Economic UPS structure with phase-controlled battery charger and input-power-factor improvement

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Indexing terms: Uninterruptible power supply, Battery charger

Abstract: A new single-phase uninterruptible power supply (UPS) scheme is proposed. Its advantages when compared with existing UPSs are: no transferring time, high efficiency, low implementation cost and high power density. It mainly consists of a minimised power converter which is capable of providing specified constant output voltage, a phase-controlled battery charger, and input-power-factor improvement. The experimental results of the developed prototype show a superior performance.

List of symbols

$\mathbf{V}_{in}$ = voltage vector of mains
$\mathbf{V}_{out}$ voltage vector of output
$\mathbf{V}_z$ = voltage vector of link inductor
$\mathbf{I}_{out}$ = current vector of UPS output
$\mathbf{I}_{ups}$ = current vector of converter output
$\mathbf{I}_{in}$ = current vector of UPS input
X_z = ωL_z = input link reactance
$v_{in}(t)$ = mains voltage
V_{in} = peak value of mains voltage
ω = angular frequency of the mains
$v_{out}(t)$ = output voltage
V_{out} = peak value of output voltage
α = phase displacement angle between $\mathbf{V}_{in}$ and $\mathbf{V}_{out}$
$i_{out}(t)$ = output current
I_{out} = peak value of output current
β = phase displacement angle between $\mathbf{V}_{out}$ and $\mathbf{I}_{out}$
L_z = input link inductance
$i_{in}(t)$ = input current
I_{in} = peak value of input current
δ = input power factor angle
$i_{ups}(t)$ = converter current
I_{ups} = peak value of converter current

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IEE Proceedings online no. 19971132
Paper first received 29th July and in revised form 23rd December 1996
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θ = phase displacement angle between $\mathbf{V}_{in}$ and $\mathbf{I}_{ups}$
θ' = 180° − (phase displacement angle between $\mathbf{I}_{ups}$ and $\mathbf{I}_{in}$)
γ = phase displacement angle between $\mathbf{V}_{out}$ and $\mathbf{I}_{out}$
P_{ups} = real power supplied by converter
P_{bat} = real power going to battery set
I_{bat} = charging current
pf = input power factor
C = DC-link capacitor
L_o = filter inductor of converter output
C_o = filter capacitor of converter output

1 Introduction

With the information industry prospering, computer and related equipment become more and more important. But the mains power is usually fluctuating and is contaminated by the proliferation of electronic facilities and shortage of electricity capacity e.g. spikes, harmonics, sags, brownout and outage etc., these voltage disturbances usually cause data and financial loss [1]. Thus, uninterruptible power supply (UPS) is vital for the critical equipment [1–12].

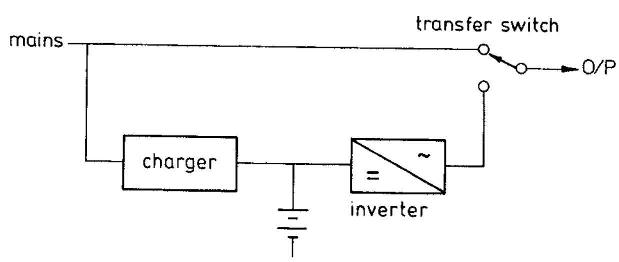

Fig. 1 *Configuration of standby UPS*

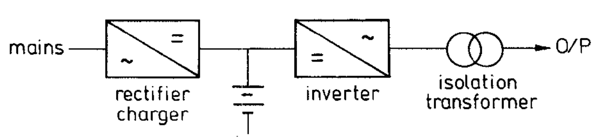

Fig. 2 *Configuration of on-line UPS*

Figs. 1–5 show the UPS types along with the comparison chart of Table 1. We can find their advantages and disadvantages comparatively. Fig. 1 shows the configuration of the conventional standby UPS. It consists of a charger, battery set, inverter and transfer-switch. The power stage is not complicated, but it has transferring time and unregulated output voltage during AC-line normal operation [2]. Fig. 2 shows the online UPS

