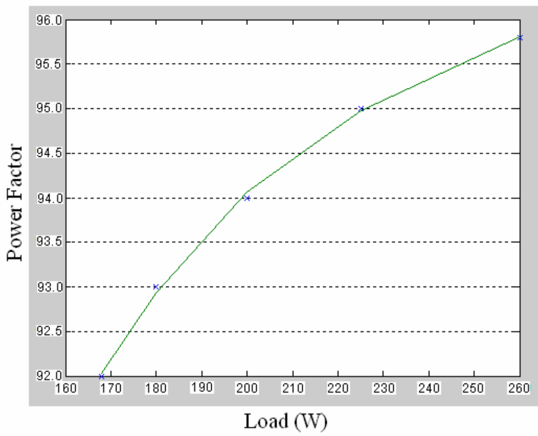
Experimental study has been conducted on the designed active PFC and the UPS system with backup PEMFC/battery hybrid power source. The performances of the proposed hybrid UPS system are tested with the following specifications: input voltage of the utility grid: 160-275 VAC; the output voltage frequency: 50±5% Hz; the rated voltage of PEMFC/battery: 36 VDC, and the output power: about 300 W.

The experimental loads include a DELL™ computer whose model is HP-U2106F3 and maximum input power is 213 W, and a monitor whose model is E772p with input power of 73 W. The experimental results show that when the main supply is in the range of 160-275 V (if less than 160 V, the PEMFC and battery supply DC power), the active PFC rectifier can achieve a steady DC output voltage ±380 VDC. At the full load of P_o=300 W, it can reach η=95%, PF=0.99, and THD<5%. The designed active PFC AC/DC rectifier makes the load behave like a resistor, resulting in a near unity power factor. The input current waveform is similar to the input voltage, and they are almost in phase.

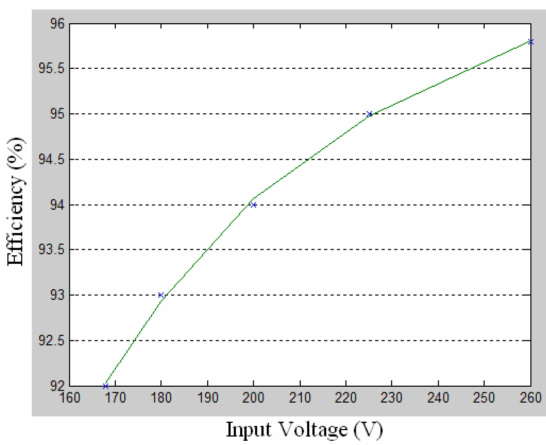
Fig. 5(a) plots the experimental waveform of input current, in which the ripple is not small. This may be caused by the nonlinear load of the computer and the unbalanced loads due to the asymmetry of the switches in the DC/AC half-bridge inverter of the UPS system. Fig. 5(b) illustrates the measured curve of the PF against different output loads when U_{in}=240 V. It can be seen that the PF values of active PFC are over 0.98 in the power range of 200-300 W. Fig. 5(c) shows the measured curve of efficiency versus U_{in} at the full load. It can be found that when u_{in} is in the range from 160 to 275 V, the full load efficiency of the active PFC is over 92%.



(a) Measured U_{in} and I_{in} under full load



(b) Measured PF versus load (W) when U_{in}=240 V



(c) Measured efficiency (%) versus input voltage (V) at full load

Fig. 5 Experimental results

V. Conclusion

This paper has analysed and designed a 300 W boost active PFC for single-phase high frequency uninterrupted power supply (UPS) for backup and emergency power applications, based on the design idea of adopting mature technologies and using the high power factor pre-regulator UC3854 control chip. The active PFC can work well in the range of the universal input voltage. All of its performance indexes have been achieved, including the requirement of the harmonic criterion IEC 61 000-3-2 amended by the Institute of Electrical Engineering. The system is reliable and has been successfully applied to single phase high frequency network UPS system with backup PEMFC/battery hybrid power source. In spite of the simplicity of circuit configuration, the experimental results show that satisfactory performance can be achieved. The PF is nearly unity and the THD is less than 5%.

VI. References

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