Development of a single-phase half-bridge active power filter with the function of uninterruptible power supplies

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Abstract: Analysis and implementation of a single-phase half-bridge active power filter with the function of uninterruptible power supplies is presented. The system provides the combined functions of battery bank energy storage, power-factor compensation, harmonics elimination and uninterruption of the power supply. When the utility is in normal operation, the proposed system will not only supply DC power for battery charging, but also function as an active power filter for improving the power factor and reducing the current harmonics on the utility side. If the utility power fails, the proposed system will function as an inverter immediately, to supply the battery power to the AC load. Analysis for the proposed system is given first, and a personal computer is then used to implement digitised control of the proposed system to facilitate experimental evaluations for a 1 kVA prototype. The feasibility and multi-functional results obtained indicate that the proposed system can be realised by using a digital signal processor as the core controller for cost reduction and reliability enhancement.

List of symbols

\[ d_1, d_2 = \text{switching functions of the insulated-gate bipolar transistors (IGBTs)} \]
\[ d_1^* = \text{duty ratio of } d_1 \]
\[ i_l = \text{current of the AC-side inductor, } L_n \]
\[ i_g^* = \text{command current of } i_g \]
\[ i_d = \text{current of the battery-side inductor, } L_d \]
\[ i_d^* = \text{command current of } i_d \]
\[ i_b^{ave} = \text{average command current of } i_d \]
\[ i_{cs} = \text{current of AC-side filter capacitor, } C_s \]
\[ i_{cs}^* = \text{command current of } i_{cs} \]
\[ i_f = \text{fundamental component of the load current} \]
\[ i_l = \text{load current} \]
\[ i_{l,s} = \text{absolute value of } i_l \]
\[ i_h = \text{amplitude of the } n\text{-th order harmonic of the load current} \]
\[ i_b = \text{source current} \]
\[ i_{b}^* = \text{command of source current, } i_b \]
\[ i_{so}^{ave} = \text{amplitude of source command current} \]
\[ i_{so1} = \text{amplitude of real component of the fundamental load current} \]
\[ i_{so2} = \text{part of the amplitude of the source command contributed to by the battery-charging power} \]
\[ i_u = \text{unit sine wave in phase with } v_i \]

\[ K_P \sim K_{Pq} = \text{proportional controllers gain} \]
\[ K_I \sim K_{Iq} = \text{integral controllers gain} \]
\[ P_L = \text{average real power of load in one utility cycle} \]
\[ T = \text{period of source} \]
\[ T_m = \text{switching period of the IGBT} \]
\[ V_{cb} = \text{average voltage of } v_{cb} \text{ in one utility cycle} \]
\[ V_m = \text{peak value of the source voltage} \]
\[ v_b = \text{voltage of battery bank} \]
\[ v_{bat} = \text{battery-gassing voltage} \]
\[ v_{cb1} + v_{cb2} = \text{voltage of the DC-link capacitor, } C_a \]
\[ v_{cb}^* = \text{command voltage of } v_{cb} \]
\[ v_{so} = \text{average voltage of } v_{so} \]
\[ \Delta v_{so} = v_{so}^* - v_{so} \]
\[ v_{so}^* = \text{command voltage of } v_{so} \]
\[ v_{cb} = \text{voltage of the battery filter capacitor, } C_b \]
\[ v_{cb}^* = \text{command voltage of } v_{cb} \]
\[ v_{so1} = \text{voltage of the load-side DC filter capacitor, } C_o \]
\[ v_s = \text{voltage of the AC filter capacitor, } C_s \]
\[ v_{diode} = \text{diode forward voltage} \]
\[ v_i = \text{source voltage} \]
\[ \theta_n = \text{phase of the } n\text{-th order harmonic of the load current} \]
\[ \omega = \text{angular frequency of source} \]

1 Introduction

Since power-electronics techniques are widely applied to industrial devices, a great number of single-phase nonlinear loads, such as AC/DC motor drives, AC/DC power supplies and lighting loads etc., usually introduce harmonics...
into the utility. They also cause poor input power factors and low efficiency, and result in the destruction of other equipment. To improve the power quality of utilities, many single-phase active power filters have been proposed [1–3]. The active power filters inject a compensation current into the utility to maintain the source current as a sine wave in phase with the utility voltage.