Table 1: Comparison chart for different types of UPS

UPS types	Transferring time	Power stage	Harmonic suppression	Power factor correction
Standby	yes	intermediate	no	no
Online	no	complicated	no	no
Parallel	yes	simple	yes	yes
Bidirectional	yes	intermediate	no	no
Proposed	no	very simple	no	yes

configuration consisting of a rectifier-charger, battery set, inverter and isolation transformer. Whether or not the mains is normal, the UPS always governs the output voltage without any transferring time. However, the input current is distorted by the prestage rectifier in this structure unless an extra power factor correction (PFC) is added as a preregulator but it will have more power devices if this is done [3–6]. A multifunctional converter has been developed (see Figs. 3 and 4). It mainly consists of a multifunctional converter which can work as an inverter and charger bidirectionally. Fig. 3 shows a parallel processing UPS. When the mains is normal, the UPS works as a harmonic suppressing machine; hence the inverter cannot regulate output during this period unless an expensive bulk constant voltage transformer (ferroresonant transformer) is added to the output [7–10]. The configuration shown in Fig. 4 has a similar function except for harmonic suppression but it must have a bulk isolation transformer on the output [11, 12].

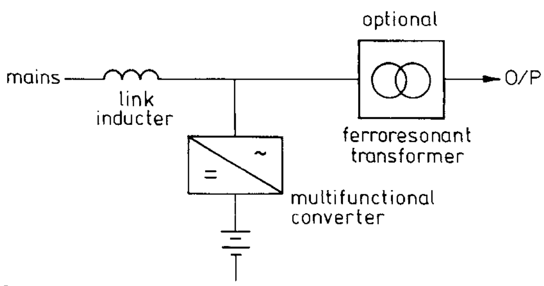

Fig. 3 *Configuration of parallel processing UPS*

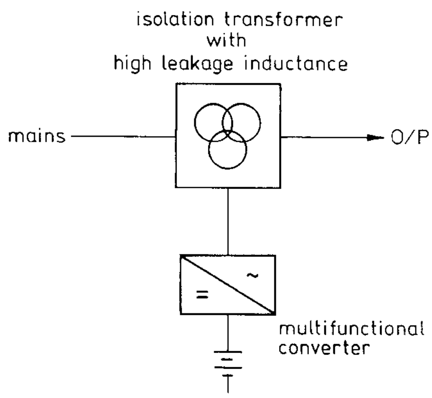

Fig. 4 *Configuration of bidirectional UPS*

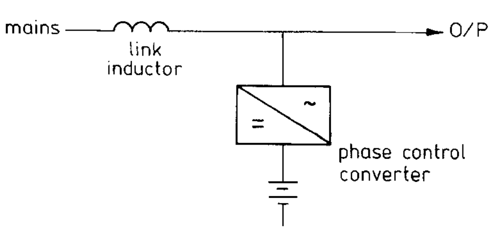

Fig. 5 *Configuration of the proposed UPS*

Fig. 5 shows the proposed UPS configuration. It consists of a phase control converter, battery set and link inductor. The power stage is the simplest amongst these UPS structures. A minimised topology is used for this converter, and a new control scheme is also developed.

2 Proposed UPS

2.1 Power circuit description

Fig. 6 shows the configuration of the proposed UPS. It consists mainly of a link inductor, a power converter and a centre-tapped battery set. The proposed scheme uses fewer semiconductor devices and hence is cost effective. The major part of the system is the power converter which employs two active semiconductor devices to construct a half-bridge type converter, i.e. switches T_1 and T_2, and they are operated in PWM fashion to yield PWM waveforms through the L_0/C_0 filter and then to the output. The simulated operating waveforms are shown briefly in Fig. 7.

