SMPS WITH ZERO STANDBY POWER FOR ELECTRONIC HOUSEHOLD EQUIPMENT

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Abstract

This paper presents a 6.8 W ac–dc Switch-mode Power Supply (SMPS) for electronic household equipment that enables the appliance to shut down automatically at the end of the working cycle and that consumes zero power (according to IEC62301 Clause 4.5) from the power line while in this “off-mode” condition. This functionality is realized by a specifically designed high-voltage switcher IC featuring the so-called “Zero-power function”, which is applicable to other market segments too. An additional application example is provided.

1 Introduction

Most of electrical and electronic household and office equipment consume some electric power when they are switched off or not performing their primary function. This wasted power, which we must pay for anyway, is commonly referred to as standby power.

The typical standby power per piece of equipment is low but, considering the huge overall number of pieces permanently connected to the power line, the worldwide standby losses represent a significant fraction of total electricity use. Several studies in different countries estimate that this fraction lies between 5% and 10% of the residential electrical consumption [1]. Other studies estimate that in 2007 the standby power produced 1% of the world's carbon dioxide (CO₂) emissions [2]. This is not negligible if one thinks that total air travel contributes less than 3% of global CO₂ emissions [3].

Therefore, the waste of electricity associated with standby power and its associated CO₂ emissions have been recognized as an issue, which has drawn a lot of attention since the beginning of the twenty-first century. As a result, a large number of programs, both voluntary and mandatory, that aim to reduce standby power are currently running. In some cases these programs target standby power only, while others target appliance's total energy use, treating standby power just as one component.

Among them, the European Regulation 1275/2008 and its updated/amended version 801/2013 are particularly noticeable. In fact, they have changed the criteria for energy labelling of household and office appliances, since also the energy consumed while these devices are not performing their primary function is taken into account.

In this respect, two phases of the typical working cycle, graphically shown in fig. 1, in appliances such as dishwashers or washing machines are particularly relevant:

- The “OFF-mode”, i.e. when the appliance is turned off with no indications given to the user, who is the one supposed to switch it on; this phase may persist for an indefinite time while the appliance is connected to the power line.
- The “left-ON mode”, i.e. when the appliance has finished its working cycle and remains switched on with some indications given to the user; this phase may persist for an indefinite time after the completion of the cycle without further intervention of the user.

To achieve the highest labelling grade, it is desirable to limit the duration of the left-ON mode and let the appliance enter the OFF-mode automatically as it completes its working cycle, as graphically indicated by the backward arrow in fig. 1. Additionally, as far as energy consumption calculations for labelling are concerned, IEC62301 Clause 4.5 states that power measurements lower than 5 mW can be rounded down to zero. Hence, if during the “OFF-mode” the consumption of the appliance is lower than 5 mW, no contribution at all to energy consumption needs to be considered while the device is not performing its primary function.

This dual objective – automatically entering the OFF-mode at the end of the working cycle and consuming less than 5 mW while in the OFF-mode - is usually fulfilled using latching or impulse relays or other bistable electro-mechanical devices able to perform a similar function. These are typically quite more expensive compared to standard “single side stable” relays. Being able to get rid of them would help reduce the cost of the appliance.

![Fig. 1. Typical working cycle of an appliance (e.g. washing machine)](image-url)
This paper presents a Switch-mode Power Supply (SMPS) for electronic household equipment that fulfills this dual objective with no need of bistable electromechanical switches. In fact:

- The SMPS can be shut down by the microcontroller supervising the operation of the appliance and enter a special state where it delivers no voltage at its output terminals.
- Once in this state, the SMPS is ready to be manually restarted by the user while consuming less than 5 mW from the power line at 230 Vac.

This functionality is realized by the so-called “Zero-power function” available in the VIPer0P, a specifically designed high-voltage switcher that embeds the converter control circuit and the power MOSFET in the same package for a compact and cost-effective solution.

This paper is arranged as follows: in section 2 a quick description of the IC, particularly focused on its “Zero-power function”, which is the core of the SMPS under consideration, is provided; in section 3 the SMPS, tailored to typical specifications of washing machines, is described and some evaluation data coming from the bench evaluation of a number of working samples are given. Section 4 discusses the application of this type of SMPS and shows that the concept of “Zero-power function” may address not only appliances with a working cycle initiated by the user and autonomously terminated like that shown in fig. 1, but also appliances (e.g. air conditioners, TV sets) that the user should be able to switch on and shut down by means of a remote control.

### 2 VIPer0P and its Zero-power Function

The VIPer0P, as shown in fig. 2a, is a multi-die device made up of two chips assembled in the same package: a low-voltage chip (“Control IC”) embedding a fixed-frequency PWM controller and the control functions of a typical offline flyback converter and a high-voltage chip embedding an 800 V / 20 Ω “smart” MOSFET. The attribute “smart” stems from the fact that it integrates a high-voltage start-up cell and a temperature sensor in addition to the mere MOSFET, so that it should be regarded more as a small-scale integration (SSI) high-voltage IC rather than a discrete component (see fig. 2b).