Generally, diesel-engine generators are used as the spare power, however, they can not be started immediately. This necessitates the use of an uninterruptible power supply (UPS) [4] to keep the load operating until the utility power is recovered or the spare power takes over. Several researchers [5–7] have focused on a system which combines the functions of an active power filter and a UPS. However, there has been little work published on the increase of the life cycle of the battery with respect to its charging and discharging operations.

This paper presents the design and implementation of a single-phase half-bridge active power filter with the function of uninterruptible power supplies. It combines the functions of an active power filter, battery-energy storage and a UPS, which together improve the power quality and reliability of the utility. Fig. 1 shows the block diagram of the proposed system. It is seen from Fig. 1 that, on the utility side, a half-bridge switch-mode rectifier [8–10] is used as either an active power filter or inverter. The charging and discharging of the battery bank are conducted by a buck/boost DC chopper [11]. When the utility is normal, the proposed system, which serves as an active power filter, calculates the current command of the rectifier from the load current and the required energy of the battery to control the source power, with improved input harmonics and power factor. Meanwhile, depending on the voltage level of the battery bank, the constant-current and constant-voltage control methods are applied alternately to control the DC chopper, which sustains the battery life. When the utility fails, the half-bridge switch-mode rectifier will function quickly as an inverter to supply the power to the load. The DC chopper discharges the battery to keep the DC-link voltage at a fixed level. To overcome the transient delay due to the mode change, a power balance and feedforward control methods will be applied to improve the performance. In addition, a current-predicted control [12] technique will be used to determine the switching states of the half-bridge switch-mode rectifier. Simulated and experimental results for a 1 kVA prototype indicate that the total harmonic distortion of the input current is reduced from 45.9% to 7.3% with a near-unity power factor for the nonlinear load. In addition, the mode change will be finished within 1.5 ms, in both the cases of power failure and power recovery, and so the system is operated as an uninterruptible power supply.

2 Power circuit

The power circuit of the proposed system is shown in Fig. 2. It is seen from Fig. 2 that the proposed system contains two insulated-gate bipolar-transistor (IGBT) modules. \( T_1^+ \) and \( T_2^- \) are the first pair of IGBT modules which is used in the half-bridge switch-mode rectifier for AC/DC conversion, while \( T_3^+ \) and \( T_4^- \) are the second pair of IGBT modules which is used in the buck/boost DC chopper for DC/DC conversion. The DC-link is a cascaded connection using two identical capacitors \( C_a \) and \( C_b \). \( L_1, C_1, L_2 \) and \( C_2 \) are used for attenuating high-frequency components. \( FS_{a1} \) and \( FS_{a2} \) are fast AC switches. When the utility is in normal operation, \( FS_{a1} \) is turned on and \( FS_{a2} \) is turned off, the system functions as an active power filter and the battery is in the energy-storage mode. On the other hand, when the utility fails, \( FS_{a1} \) is turned on and \( FS_{a2} \) is turned off, and the system is in inverter mode, functioning as an uninterruptible power supply.

It is noted in Fig. 2 that the two IGBTs which belong to the same module cannot be turned on simultaneously. For example, when \( T_1^+ \) is on, \( T_2^- \) is off, and vice versa. Assume that the IGBTs are ideal switches with the switching functions \( d_1 \) and \( d_2 \). When \( T_1^+ \) is on, \( d_1 = 1 \), whereas when \( T_2^- \) is on, \( d_2 = 1 \). Thus Fig. 2 can be simplified to its equivalent circuit shown in Fig. 3. From the above discussion, it is obvious from Figs. 2 and 3 that only one of the two switching devices of each IGBT module can conduct at any one instant. This indicates that the proposed system can be expected to operate highly efficiently [9].