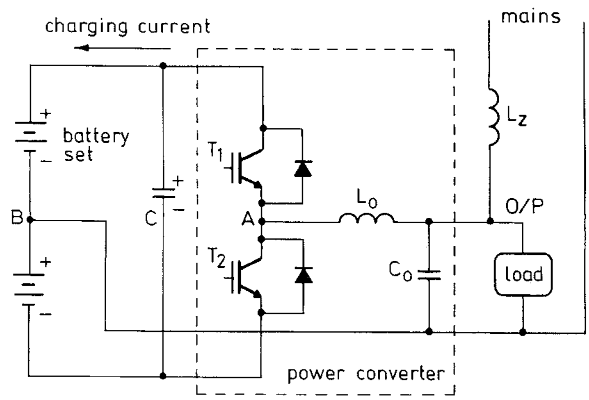

Fig. 6 *Schematic of power circuit of proposed UPS*

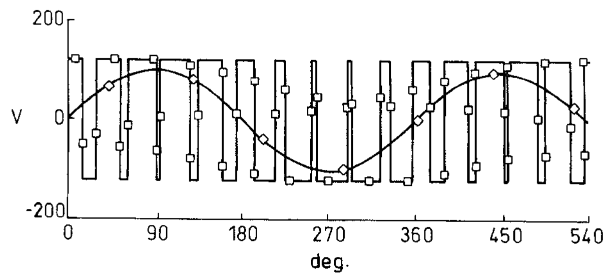

Fig. 7 *Operating waveforms of power circuit of proposed UPS*
□ V_{AB}
◇ V_{out}

When the mains is normal, the link inductor provides an interface of voltage vector to synthesise the mains- and the output-voltage vectors. The link inductor can also stabilise the output and suppress mains transients between the mains and the output. Because the current flow direction of the power converter is determined by the relationships of these voltage vectors, it is a two-way converter which can work either as an inverter or as a charger. In the meantime, the power converter provides regulated output voltage (inverter function) as well as providing the battery charging function. Additionally, through the output voltage controlling the phase angle, the proposed UPS can also provide a very high input power factor. When the mains fails, the power goes on supplying the load uninterruptedly. Meanwhile, it is operated as an inverter converting battery power to AC power for the load until the mains returns or it is shut down, if running out of energy from the battery.

In this UPS configuration, the UPS can always maintain a specified constant voltage on the output without the help of an expensive bulk ferroresonant transformer. It also saves a battery charger and an extra PFC. These features are difficult to achieve in the conventional online or standby UPSs.

It should be noted that this UPS structure has no output transformer, which can work as an isolation component, can vary output voltage, e.g. the UPS input voltage is 220V AC but the output voltage is 110V AC, and serve as multi-output, if necessary. This UPS structure also needs two symmetric battery sets (or an even number of batteries) because it requires the centre-tape of the battery string to be connected to the half-bridge converter.

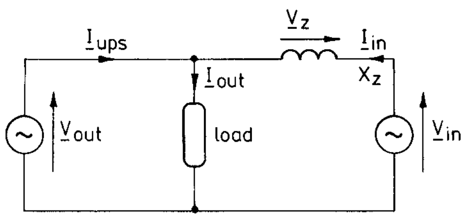

Fig. 8 *Simplified equivalent circuit for proposed UPS*

2.2 Basic theory

The operating principles of the proposed UPS power stage are discussed next with the help of the equivalent circuit as shown in Fig. 8. In this circuit V_{in} represents the mains voltage, L_z the link inductance, V_{out} the output voltage, i_{ups} the converter current, i_{in} the input current, and finally i_{out} the output current. These give

$$\mathbf{V}_{in} = \mathbf{V}_{out} + \mathbf{V}_z \tag{1}$$

$$\mathbf{I}_{out} = \mathbf{I}_{ups} + \mathbf{I}_{in} \tag{2}$$

$$\mathbf{I}_{in}\mathbf{V}_z/jX_z \tag{3}$$

where X_z equals ωL_z. Furthermore, Figs. 9 and 10 show two sets of the phasor diagrams for eqns. 1–3, but different phases of output voltage. The mains voltage is assumed to be a pure sine wave and is expressed as

$$v_{in}(t) = V_{in}\sin(\omega t) \tag{4}$$

If the output voltage of the converter is assumed to be

$$v_{out}(t) = V_{out}\sin(\omega t - \alpha) \tag{5}$$

and one assumes that the fundamental component of load current $\mathbf{I}_{out}$ lags $\mathbf{V}_{out}$ by β, then

$$i_{out}(t) = I_{out}\sin(\omega t - (\alpha + \beta)) \tag{6}$$

From eqns. 4 and 5, the mains current can be obtained as

$$i_{in}(t) = \frac{1}{\omega L_z}\int_0^t (V_{in}\sin(\omega t) - V_{out}\sin(\omega t - \alpha))d(\omega t)$$
$$= I_{in}\sin(\omega t - \delta) \tag{7}$$

