Comparative investigation of the energy recycler for power electronics burn-in test

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Abstract: Conventional power electronic burn-in testing consumes a huge amount of energy and adds up to a significant part of the manufacturing cost. To improve this situation, a regenerative load system can be used to feed back burn-in test power to the utility system for energy recycling, and a number of solutions in accordance with the test equipment can be chosen. The paper analyses feasible ideas presented in recent literature, and proposes a novel strategy for the implementation of the energy recycler to power electronics burn-in test. The proposed idea is based on the voltage source inverter which uses current-mode control, and is regulated by conventional PWM strategy. It has an additional function of reactive power and current harmonic compensation in comparison with the other literature. A family of energy recyclers is presented, that has the same control strategy in order to include all possible applications. Comparative case studies using uninterruptible power supplies (UPSs), battery chargers and adjustable speed drives (implemented by scalar control) are demonstrated by means of prototype experiments to prove the performance and effectiveness.

1 Introduction

To verify the stiffness of new power electronic equipment and to improve their defective index, reliability and stability, a burn-in test is executed. A consumptive load bank is generally used as the load, and significant energy is wasted. With the increase of rating of power electronic products, such as DC power supplies, chargers, uninterruptible power supply systems (UPSs), AC motor drives etc., the waste energy during the burn-in test which is usually implemented with a duration of 24 to 72 hours has become large. From the viewpoint of energy conservation and reducing production cost, saving of burn-in test energy is a very important task, so use of the conventional method should not be encouraged in the future.

To improve this situation, a load-consumption-free method is needed. By replacing the consumptive load with a newly developed power electronic technology, the consumed energy can be fed back to the utility system. Recently, some methods for UPS and DC power supply burn-in tests have been proposed and demonstrated [1–5]. These design ideas are mainly based on the principle of parallel operation transmission. It offers many advantages over the conventional load bank including energy cost reduction, test space reduction, reduced air ventilation requirement and lower peak power demand [1]. However, most of them adopt voltage control, and there is very little literature which considers an AC motor drive; furthermore, none have considered improving the utility reactive power and harmonics induced by the burn-in test equipment.

A different idea proposed by the authors intended to content with this function of harmonics compensation has been verified [6]. In this paper, a comparative study about a family of energy recycling applications including three typical cases of power electronic products has been presented to confirm the proposed idea. These cases include UPSs, battery charger systems and adjustable speed drives (implemented by scalar control). A comprehensive analysis about the feasible technology proposed in recent literature is also presented to provide a clear insight. Finally, the theoretical expectation is verified by the experimental results in these types of laboratory prototype system.

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2 System configuration

2.1 Electrical equipment type

2.1.1 Synchronised electrical equipment: Electrical equipment which is synchronous with the utility source is defined as synchronised electrical equipment. The characteristic of this tested equipment is that its output voltage is phase-locked with the utility. This system is mostly used in the UPS. Most of the recent research has focused on this type of burn-in test. Figs. 1 and 2 show the feasible solutions presented in these papers. In Fig. 1*a*, the voltage-mode control is the only possible strategy used in this system, then a control voltage V_c is used to regulate the phase angle and amplitude between the tested equipment output and the utility. V_c contains two terms: one is the in-phase term Vx, which is in phase with the utility phase voltage, the other term is the quadrature term V_y, which is in quadrature with the utility phase voltage. Fig. 1*b* shows the related phasor diagram. In such an arrangement, the real power P_s and reactive power Qs can be changed individually by adjusting the corresponding terms V_y and V_x. The power flow equation can be represented as follows:

$$P_s = \frac{V_s V_r}{\omega L_r} \sin\delta \tag{1}$$

$$Q_s = \frac{V_s V_r}{\omega L_r} \cos\delta - \frac{V_s^2}{\omega L_r} \tag{2}$$

where $V_r = (V_s + V_x) + jV_y$ and L_r is the equivalent inductance of the series transformer. It is clear that the real and reactive power transferred through the tested system is dependent on the phase angle and amplitude of the injecting voltage V_c. These two equations are simultaneously solved to get the real and reactive power between two terminals.