From Fig. 3, one obtains the state equation of the proposed system as follows:

\[
L_a \frac{d}{dt} i_a = -\nu_s - R_a i_a + d_1 \nu_{ca1} - (1 - d_1) \nu_{ca2} \tag{1}
\]

\[
L_b \frac{d}{dt} i_b = d_2 \nu_{ca1} + d_2 \nu_{ca2} - R_b i_b - \nu_{cb} \tag{2}
\]

\[
C_{a1} \frac{d}{dt} \nu_{ca1} = -d_1 i_a - d_2 i_b \tag{3}
\]

\[
C_{a2} \frac{d}{dt} \nu_{ca2} = (1 - d_1) i_a - d_2 i_b \tag{4}
\]

\[
C_a \frac{d}{dt} \nu_{cb} = i_s + i_a - i_f \tag{5}
\]
\[ C_b \frac{d}{dt} v_{cb} = i_{bd} - (v_{cb} - v_b)/R_b \quad (6) \]

It is seen from eqns. 1-6 that if the DC-link command voltage is \( v_{w1} \), and the command current of the battery-side inductor is \( i_{bd} \), one can feed back the voltages \( v_o, v_w, v_{cb}, v_o, v_{cb} \) and the currents \( i_b, i_d, i_b \) to design the switching functions \( d_1 \) and \( d_2 \) for the proposed system.

To better illustrate the effect of the system in both the rectifier and inverter modes, a typical nonlinear load, such as the single-phase full-bridge rectifier shown in Fig. 4, is introduced deliberately. Besides diodes, other elements of Fig. 4 include a smoothing capacitor \( C_s \), a series inductor \( L_s \), and a resistance \( R_o \), which characterises the DC load.

![Fig. 4: A single-phase nonlinear load circuit](image)

From Fig. 4, the state equations of the nonlinear load on the DC side can be expressed as follows [15]:

\[ L_s \frac{d}{dt} i_{Ld} = |V_s| - v_{co} - 2V_{drop} \quad \text{if} \quad |V_s| > v_{co} \]
\[ = 0 \quad \text{otherwise} \quad (7) \]

\[ C_o \frac{d}{dt} v_{co} = i_{Ld} - v_{co}/R_o \quad (8) \]

Based on eqns. 1-8, the decision of the control parameters and the computer simulation for the proposed system will be given.

3 Control of the multi-function system

In this paper, a current-control scheme is used to control the switch-mode rectifier and the buck/boost DC chopper. Before deciding the IGBTs' switching functions, the command currents \( i_{bd}^* \) and \( i_{dd}^* \) of the inductors must be calculated first. These are derived below.

3.1 Active power filter mode

Let the utility voltage be sinusoidal and represented by

\[ v_s = V_m \sin \omega t \quad (9) \]

Also let the nonlinear load current be expressed by

\[ i_L = \sum_{n=1}^{\infty} I_n \sin(n\omega t + \theta_n) = I_1 \sin(\omega t + \theta_1) + \sum_{n=2}^{\infty} I_n \sin(n\omega t + \theta_n) \quad (10) \]

Assume that \( i_L \) is the unit sine wave and in-phase with the source voltage. Using Fourier analysis, one can obtain the amplitude of the real component of the fundamental load current, which is in-phase with the source voltage as

\[ I_{sm1} = \frac{2}{T} \int_0^T i_L \, dt = I_1 \cos \theta_1 \quad (11) \]

Physically, \( I_{sm1} \) is the amplitude of the utility current, which provides the average real power for the nonlinear load. In this paper, the \( I_{sm1} \) of eqn. 11 was calculated by integrating the term \( 2V_{drop} \), which was sampled, held and reset by the zero-crossing signal of the utility voltage in every utility cycle. Referring to Fig. 2, it is seen that the utility will supply the real power for not only the nonlinear load but also the battery charging and system operation loss. In the steady state, the real power of the system will balance in one utility cycle. From Fig. 2, it can be found that if the nonlinear load is switched off, the system operation loss is negligible, the source current is a sine wave, which is in phase with the source voltage and with an amplitude of \( I_{sm1} \), and the amplitude of the source current \( I_{sm2} \) can be obtained as

\[ I_{sm2} = 2V_{cb}I_{bd}/V_m \quad (12) \]