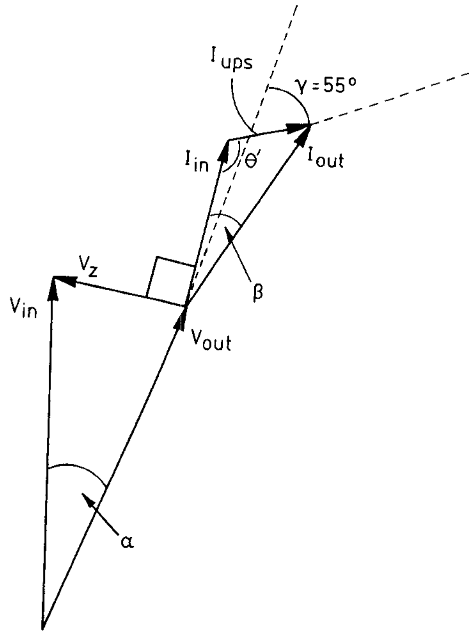

Fig. 9 *Phasor diagram of proposed UPS*
$\gamma = 55°$

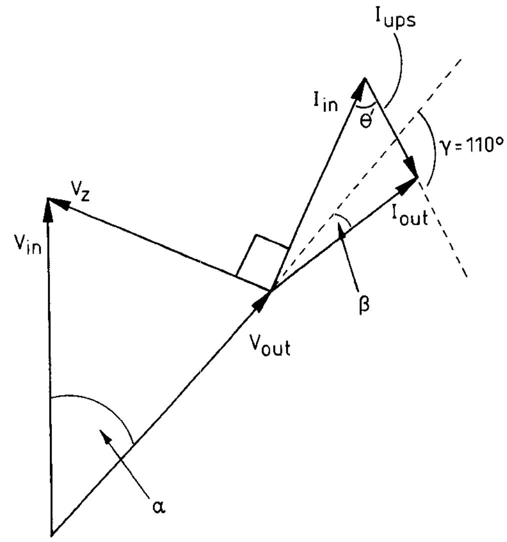

Fig. 10 *Phasor diagram of proposed UPS*
$\gamma = 110°$

where

$$I_{in} = \frac{1}{X_z}\sqrt{(V_{out}\sin(\alpha))^2 + (V_{out}\cos(\alpha) - V_{in})^2} \tag{8}$$

$$\delta = \sin^{-1}\left(\frac{(V_{in} - V_{out}\cos(\alpha))}{\sqrt{(V_{out}\sin(\alpha))^2 + (V_{out}\cos(\alpha) - V_{in})^2}}\right) \tag{9}$$

Hence from eqns. 6–9, $i_{out}(t)$ and $i_{in}(t)$ are both sinusoidal signals. It should be noted that $i_{in}(t)$ is independent of load current, and i_{ups} must be a pure sine wave because they are at the same node. Thus it can be seen that

$$i_{ups}(t) = I_{ups}\sin(\omega t - \theta) \tag{10}$$

From the phasor diagrams of current part in Fig. 9, we can apply trigonometry to obtain

$$I_{ups} = \sqrt{I_{in}^2 + I_{out}^2 - 2I_{in}I_{out}\cos(\alpha + \beta - \delta)} \tag{11}$$

According to the law of sines, we have

$$\sin(\alpha + \beta - \delta)/\sin(\theta') = I_{ups}/I_{out} \tag{12}$$

Then, θ' can be expressed as

$$\theta' = \sin^{-1}\left(\frac{I_{out}}{I_{ups}}\sin(\alpha+\beta-\delta)\right) \tag{13}$$

Hence

$$\theta = 180^\circ - \theta' + \delta \tag{14}$$

Using eqns. 5, 10 and 14, the phase angle γ between the output voltage and converter current can be obtained and represented as

$$\gamma = \theta - \alpha = 180^\circ - \theta' + \delta - \alpha \tag{15}$$

The above relationship equations can be used to control power flow and input power factor as in the following Section.