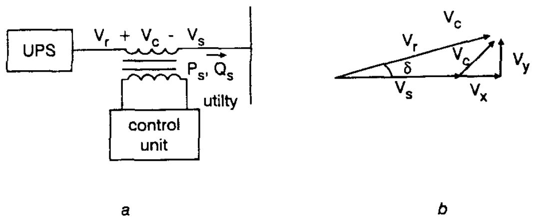


Fig. 1 *Single line and phase diagrams proposed by [1, 2]*
a Single line diagram
b Phase diagram

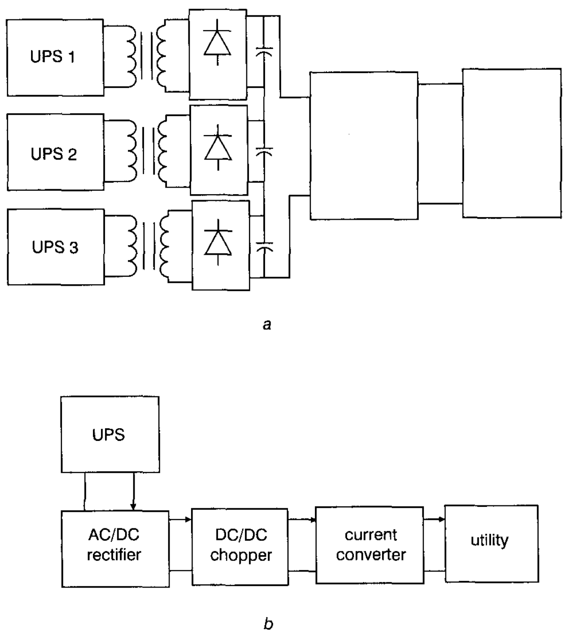


Fig. 2 *Previous proposed block diagrams*
a Proposed by [3]
a Proposed by [4]

There are two methods to generate the desired variable voltage source for injection into the power circuit [1]: one uses a regulation transformer [2] and the other uses an inverter with variable output voltage amplitude and phase angle. Normally, the system is preferred to transfer real power P_S to the utility and let reactive power be zero, thus $V_x = 0$. Eqn. 1 shows the transferred real power range is varying from 0 to 1p.u., if V_y is varying from 0 to 0.1p.u., where ωL_r is adopted as 0.1p.u., and the rating of either the regulation transformer or the inverter is only about 10% of the burn-in test power in that condition. This strategy [1] shows a very positive solution for the UPS burn-in test, not only for the test efficiency but also the test equipment rating. However, this strategy is valid only for synchronised electrical equipment like the UPS, and the current harmonics produced by the tested equipment is uncontrollable in this way.

Fig. 2*a* shows a two-stage energy conversion scheme, which has a different structure and control strategy to that of Fig. 1*a*. It is suited for testing simultaneously a number of small UPSs and is also valid for nonsynchronised equipment. It has about 80% efficiency of energy recycling. There are two methods for the latter stage to parallel connection with the utility: one is the voltage-mode control and the other is the current-mode control. A detailed discussion about these two control modes is shown in the following Section.

Fig. 2*b* shows another solution with three conversion stages. This structure is also valid for nonsynchronised electrical equipment. As it consists of three stages, the total conversion efficiency must be highlighted in this structure. In order to improve the efficiency, it is preferable to use the diode rectifier in the first stage, the line-commutated inverter in the last stage and a DC/DC chopper with high-frequency insulation as the second stage.

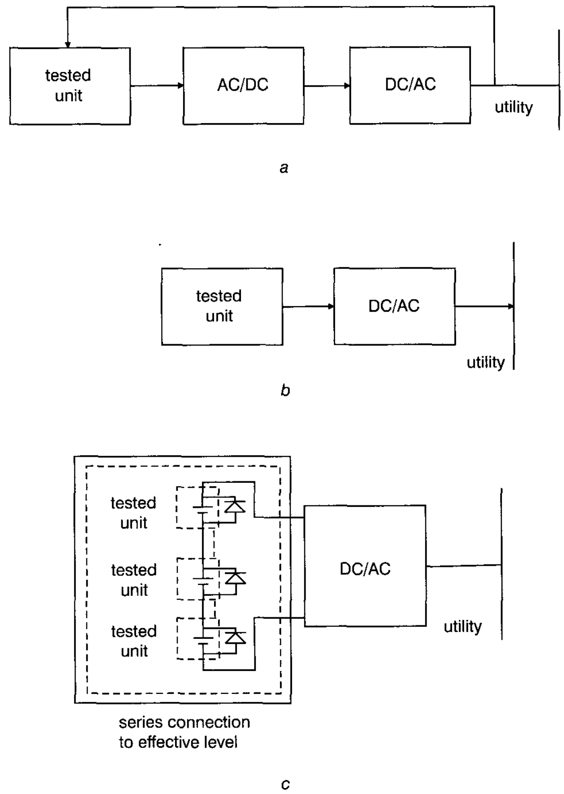


Fig. 3 *Block diagrams for tested units*
a AC nonsynchronised tested unit proposed by [1]
b DC tested unit
c Low-voltage tested unit