In addition, to ensure proper operation for the half-bridge switch-mode rectifier [9], a proportion-integral (PI) controller is used to keep the DC-link voltage above \( 2V_{sm} \). Thus the amplitude of the source current command can be represented by

\[ I_s^* = \left( K_{p1} \Delta v_{cm} + K_{i1} \int \Delta v_{cm} \, dt \right) + I_{sm1} + I_{sm2} \quad (13) \]

The source command current can then be obtained by multiplying \( I_s^* \) by \( i_N \) as

\[ i_s^* = I_s^* \sin \omega t \quad (14) \]

From Fig. 2, the active power filter compensation current \( i_{cs}^* \) can be calculated by subtracting the source command current \( i_s^* \) from the load current \( i_L \). This yields

\[ i_{cs}^* = i_L - i_s^* \quad (15) \]

The control block diagram of \( i_{cs}^* \) is shown in Fig. 5.

![Fig. 5: Block diagram of the compensation current command, \( i_{cs}^* \)](image)

3.2 Inverter mode

When the utility fails, the half-bridge switch-mode rectifier is operated in the inverter mode. Consequently, the DC-link capacitors can supply the power to the nonlinear load uninterruptedly with appropriate control of the duty ratio \( d_t \). To minimise the effect of the load voltage fluctuation, the output command voltage of the inverter will be in phase with the utility as power outage occurs. It can be represented by

\[ v_{cs}^* = V_m \sin \omega t \quad (16) \]

From eqn. 16, one can obtain the command current of the filter capacitor \( C_s \) as

\[ i_{cs}^* = C_s \frac{dv_{cs}^*}{dt} = \omega C_s V_m \cos \omega t \quad (17) \]
The output voltage of the inverter will be affected by a change of load. Assuming that the fluctuating voltage of the load is $\Delta v_L = v_L^* - v_L$, one can obtain appropriate compensation using a proportion-integral controller. To improve the transient response, the load current $i_L$ is also added to command current for feedforward control. This gives the inverter output command current

$$i_a^* = i_{ca} + \left( K_{P2} \Delta v_L + K_{I2} \int \Delta v_L \, dt \right) + i_L. \tag{18}$$

In this paper, the current control of the half-bridge switch-mode rectifier is modelled using the current-predicted control technique [13, 14]. The error between the command current and the actual current is used to compute the switching duty ratio in one period. Owing to the fact that the utility frequency is much lower than the switching frequency, the switching function $d_i$ can be replaced by its duty ratio $d_i^*$ [14], and eqn. 1 can then be rewritten as

$$\nu_s + R_s i_a + L_s \frac{d}{dt} i_a = d_i^* \nu_{co1} - (1 - d_i^*) \nu_{co2} \tag{19}$$

Assume that $T_{sw}$ is the switching period. Then

$$\frac{d}{d_t} i_a = \frac{1}{T_{sw}} (i_a' - i_a) \tag{20}$$

Substituting eqn. 20 into eqn. 19, one obtains the duty ratio command of the first IGBT module, $d_i^*$, as

$$d_i^* = \frac{1}{\nu_{co2}} \left[ \nu_s + \left( R_a - \frac{L_a}{T_{sw}} \right) i_a + \frac{L_s}{T_{sw}} i_a' + \nu_{co2} \right] \tag{21}$$

It can easily be seen from eqn. 21 that using the duty ratio command $d_i^*$, the actual current can follow the command current in one period at high switching frequency. The voltage $v_{co2}$ in eqn. 21 can be replaced by $0.5v_{co}$ for implementation, and the voltage $v_s$ in eqn. 21 can be replaced by $v_{co}$ for inverter-mode control.

When the utility fails, the DC chopper operates at boost chopper mode and the battery discharges quickly to keep the DC-link voltage at the voltage command $v_{cb}^*$. In the steady state, if the system operation loss is negligible, the battery discharging power will be equal to the real power of the nonlinear load in one utility cycle. Then, the battery discharging command current can be written as

$$i_{cb}^* = - \left( K_{P3} \Delta v_{cb} + K_{I3} \int \Delta v_{cb} \, dt \right) + \frac{P_L}{V_{cb}} \tag{23}$$

In eqn. 23, $P_L$ is the average real power of the load in each cycle. It can be calculated from $l_{out}$ of eqn. 11 as

$$P_L = \left( V_{in} I_{sm1} \right)/2 \tag{24}$$

The feedforward control can be accomplished by the last term on the right-hand side of eqn. 23 to improve the transient response. The current control of the DC chopper is modelled using the hysteresis current-control method, to avoid the change of parameters due to battery charging and discharging.