2.3 Control principles

There are two conditions of the mains during UPS operation. When the mains is in outage, the converter only does a pure inverter job, i.e. yielding regulated voltage to the load, without considering the phase angle of the output voltage. Thus the interesting aspect is how to control the converter voltage and phase angle during AC line in normal operation to ensure that the battery set is charged and the input power factor is improved. To easily control the converter, there are two operation modes during this period.

2.3.1 Mode I: Recovering battery energy: As soon as the mains returns to normal operation, the UPS will go to this mode. In this mode, just after going through the battery set discharging energy during outage, the converter will absorb energy from the mains to recharge the batteries. Referring to the phasor diagrams of Figs. 9 and 10, the power from the converter can be given by

$$P_{ups} = V_{out}I_{ups}\cos(\gamma) \tag{16}$$

where $\cos(\gamma)$ can be a positive or negative value that determines the power flow, for instance, $\cos 55^\circ = 0.53$ and $\cos 110^\circ = -0.34$ as shown in Figs. 9 and 10. $P_{ups} > 0$ means the converter power is going to the load and the battery set is discharging energy, and $P_{ups} < 0$ means that the converter is absorbing power from the mains and the battery set is charging. Hence, its real power flow is bilateral, going from the converter to the mains, and vice versa. We can make $90^\circ < \gamma < 180^\circ$ by controlling α of eqn. 15, thus $\cos(\gamma) < 0$ resulting in $P_{ups} < 0$. If the converter is lossless, the power P_{bat} going to the battery will equal P_{ups}, then

$$P_{ups} = P_{bat} = V_{bat}I_{bat} \tag{17}$$

where I_{bat} is the charging current.

We have

$$I_{bat} = P_{ups}/V_{bat} \tag{18}$$

Hence, using eqns. 16 and 18, it is found that P_{bat} and I_{bat} can be controlled by γ. Meanwhile, the mains primarily provides the load and battery energy; however, the UPS must temporarily put aside the power-factor-correction task. Thus $pf = \cos(\delta)$, where δ is given by eqn. 9.

Because the UPS must maintain a specified output voltage to the load, the amplitude V_{out} has to be controlled by the duty-ratio of PWM waveforms so as to keep a constant value. As shown in the phasor diagram of Fig. 11, $\mathbf{V}_{out}$ with $\mathbf{I}_{out}$ goes counterclockwise along the dashed-line circle by controlling the phasor angle γ while the battery energy is increasing. Meanwhile, γ becomes smaller gradually such that it causes P_{bat} and I_{bat} to also become smaller. Until the battery set is fully charged (V'_{out}), then $\gamma = 90^\circ$, i.e. $P_{ups} = 0$, there are no active power flows to or from the battery. It will terminate mode I and then go into mode II.

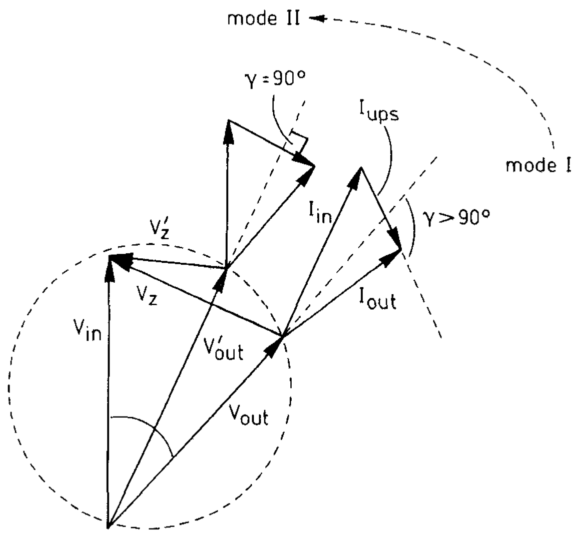

Fig. 11 *Phasor diagram of proposed UPS during mode (I) and mode (II)*

2.3.2 Mode II: Battery-set fully charged: After fully charging the battery-set, the UPS starts mode II operation. In this mode, $I_{bat} = 0$, thus $P_{bat} = 0$ if the converter is lossless. During this interval, $\mathbf{V}_{out}$ can be controlled to improve the input power factor. If $pf = 1$, eqn. 9 must be equal to zero ($\delta = 0$), then