2.1.2 Nonsynchronised electrical equipment:

Electrical equipment which is not synchronous to the utility source is defined as nonsynchronised electrical equipment. The characteristic of this tested equipment is that its output cannot be connected directly to the utility. This system is mostly used in DC power supplies, battery chargers, or in AC nonsynchronised electrical equipment. In order to connect nonsynchronised equipment to the utility to circulate consumed power, it is necessary to provide a synchronised interface between the utility and the tested equipment. This should require a DC/AC inverter for both AC and DC tested equipment, and an additional AC/DC converter for AC tested equipment. Fig. 3 shows the feasible constructions in these cases. Fig. 3*a* is valid for both AC synchronised and nonsynchronised electrical equipment. Fig. 3*b* is valid for DC tested equipment, and, as only one stage is adopted, the efficiency in Fig. 3*b* is higher than in Fig. 3*a*.

If the DC voltage of the tested equipment is at a low level, then a series string can be used to boost the DC busbar voltage, this is shown in Fig. 3*c*. Note that the bypass diodes shown in Fig. 3*c* are necessary for the fault tested unit to depart from burn-in test work.

2.2 Proposed method

In this paper, the proposed consumption power feedback unit (CPFU) structure is similar to Fig. 3*a*, but with a different control strategy. In opposition to the conventional voltage mode control presented in previous literature, the proposed CPFU uses the current-mode controller to simplify the control system design. The proposed CPFU's inverter operates for bidirectional power flow. It is suitable for both AC and DC, synchronised and nonsynchronised electrical equipment. Furthermore, as most power electronic equipment (such as switching-mode DC power supplies (SPS), uninterruptible power supplies (UPS), and AC and DC motor drives) adopts the diode rectifier as interface with both single-phase and three-phase utility supplies, thus, current waveforms are rich in harmonic content. Considering this problem with respect to the burn-in test, two operation modes, termed the power control mode and the power factor correction mode, feature the proposed CPFU system.

3 Theoretical analysis

3.1 Basic concept

3.1.1 Voltage mode operation: As the two-stage conversion is adopted, there are two methods, either voltage-mode control or current-mode control, for the latter stage to parallel connection with the utility. When the energy recycler operates in voltage-mode control, it is used to transfer the test energy by adjusting the amplitude and phase angle of the latter-stage output voltage. Fig. 4*a* shows an example of a single-phase system. In this circuit

$$V_r = V_s + V_L \tag{3}$$

$$V_L = L_r \frac{di_r}{dt} \tag{4}$$

where V_s is the utility voltage, L_r is the commutative inductance, V_r is the controlled term by the latter stage (inverter stage) and i_r follows the change of V_r.

Assuming that V_s and V_r are sinusoidal, then the power flow transferred from inverter stage to the utility can be represented by eqns. 1 and 2. It is clear that the real and reactive power transferred through the tested system is dependent on the phase angle and amplitude of the inverter output voltage V_r. These two equations are simultaneously solved to get the real and reactive power between two terminals.

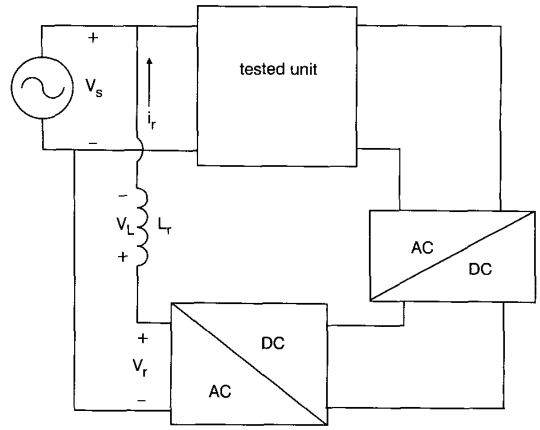
As the system is preferable to transfer the real power P_s to the utility, thus eqn. 2 must be equal to zero, then

$$V_s = V_r \cos\delta \tag{5}$$

This means the amplitude and phase angle of inverter output should keep step in order to follow eqn. 5 so as to transfer only the real power, i.e. the amplitude and phase angle will be determined uniquely if the desired test power is known. From eqns. 1 and 5, the following equations are obtained:

$$\delta = \tan^{-1} \frac{\omega L_r P_s}{V_s^2} \tag{6}$$

$$V_r = \frac{V_s}{\cos\delta} \tag{7}$$



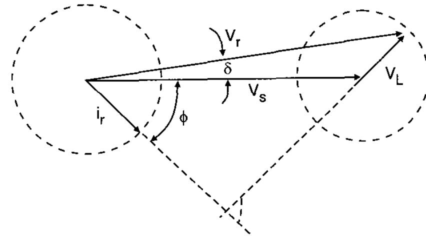


Fig. 4 *Proposed inverter and corresponding phasor diagram for the utility interface*
a Configuration of CPFU system
b Phasor diagram for variation of i_r