![Fig. 2. Multi-die structure of VIPer0P (a) and “smart” MOSFET functional schematic (b).](image)

A key feature of the device is its “Zero-Power function”, whose principle schematic is depicted in fig. 3. It consists in a special idle state (Zero-Power Mode, ZPM) where the control IC is totally shut down - except for the circuitry necessary for exiting from ZPM - and the high-voltage start-up cell (the current generator used to start up the device from the rectified power line directly by charging its Vcc capacitor Cs above the start-up threshold) does not perform its usual function.

With reference to fig. 3 and assuming the device is operating normally, when the voltage on pin OFF is pulled to ground for more than 10 ms, the “Zero-power Logic” block asserts the signals SD and ZP high. This 10 ms debounce time helps improve the immunity to disturbances.

SD asserted high disconnects nearly all the blocks of the control chip from the Vcc supply line, so that it is shut down with the gate of the main MOSFET pulled low. This stops the SMPS. The only parts of the control IC that remain alive are the “Zero-Power Logic” block and the 4V regulator that provides the bias voltage to it.

ZP asserted high turns M3 on and fixes the voltage of the gate terminal of M1 at about 15 V through the zener diode ZD2. In this way, the Vcc voltage is set at about 13 V. The 4V linear regulator supplied from Vcc provides those few μA needed to operate and keep the “Zero-Power Logic” block alive. Both pins ON and OFF are internally connected to this 4 V supply line via 50 kΩ pull-up resistors, so either of them can be used to provide a small current to some external circuit.

The overall consumption in ZPM consists of two components: that on the branch ZD1, RG, ZD2, M3 and that due to the quiescent current Iq (=1.5 μA) absorbed by the 4V regulator and the “Zero-Power Logic” block plus the current Iext delivered to an external circuit.

This consumption may be estimated as follows:

\[
P_{ZPM} = V_{in_{pk}} \left( \frac{Vin_{pk} - V_{ZD1} - V_{ZD2} + Iq + I_{ext}}{R_G} \right),
\]

with obvious symbolism. At Vin = 230 Vac and with worst-case values (RG = 28 MΩ, VZD1 + VZD2 = 20 V, Iq = 2 μA) it is PZPM = 4.2 mW + 0.325 mW/μA of Iext.
It is worth highlighting that pulling low pin OFF is the only way to enter ZPM. This makes sure that, in case of a power failure (temporary absence of the line voltage) occurring while the appliance is in operation and long enough to shut down the SMPS, the unit will restart automatically as the line voltage returns. In this way, the system may return exactly to the same condition it was before the event. It is also worth mentioning that using a dedicated pin prevents the risk of accidental triggering of ZPM that would exist in case it was combined with other functions on the same pin.

To exit from ZPM, it is necessary to pull pin ON to ground for more than a 20 μs debounce time. By doing so, the “Zero-power Logic” block asserts the signals SD and ZP low. ZP asserted low turns M3 off and releases the gate terminal of M1, while SD asserted low reconnects the blocks of the control chip to the Vcc supply line, held at 13 V by the Vcc capacitor Cs. This voltage is well above the start-up threshold of the IC (8V), so the high-voltage start-up cell is disabled by M2 turned on and switching activity restarts immediately.

Fig. 4 shows a couple of ways the pins ON and OFF can be operated. With the arrangement (a) the microcontroller (MCU) supervising the operation of the appliance shuts down the SMPS by pulling low the pin OFF through one of its GPIO pins, cutting also its own supply voltage. The restart is commanded by a pushbutton or a tactile switch pressed by the user that directly operates pin ON. The MCU wakes up after the SMPS is again up and running. This arrangement provides the minimum consumption from the power line.

With the arrangement (b) the microcontroller shuts down the SMPS by pulling low pin OFF and wakes it up as well by pulling low pin ON. Two of its GPIO pins are used. The status of the pushbutton or tactile switch is sensed by other GPIO pins of the MCU. This solution is more robust: the detection of a power-on commanded by the user may not rely only on the 20 μs debounce time of pin ON. However, the MCU (rated for 3.3V supply voltage) is powered also during ZPM, so it must be equipped with advanced features of power management such as an ultra-low consumption Standby Mode with fast wake-up. Finally, note that with a proper selection of the buffer capacitor (Cb) value this arrangement can provide significant energy to an external circuit for a limited time.

3 SMPS with Zero standby power consumption

A wide-range input, 6.8W two-output non-isolated flyback converter designed with the VIPer0P has been built, tested and evaluated on the bench. Its main electrical specification, tailored to a typical SMPS that powers the control electronics in a washing machine, is provided in Table I, while its electrical schematic is illustrated in fig. 5.

The converter provides automatic shutdown with auto-restart functionality as a protection against overload, short circuit, open loop and over temperature conditions.