$$V_{out} = V_{in}/\cos(\alpha) \tag{19}$$

Although the amplitude and phase of $\mathbf{V}_{out}$ are controlled to keep $pf = 1$ during this mode, keeping a lower tolerance on the output voltage is more important then keeping unity power factor constantly from user's application point of view [1]. The UPS is of single-conversion type [2], and it will ideally only have a displacement factor of the input current rather than a distortion factor. It will not cause current harmonic interference to the mains even though $pf \neq 1$. Hence, by setting

$$V_{out} = 1\,\text{p.u.} \tag{20}$$

For example, if $V_{in} = 0.95$p.u., from eqn. 19, we can control $\alpha = 18.2^\circ$ to make $pf = 1$. If the mains voltage range is 0.8–1.1 p.u., and using eqn. 9 and 20, the input power factor $\cos(\delta)$ can be obtained as

$$0.9 \leq \cos(\delta) \leq 1.0 \tag{21}$$

a value which is acceptable for such an input power factor range [1]. For the special case $\alpha = 0^\circ$, the angle δ of the input power factor becomes 90°, and consequently only reactive power flows (excluding losses). The UPS should avoid this useless operation case.

From the above considerations, it is easier to maintain more precise output voltage and higher input power factor than to keep a proper phase value (α) of the converter's output voltage during this phase. A block diagram of the proposed UPS is shown in Fig. 12. Basically the system has two control loops as shown in Fig. 13. Loop 1 controls the output voltage and keeps it within the specified tolerance. Hence there is a governed amplitude of V_{ref}, which is generated independently by a sinusoidal signal generator, and is followed by the output voltage. Loop 2 controls the

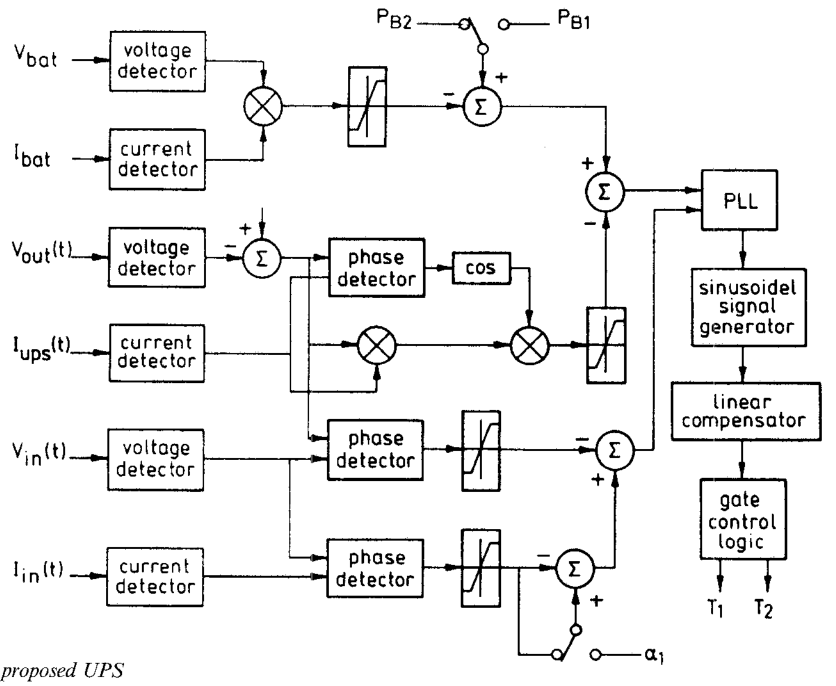

Fig. 12 *Block diagram of proposed UPS*

phase of the output voltage and thus controls the charging energy. The battery charger is operated in constant-energy mode. When the battery is at a low voltage level (initial charging or after deep discharging), the reference battery energy P_{B1} is set to be followed by the power converter (by controlling the phase angle of the output voltage). After a certain amount of energy has been charged into the battery as the battery voltage approaches its floating voltage, the battery charger energy must be charged into P_{B2}.

