A Line-Interactive UPS Structure with Built-in Vector-Controlled Charger and PFC

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Abstract

In this paper a new single-phase uninterruptible power supply (UPS) scheme is proposed. It mainly consists of a minimized structure of power converter which is capable of providing specified constant output voltage, phase-controlled battery charger, and input-power-factor improvement.

I. Introduction

With the information industry prospering, computer and related equipment become more and more important. The uninterruptible power supply (UPS) takes an vital role of guardian for the critical equipment [1-12].

From Fig. 1 to Fig. 5 show the UPS types. Fig. 1 shows the configuration of 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 on-line UPS configuration consisting of a rectifier-charger, battery set, inverter and isolation transformer. No matter whether the mains is normal or not, the UPS always governs the

output voltage without any transferring time. However the input current is distorted by the pre-stage rectifier in this structure unless adding an extra power factor correction (PFC) as pre-regulator but it will have more power devices in this way [3-6].

Recently there has been a multifunctional converter developed as shown in Fig. 3 and Fig. 4. They mainly consist of a multifunctional converter which can work as inverter and charger bi-directionally. Fig. 3 is of parallel processing UPS. When the mains is normal, the UPS works as a harmonic suppressing machine; hence the inverter can not regulate output during this period unless adding a bulk and expensive constant voltage transformer (ferroresonant transformer) to the output [7-10]. Fig. 4 configuration operates the similar function except harmonic suppression but it must have a bulk isolation transformer on the output [11,12].

Fig. 5 is our proposed UPS configuration. It consists of a phase control converter, battery set and link inductor. The power stage is the simplest one among these UPS structures. Besides we use a minimized topology for this converter, and a new control scheme is developed as well.

II. Basic Theory

The proposed UPS consists of a minimized structure of power converter which is capable of providing specified constant output voltage uninterrupted, phase-controlled battery charger, and input-power-factor improvement shown as Fig. 6.

When the mains is normal, the link inductor provides an interface of voltage to synthesize the mains and output voltage vectors. The power converter, in the meantime, provides also regulated output voltage --inverter function-- as well as it provides battery charging --rectifier function. Additionally, by controlling the phase angle of output voltage, the proposed UPS can also provide very high input power factor. When the mains fails, the power goes on supplying the load uninterrupted for being as a conventional inverter. These features above are difficult to be approached in the conventional on-line or standby UPSes [1].

The equivalent circuit is shown in Fig. 7 and the related phasor diagram in Fig. 8. Giving the following equations:

$$\underline{V}_{in} = \underline{V}_{out} + \underline{V}_z \quad (1)$$

$$\underline{I}_{out} = \underline{I}_{ups} + \underline{I}_{in} \quad (2)$$

$$\underline{I}_{in} = \underline{V}_z / jX_z \quad (3)$$

where X_z equals ωL_z .

$$V_{in}(t) = V_{in} \sin(\omega t). \quad (4)$$

$$V_{out}(t) = V_{out} \sin(\omega t - \alpha). \quad (5)$$

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

$$i_{in}(t) = I_{in} \sin(\omega t - \delta) \quad (7)$$

where

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

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

And,

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

Applying trigonometry to obtain

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

According to law of sines, we have

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

Then, θ' can be expressed as

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

Hence

$$\theta = 180^\circ - \theta' + \delta. \quad (14)$$

By using (5), (10), and (14), the phase angle γ can be obtained and represented as

$$\begin{aligned} \gamma &= \theta - \alpha \\ &= 180^\circ - \theta' + \delta - \alpha. \end{aligned} \quad (15)$$

III. Control Principles

From the above relationship equations, we can use them to control the power flow, charging current and input power factor as follows:

Mode (I): Recovering Battery Energy

This mode, after discharging battery energy during outage, absorbs energy from the mains to recover battery vigor. Referring to the phasor diagrams of Fig. 8, the power from the converter can be given by the expression

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

where $\cos(\gamma)$ can be a positive or negative value that determines the power flow. We can make $90^\circ < \gamma < 180^\circ$ by controlling α of Eq. (15), thus $\cos(\gamma) < 0$ resulting in $P_{ups} < 0$ that means the converter is absorbing power from the mains and the battery set is been charging. $P_{ups} > 0$ means discharging energy. If the converter is lossless, thus $P_{ups} = P_{bat} = V_{bat} I_{bat}$. Then we have charging current,

$$I_{bat} = P_{ups} / V_{bat}. \quad (17)$$

Mode (II): Battery Set Fully charged

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

$$V_{out} = V_{in} / \cos(\alpha) \quad (18)$$

By setting

$$V_{out} = 1 \text{ p.u.} \quad (19)$$

For example, if $V_{in} = 0.95$ p.u., from Eq. (18), we can control $\alpha = 18.2^\circ$ to make $pf=1$. If the mains voltage range is from 0.8~1.1 p.u., and from Eqs. (9) and (19), the input power factor $\cos(\delta)$ can be obtained as

$$0.9 \leq \cos(\delta) \leq 1.0 \quad (20)$$

Fig. 9 shows the block diagram of the proposed UPS.

IV. Some Test Results

Results obtained with this experimental unit are depicted in Fig. 10. Fig. 10(a) shows the phase relationship of input voltage and input current during mode (I) -- in the beginning of charging battery-set. We see the phase difference between them, however the input current keeps sinusoidal, i.e. there is no current harmonics injecting into the mains. Therefore, there would be a phase difference between input voltage and current.

With the battery getting full energy gradually, the phase difference will become smaller though. Fig. 10(b) also shows the phase relationship between them during mode(II) but after completing battery-set charging energy. We can see that input current still maintains perfect sinusoidal as well as $pf=1$. Fig. 10(c) shows that there is a phase difference between input voltage and converter output voltage during this period. There will be always a phase difference between them no matter whether it operates in mode (I) or mode (II). And, the phase difference is variable subject to the condition of input voltage, battery, and load.

V. Conclusions

In this paper a new single-phase UPS scheme has been presented. It is very satisfactory due to the superior performance and low cost of power-stage structure. It seems to be a good candidate for UPS application.

Fig. 1.: The configuration of standby UPS.

Fig. 4.: The configuration of bidirectional UPS.

Fig. 2.: The configuration of on-line UPS.

Fig. 5.: The configuration of the proposed UPS.

Fig. 3.: The configuration of parallel processing UPS.

Fig. 6.: Power circuit of the proposed UPS.

Fig. 7.: The equivalent circuit of simplification for the proposed UPS.

Fig. 8.: Phasor diagrams of the proposed UPS. (a) $\gamma = 55^\circ$. (b) $\gamma = 110^\circ$.

Fig. 9.: Block diagram of the proposed UPS.

Fig. 10.: Testing waveforms of the proposed UPS.

(a) The phase relationship of input during mode (I).

(b) The phase relationship of input during mode (II) while $pf = 1$.

(c) The phase relationship of input voltage and output voltage.

VI. References

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