3.1.2 Current mode operation: With the same structure shown in Fig. 4*a*, here, i_r is the controlled term by the inverter stage, and V_r follows the change of i_r. Assuming that V_s and V_r are sinusoidal, a phasor diagram corresponding to Fig. 4*a* is shown in Fig. 4*b*, where i_r lags V_s by an arbitrary phase angle ϕ, then the real power *Ps* and reactive power Q_s supplied by inverter to the utility are as follows:

$$P_s = V_s i_r \cos\phi \tag{8}$$

$$Q_s = V_s i_r \sin\phi \tag{9}$$

From Fig. 4*b*, $V_s + \omega L_r i_r \sin\phi = V_r \cos\delta$ and $V_L \cos\phi = \omega L_r i_r \cos\phi = V_r \sin\delta$. Thus, these equations can be represented as follows:

$$P_s = \frac{V_s V_r}{\omega L_r} \sin\delta$$

$$Q_s = \frac{V_r V_s}{\omega L_r} \cos\delta - \frac{V_s^2}{\omega L_r}$$

From these equations, it can be seen that the inverter with current-mode control can be used to transfer the test energy, and the effect is the same as the voltage-mode control. Fig. 4*b* shows how V_r can be changed by controlling the magnitude and phase of i_r.

Even though these two methods lead to the same object, there are some differences. From eqn. 1, the following equation can be derived:

$$\left|\frac{dP_s}{d\delta}\right| = \frac{V_s V_r}{\omega L_r}\cos\delta \tag{10}$$

and, in a similar manner, eqn. 11 can be derived from eqn. 8:

$$\left|\frac{dP_s}{d\phi}\right| = V_s i_r \sin\phi \tag{11}$$

These two equations show that voltage control is more sensitive to angle variations than the current control, and tends to fluctuate easily. Hence, the current control method is adopted in this paper.

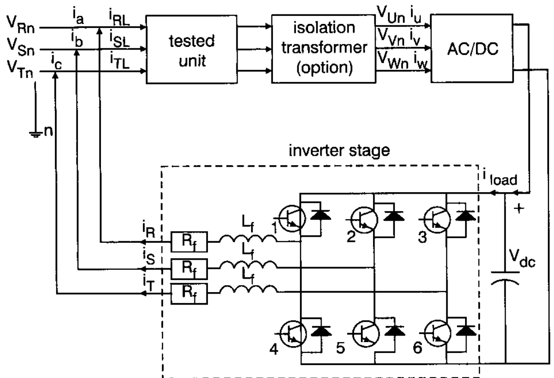


Fig. 5 *Main circuit of the proposed CPFU system*

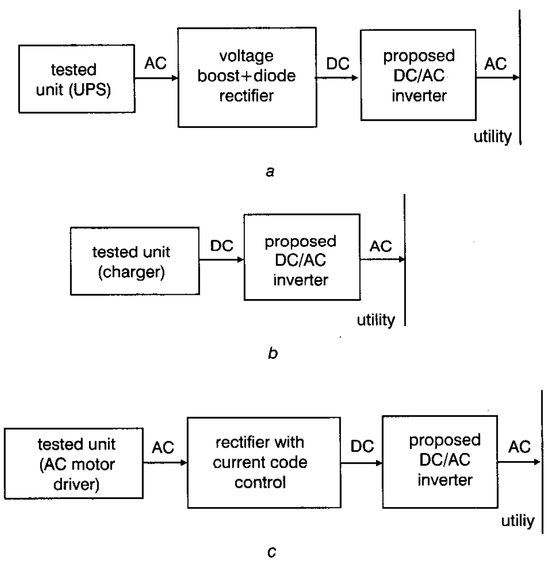


Fig. 6 *Proposed structure for burn-in tests*
a UPS
b Charger
c AC motor drive

3.2 AC/DC stage operation

This paper adopts the current-mode operation as the control strategy. Fig. 5 shows the proposed CPFU system for three types of application: consisting of two stages, the AC/DC stage and the DC/AC stage, and an isolation transformer which is an option, and is decided based on the tested unit. If the tested unit has isolation between input and output, then it can be omitted, otherwise, it must be added. The AC/DC (rectifier) stage is versatile, it can be used to imitate the RL load characteristic for the adjustable speed motor drive test, or replaced by a simple diode bridge structure for the UPS test, or omitted for the DC charger test. Fig. 6 shows the proposed three types of burn-in test structures shown in this paper. As the first two cases shown in Figs. 6*a* and *b* are with no control for this stage, this is focused on in the case shown in Fig. 6*c*.