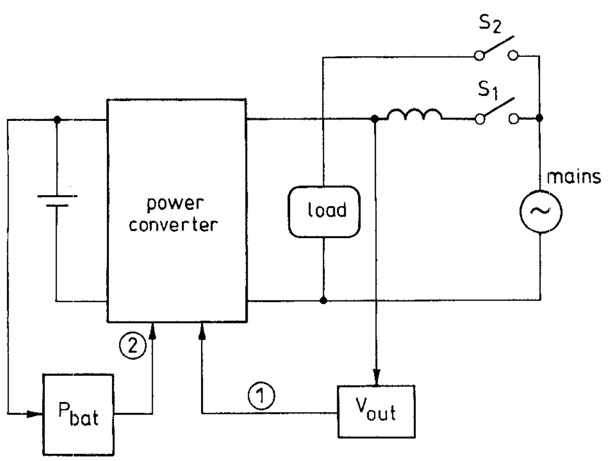

Fig. 13 *Control loops of proposed UPS with mains and bypass switches added*

In principle the system is now functional. In practice some features have to be added as illustrated in Fig. 13 and described as follows:

(i) Mains switch (S_1): The mains has to be disconnected in case of a mains failure such that the inverter would not supply all the other loads on the mains. A thyristor switch is suggested for this task as it will turn on and off quickly.

(ii) Bypass switch (S_2): The bypass can be designed to operate in the case of overload on the output or manually. In this situation, the bypass branch will take over the load uninterruptedly until the malfunction is over. The bypass branch can also be connected with another power source such as a generator.

However, if the fault function short circuits on the output or the other internal parts, the UPS will shut down, i.e. it no longer drives T_1 and T_2 so the output will be zero voltage, and it will also trip S_1 and S_2 simultaneously to protect the power converter and load.

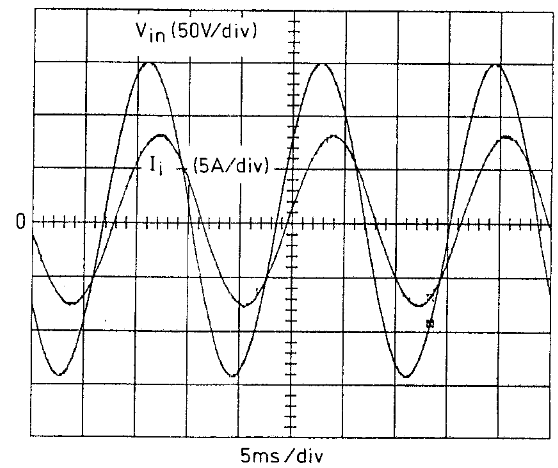

Fig. 14 *Testing waveforms of proposed UPS*
Phase relationship of input during mode (I)

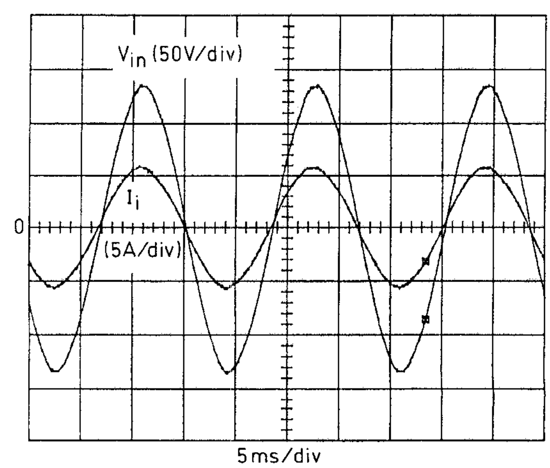

Fig. 15 *Testing waveforms of proposed UPS*
Phase relationship of input during mode (II) while $pf = 1$