### 4 Simulation and experimental results

To verify the performance of the proposed system, the complete system was simulated using the MATLAB-SIMULINK software package and a 1kVA prototype was built and tested. The control block diagram of the proposed system is shown in Fig. 7. The major parameters used in the simulation and implementation of Fig. 7 are as follows:

- AC source voltage = 100Vrms (60Hz), DC-link capacitors $C_{dc} = 3000\mu F$, AC capacitor $C_0 = 40\mu F$, inductor $L_\delta = 3.6mH$, inductor $L_{d1} = 9.6mH$, battery bank voltage = 175V, (14 pieces, 12V, 24Ah batteries serial), inductor $L_s = 4mH$, load capacitor $C_0 = 3000\mu F$, load resistance $R_s = 17.5\Omega$, digital controller switching period $T_s = 100\mu s$, and the control parameters are $K_{p1} = 1.3$, $K_{p2} = 1.8$, $K_{p3} = 36$, $K_{i1} = 1.2$, $K_{i3} = 10$, $K_{i4} = 0.1$, $K_{i4} = 1.2$.

The experimental results of the nonlinear load are shown in Fig. 8, where the load is 1kVA and the utility-side input power factor is 0.78. Fig. 8c is the spectrum of the utility current. There exists large harmonics at 180Hz, 300Hz, 420Hz etc., and the total harmonic distortion of the utility current is 45.9%. Figs. 9 and 10 show the simulated and experimental results of normal operation, respectively, where the DC-link voltage command $v_{cb}^*$ is 360V, the load is 1kVA, the battery charging current is 1A and the utility-side total input power is 1.04kVA. Fig. 10d is the spectrum of an experimental source current whose total harmonic distortion is improved to 7.3%. In this case, the utility-side input power factor is 0.995 and the system efficiency is 92.4%. When the battery charging is removed, the utility-side total input power is 815VA, the input power factor is 0.993 and the system efficiency has been increased to 96.3%. Figs. 11 and 12 show the simulated and experimental results for the transient response of the utility-break, where the load is 1kVA and the battery charging current is 0.5A. It can be seen from Fig. 12b that the battery discharges quickly. In addition, it is obvious from Fig. 12c that, even in the case of the utility failure, the inverter supplies the load with only 1.5ms delay and in phase with the utility. When the system is in the inverter mode with full-load operation, the total harmonic distortion of the load voltage is 3.2%. Fig. 13 shows the transient response of the experimental results, before and after utility power recovery, where the corresponding load is 1kVA and the battery charging current is 0.5A. When the utility power
reovers, the system operates at the inverter mode until the inverter voltage is in phase with the utility voltage. From Fig. 13c, it can be seen that the load voltage is almost in phase with the utility voltage when the system changes the operation mode from inverter to active power filter. Finally, it is important to note, from Figs. 9–12, the close agreement between the corresponding simulation and experimental results.

5 Conclusions

In this paper, a single-phase high performance half-bridge active power filter with the function of the uninterruptible power supplies was explored. The operation with the proposed system configuration, which combines the functions of the active power filter, energy storage and uninterruptible power supplies, is verified by simulation and the experimental results of a 1kVA prototype. A personal computer is used to implement digitised control of the system. The results demonstrate that the system possesses a near-unity
power factor and low harmonics on the utility side. In addition, the system efficiency is excellent and the load operates uninterruptedly. The performance evaluation also
indicates that a fast transient response is obtained using a power balance and feedforward control scheme. It is also worth noting that the load voltage is almost in phase with the utility voltage in both the cases of power failure and power recovery. As discussed above, the proposed UPS, when widely used, can effectively improve the quality and reliability of the power utility. In order to reduce the cost, a digital signal processor (DSP) should be used to implement digitised control of the proposed system in the future.

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7 References

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