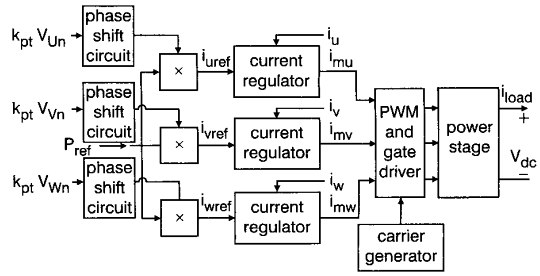


Fig. 7 *Simplified functional block diagram of the proposed rectifier stage for the AC motor drive burn-in test*

Fig. 7 shows the simplified functional block diagram of the proposed rectifier stage for the adjustable speed motor drive test. It must be pointed out that this stage has almost the same functional block diagram with the inverter stage shown in Fig. 8, except for the DC busbar voltage regulation loop. The major objective in this stage is to draw the test energy through the burn-in test equipment and pass it to the inverter stage. The amplitude of the current command is determined by the desired test power in the burn-in test work. The phase shift circuit is used to provide a suitable phase shift for the current command in order to simulate the RL load characteristic to the AC motor drive. Furthermore, for the adjustable speed motor drive, it is necessary to settle the drive output to the normal situation (220V, 60Hz), in order to make a full rating operation. The three reference signals of phase voltages can be deduced from the related three-phase line-to-line voltages and can be shown as follows:

$$V_{Un} = \frac{1}{3}(V_{UV} - V_{WU}) \tag{12}$$

$$V_{Vn} = \frac{1}{3}(V_{VW} - V_{UV}) \tag{13}$$

$$V_{Wn} = \frac{1}{3}(V_{WU} - V_{VW}) \tag{14}$$

3.3 DC/AC stage operation

The DC/AC (inverter) stage is a kernel in this system. It provides a novel control strategy and can be operated in two operation modes, termed the power control mode and the power factor correction mode. Fig. 8 shows the simplified functional block diagram in this stage for the adjustable speed motor drive test. For the first two cases shown in

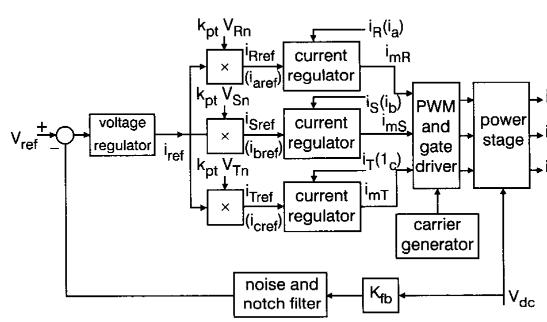


Fig. 8 *Simplified functional block diagram of the proposed inverter stage for the AC motor drive burn-in test*

Figs. 6*a* and *b*, the outer DC busbar voltage regulation loop shown in Fig. 8 is omitted because it has been settled by the tested equipment. Thus, the circuit configuration of the inverter stage is the same as the converter stage in this situation. Furthermore, the three reference signals of phase voltages can be deduced from the related three-phase line-to-line voltages in a similar manner shown as the rectifier stage.

3.3.1 Power control mode: When the proposed inverter stage operates in the power-control mode, it is used to transfer the test energy by feeding in-phase current to the utility. As it is simple to achieve, no further discussion is presented here. However, any type of current controller, such as hysteresis current control, PWM current control and predict current control [7], can be chosen freely.

3.3.2 Power-factor correction mode: When the proposed inverter stage operates in the power-factor correction mode, it can be used to transfer the test energy and to reduce the reactive and harmonic current drawn from the utility by the tested equipment. If the following is assumed:

$$V_{Rn}(t) = v_m \sin \omega t \tag{15}$$

then, representing i_{RL} by a Fourier series expansion:

$$i_{Rl}(t) = \sum_{n=1}^{\infty} a_n \sin n\omega t + \sum_{n=0}^{\infty} b_n \cos n\omega t \tag{16}$$

There are two strategies to achieve the proposed CPFU operating in this mode. The first one is to detect the harmonic content, then the proposed CPFU generates the detected harmonics plus the delivered test energy. Several harmonic detection schemes such as the integration method and synchronous detection method [8] can be used to separate this term from the others. For three-phase application systems, a progressive compensation theory, called the instantaneous reactive power theory by Akagi [9, 10], can be applied because of its excellent decouple performance. It can simply separate the real part and reactive part of the power demand, and compensate for the current harmonics. However, it is noted that the proposed CPFU system has an additional control term of test power demand, thus it results in a small difference from the active power filter [6].