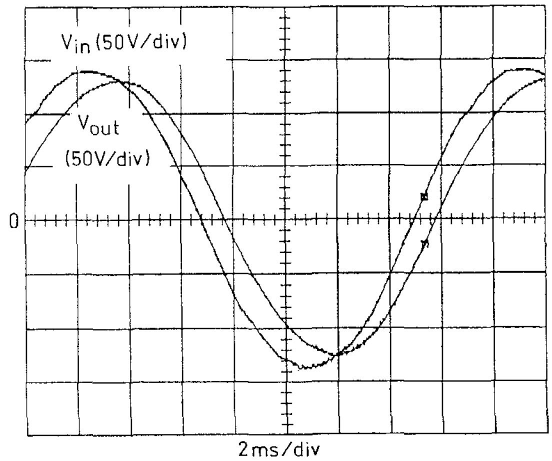

Fig. 16 *Testing waveforms of proposed UPS*
Phase relationship of input voltage and output voltage

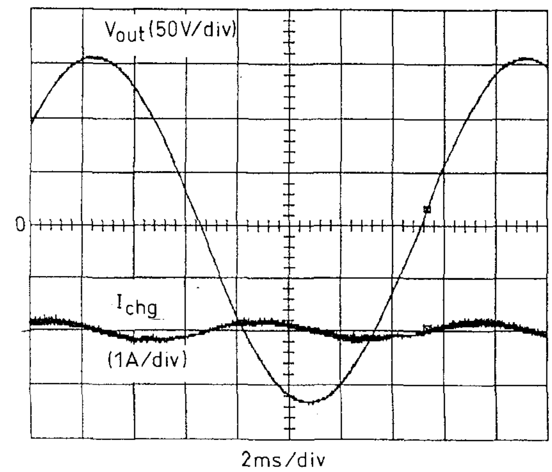

Fig. 17 *Testing waveforms of proposed UPS*
Output voltage and charging current waveforms during mode (I)

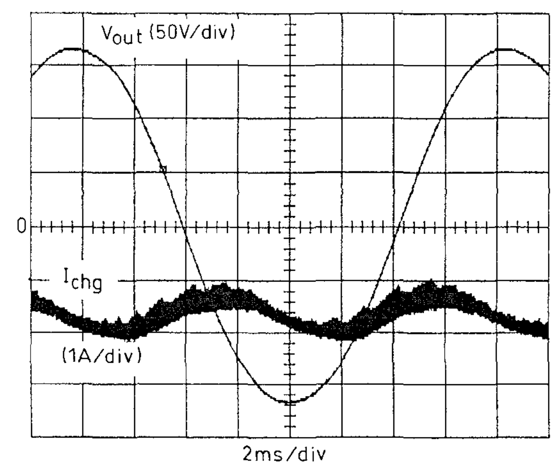

Fig. 18 *Testing waveforms of proposed UPS*
Output voltage and charging current waveforms during mode (II)

3 Test results

To verify the performance of the proposed UPS, a 1KVA prototype unit was implemented using IGBTs and fast recovery diodes (30 12V/2AH-batteries, back-up time = 30 min, input voltage = 110V AC/60Hz). The results obtained with this experimental unit are shown in Figs. 14–18. Fig. 14 shows the phase relationship of the input voltage and input current during mode I — at the start of charging the battery set. We see the phase difference between them, however, the input current remains sinusoidal, i.e. there are no current harmonics injecting into the mains. This is because the UPS is operating in mode I. During this period, the power converter recharges the batteries and regulates the output voltage regardless of the input power factor correction. Therefore, there would be a phase difference between the input voltage and current. With the battery gradually obtaining full energy, the phase difference will become smaller. Fig. 15 also shows the phase relationship between them during mode II after the charging has been completed. We can see that input current still maintains perfect sinusoidal form as well as pf = 1. Fig. 16 shows that there is a phase difference between the input voltage and converter output voltage during this period. There will be always a phase difference between them whether the input current operates in mode I or mode II. The phase difference is variable subject to the condition of input voltage, battery, and load. Figs. 17 and 18 show the output voltage and charging current waveforms during modes I and II, respectively. The charging current (negative value) remains fairly smooth even though it has a 120Hz ripple influenced by the operation of power converter.

4 Conclusions

A novel single-phase UPS scheme using minimised structure has been proposed. It improves the battery charging and the input power factor. Experimental results agree with the theoretical conclusions. The power circuit is satisfactory due to the superior performance and low cost structure. Therefore, it provides a good circuit candidate for future UPS application.

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