The second method is present in [11]. This strategy is with no dectection, but only regulates the utility to supply the in-phase sinusoidal current which is corresponding to the fundamental term a_1. The declarative method is based on the idea that the active-power filter forces the mains current to be a sine wave and in phase with the mains voltage in spite of the load characteristics. It presents the same good performance with the first method in normal cases, but with a superior response in the situation of the main voltage unbalance and/or harmonic.

This paper adopts the second method with a little modification (due to the additional power demand in burn-in test) as the control strategy. That is, the proposed CPFU's inverter will play the parallel active-power filter role together with additional function of test energy transfer when it is operating in power-factor correction mode. This idea is different from that proposed in the previous literature. As the CPFU's inverter has to improve the mains reactive power and current harmonics, the original controlled feedback signals i_R, i_S and i_T shown in Fig. 5 must be substituted by i_a, i_b and i_c, respectively. Then, using a similar manner of power balance idea in the DC busbar voltage, the proposed CPFU can achieve the expected two functions with no change of controllers. Therefore, by regulating the DC busbar voltage with a sinusoidal current command just as the power mode does, the test energy can feed back to the utility, and the utility current harmonics and reactive power caused by the tested equipment can be also reduced. Fig. 8 has shown the simplified functional block diagram for the proposed inverter stage operated in these two operation modes. As it is almost the same as the conventional PWM rectifier control, no additional discussion is presented here.

4 Experimental results

In this paper, three typical cases of equipment for burn-in test application have been presented, and three sets of combinations for the proposed CPFU system with respect to the test equipments have also been used to verify the feasibility. The experimental cases include UPS system, charger system and AC motor drive system.

4.1 UPS burn-in test

Fig. 6*a* shows the circuit configuration of the three-phase UPS burn-in test system. The CPFU consists of two stages: the front stage is the AC/DC converter, which is used to transfer the UPS output energy to the DC busbar, and the latter stage is the proposed DC/AC inverter, which is used to feed back the energy from the DC busbar to the utility. As the UPS is permitted to connect with a full bridge diode rectifier, a diode rectifier is chosen for the front stage to increase the test efficiency. However, a voltage boost transformer is necessary to ensure the latter stage works well. Table 1 demonstrates the experimental results.

Table 1: Power control mode for UPS

CPFU's input, W	CPFU's output, W	Efficiency, %
950	834	87.8
1340	1182	88.2
1720	1532	89.1
2520	2230	88.5

4.2 Charger burn-in test

Fig. 6*b* shows the circuit configuration for the three-phase charger burn-in test system. As the DC busbar voltage is valid, the proposed CPFU system consists of only one stage (the DC/AC inverter) in this case, thus resulting in a higher test efficiency. Table 2 shows the experimental results.

Table 2: Power control mode for charger

CPFU's input, W	CPFU's output, W	Efficiency, %
920	820	89.1
1530	1388	90.7
2050	1880	91.7
2430	2250	92.6
2820	2610	92.5

It must be emphasised that, if the DC busbar voltage of the charger is too low, such as 48 VDC for the telecom power, to directly transfer the test energy to the utility, then an additional DC/DC boost chopper or a voltage boost transformer is necessary there. Thus, the total efficiency will be lower than the value shown in Table 2.

4.3 Adjustable speed motor driver burn-in test

As the AC motor drive is not synchronised with the utility, the proposed CPFU system consists of two power stages.

In order to make a complete comparison of the recycling efficiency, the former stage is adopted with a switching mode AC/DC converter which is used to imitate the RL characteristic of the AC motor load, then the second stage is sent back the recycling energy to the utility. Fig. 6*c* shows the circuit configuration for this system. As most of the adjustable speed motor drives use diode bridge rectifiers as the front stage, this involves the utility current to be rich in harmonics, thus a power factor correction mode should be preferred in this type of burn-in test. In this case, two operation modes as described in the preceding text are tested, and the efficiency and the harmonic compensation effect will be presented in the following.

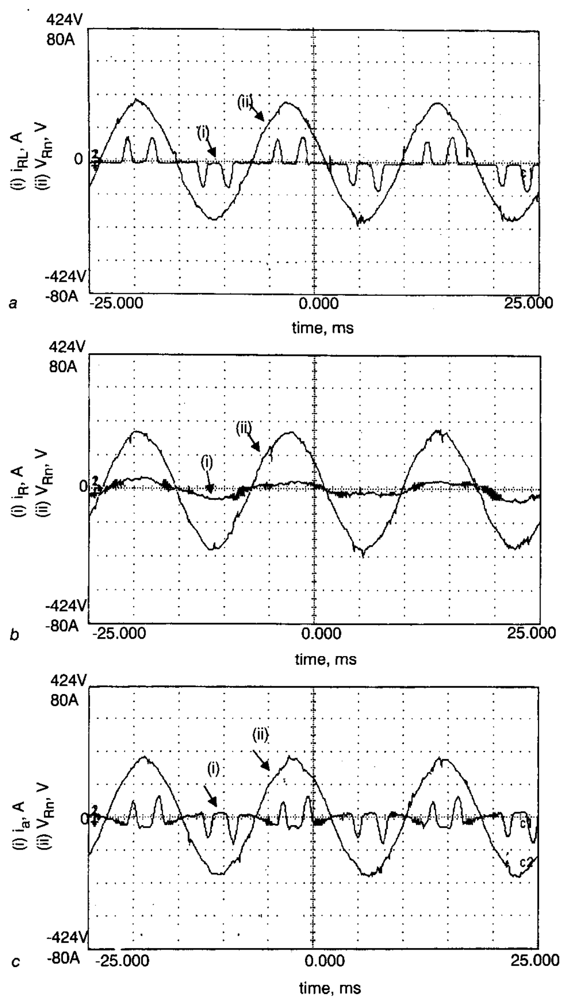


Fig. 9 *Experimental results of power control mode for the AC motor drive burn-in test*
a Utility voltage V_{Rn} and AC motor drive input current i_{RL}
b Utility voltage V_{Rn} and the CPFU's inverter output current i_R
c Utility voltage V_{Rn} and the current i_a which is used to compensate the switching loss, including the tested AC motor drive and the proposed CPFU

Fig. 9 shows the experimental results of the proposed AC motor drive burn-in test which operates in power control mode. Fig. 9*a* shows the utility voltage and AC motor drive input current, Fig. 9*b* shows the utility voltage and the CPFU's inverter output current. It shows clearly that the CPFU's inverter output current is in phase with the utility and that it is sinusoidal. This means that only real power passes through the proposed CPFU's inverter. Fig. 9*c* shows the utility voltage and the current which is used to compensate the switching loss, including the tested AC motor drive and the proposed CPFU. Measured results are shown in Table 3.

Table 3: Power control mode for AC motor driver

CPFU's input, W	CPFU's output, W	Efficiency, %	Utility input current (RMS), A
620	470	75.8	3.4
780	530	77.9	4.1
910	720	79.1	4.5
1270	1020	80.3	5.9
1580	1300	82.3	6.6
1810	1530	84.5	7.4
1940	1630	84.0	7.9
2310	1980	85.7	9.2
2428	2130	85.9	9.5
2860	2480	86.7	10.5
3060	2650	86.6	11.1

In Table 3, the overall efficiency of the proposed CPFU is lower in small test levels and is higher in large test levels. The dissipation includes the switching loss in the main circuit and control circuit, and the cooling fan loss. The total efficiency presented in the utility is above 80%, i.e. about 80% of the test energy through the AC motor drive can be fed back to the utility.

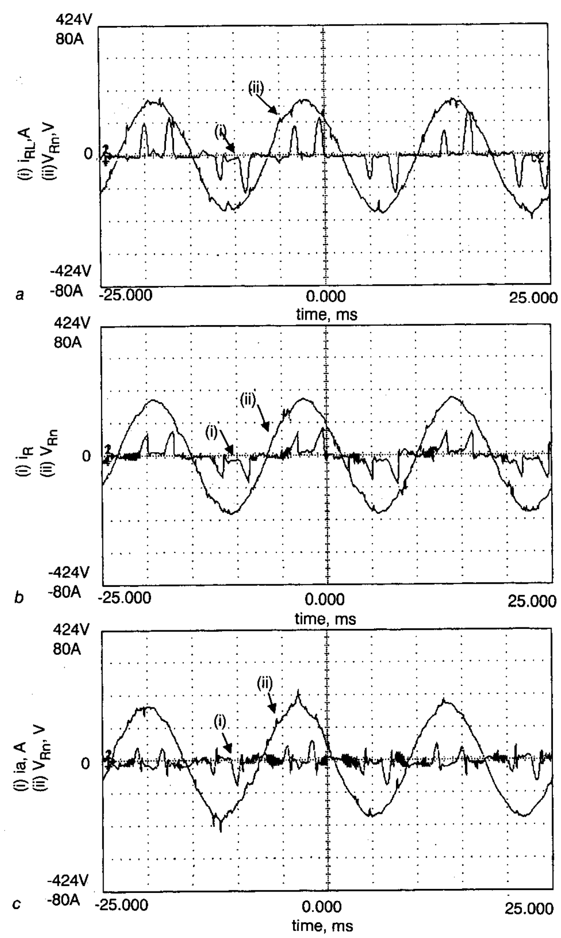


Fig. 10 *Experimental results of power factor correction mode for the AC motor drive burn-in test*
a Utility voltage V_{Rn} and AC motor drive input current i_{RL}
b Utility voltage V_{Rn} and the CPFU's inverter output current i_R
c Utility voltage V_{Rn} and the current i_a which is used to compensate the switching loss, including the tested AC motor drive and the proposed CPFU

Fig. 10 shows the experimental results for the CPFU operating in the power correction mode. Fig. 10*a* shows the utility voltage and AC motor drive input current. Fig. 10*b* shows the proposed CPFU's inverter output current, it shows the proposed CPFU output current is switched to compensate for the harmonics generated by the AC motor drive which is rich in harmonics. Fig. 10*c* shows the net input current drawn from the utility.

Comparing the experimental results in Fig. 9*c* with the experimental results in Fig. 10*c*, note that the power factor correction mode draws little reactive power from the utility. This point can also be verified by the measured data shown in Table 4.

Table 4: Power factor correction mode for AC motor drive

CPFU's input, W	CPFU's output, W	Efficiency, %	Utility input current (RMS), A
650	490	75.4	1.5
930	730	78.5	2.2
1130	900	79.6	2.8
1520	1250	82.2	3.9
1700	1410	82.9	4.5
2180	1850	84.9	5.6
2380	2030	85.2	6.1
2630	2260	85.9	6.8

From these tables, it can be seen that the proposed power factor correction mode draws less reactive power from utility than power control mode. If the tested system is large, then it is necessary to operate in this mode.

4.4 Cost analysis

This paper will consider the cost analysis of a 10kW capacity burn-in test system. Now, some assumptions should be made as follows regarding local conditions in Taiwan:

(i) The original load bank is 10kW, and so the CPFU must ideally transfer 10kW real power to the utility.

(ii) The burn-in test lasts for 16 hours per day, and only 25 working days per month on average.

(iii) The efficiency for the CPFU is conservatively estimated to be about 90% for a one-stage CPFU structure, and about 80% for a two-stage CPFU structure.

(iv) The utility cost is NT$ 2.22 per kilowatt-hour.

The annual energy saving for one-stage CPFU system is estimated to be about $10 \times 16 \times 25 \times 12 \times 0.9 \times 2.22 =$ 95 904 NT$/year and for two-stage CPFU system is about $10 \times 16 \times 25 \times 12 \times 0.8 \times 2.22 =$ 85 248 NT$/year.

The estimated cost for a 10kW one-stage CPFU system is about NT$ 30000, and for the two-stage CPFU system is about NT$ 50000. The additional benefits obtained are as follows:

(*a*) Energy saving for the 10kW one-stage CPFU system is NT$ 95 904/year, and two-stage CPFU system is NT$ 85 248/year, so the initial capital required for the one-stage CPFU system will be retrieved in one-third of a year, and about half a year for the two-stage CPFU system.

(*b*) Conventional load bank cost, heat dissipation space and ventilation costs are eliminated.

(*c*) Peak power demand is reduced.

5 Conclusion

A comprehensive comparison for consumption power feedback of a power electronic burn-in test has been described. In order to improve the shortcomings of the conventional methods using load banks, a CPFU system with current-mode control has been used instead of voltage-mode control due to the following reasons:

(i) Simple implementation.

(ii) Phase-shift transformer or phase-locked loop elimination.

(iii) Insensitive power variation due to control variable's phase angle perturbation.

(iv) Inherent overload protection at utility voltage sudden drop.

(v) Immunity from utility frequency variation.

(vi) Utility power factor and harmonics improvement.

Prototype experiments have proven the performance of the proposed method to be effective. Three types of application cases show the proposed CPFU system is full of possibilities. Different combinations of CPFU systems with respect to distinct application cases show varied efficiencies. Additional benefits have also been obtained beyond the basic function of CPFU operation. The proposed method is suitable for AC and DC, synchronised or nonsynchronised equipment and can reduce energy costs during product burn-in tests. Cost-effective analysis shows the developed method to be valuable for the power electronics industry.

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