It meets IEC55022 Class B conducted EMI. Further, as far as energy saving requirements are concerned, it meets:

- ErP Lot 6 Tier 2 requirements for household and office equipment;
- European regulation 1275/2008 regarding eco-design requirements for standby and off-mode electric power consumption of household and office equipment;
- European CoC ver. 5 Tier 2 requirements for External Power Supplies.
- Five-star energy efficiency rating system for no-load consumption of mobile phone chargers (<30 mW).

<table>
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<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
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<tr>
<td>Power line voltage range</td>
<td>Vin</td>
<td>85 - 265</td>
<td>Vac</td>
</tr>
<tr>
<td>Power line frequency range</td>
<td>fLin</td>
<td>47 - 63</td>
<td>Hz</td>
</tr>
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<td>±5 ± 3%</td>
<td>Vdc</td>
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<td>Rated output Power (Out #1)</td>
<td>Pout1</td>
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<td>W</td>
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<tr>
<td>Regulated output voltage (Out #2)</td>
<td>Vout2</td>
<td>±7 ± 10%</td>
<td>Vdc</td>
</tr>
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<td>Pout2</td>
<td>2.8</td>
<td>W</td>
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<td>mW</td>
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<tr>
<td>Max. input power in ZPM (@230 Vac)</td>
<td>PInZPM</td>
<td>5</td>
<td>mW</td>
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</table>

Table 1. Main electrical specification of the 6.8W SMPS with Zero-power function (non-isolated flyback converter) case study.

Fig. 4. Examples of usage of ZPM pins of VIPer0P with a microcontroller and a pushbutton or a tactile switch.

Fig. 5. Electrical schematic of the SMPS with Zero-power function specified in Table 1.
The converter front-end includes a single-wave rectifier with a C-L-C arrangement that serves both as energy reservoir and differential mode EMI filter. Shielding techniques have been used in the construction of the transformer TR1 to reduce common mode EMI displacement currents. This, along with IC’s frequency jitter function, makes this filter arrangement adequate to provide excellent EMI performance.

The main output \( V_{out} \) is tightly regulated simply using a resistor divider connected to pin FB of the VIPer0P. This is possible because the transconductance error multiplier available in the device is referred to a separate ground (EAGND) that can float down to -12 V with respect to the ground of the IC (SGND). The C-R-C network from pin COMP to SGND provides frequency compensation to the feedback loop that regulates the voltage of the main output. The secondary output \( V_{out2} \) is semi-regulated by magnetic coupling through the turn ratio of the two output windings.

The VIPer0P is supplied from \( V_{out2} \) via the diode D3. D3 protects the current delivered by the high-voltage start-up generator from charging the output capacitor C8 as well. With a direct connection start-up would be extremely slow and might even be prevented by a load connected to the \( V_{out2} \) bus.

The converter has been completely characterized. However, considering the context, only the results related to energy saving requirements are reported. Table 2 shows the results of the input power measurements in ZPM and no-load.

Figures 6 and 7 show the load-light efficiency measurements and the so-called active mode efficiency (average of the efficiency measurements at 25%, 50%, 75% and 100% of the rated load as per the European CoC) respectively, performed on the equivalent single-output 12 V / 6.8 W converter, simply obtained connecting the load across the \( V_{out1} \) and \( V_{out2} \) lines.

<table>
<thead>
<tr>
<th>Vin</th>
<th>ZPM input power consumption [mW]</th>
<th>No-load input power consumption [mW]</th>
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<tr>
<td>115 Vac</td>
<td>0.8</td>
<td>6.5</td>
</tr>
<tr>
<td>230 Vac</td>
<td>3.5</td>
<td>9.1</td>
</tr>
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</table>

Table 2. ZPM input power and no-load input power of the SMPS with Zero-power function shown in Fig. 5.

The data in Table 2 show the SMPS, when in ZPM, is ratified to have zero-power input consumption as per IEC62301 Clause 4.5 and is Five-star energy efficient when operating with no load.

The diagrams in fig. 6 show that the equivalent 12 V / 6.8 W SMPS is compliant with the ErP Lot 6 Tier 2 requirements in off-mode (same as ER 1275/2008) and the 10% load efficiency target envisaged by the European CoC ver. 5 Tier 2.

The diagrams in fig. 7 show the compliance of the equivalent 12 V / 6.8 W SMPS with the 4-point average, active-mode efficiency envisaged by the European CoC ver. 5 Tier 2.

It is worth noticing that the efficiency of the equivalent single-output SMPS is adversely affected by the double voltage drop across D4 and D5. In a true 12 V / 6.8 W SMPS (with a single secondary rectifier) it is reasonable to expect efficiency values 3-4% higher on average.

The oscilloscope picture in fig. 8 shows the SMPS entering ZPM about 10 ms after pulling pin OFF to ground: switching activity is stopped and the output voltage \( V_{out1} \) falls to zero. Note how the voltage on pins ON and OFF while the SMPS is in operation is affected by switching noise with no malfunction.

The oscilloscope picture in fig. 9 shows the SMPS exiting ZPM. Switching activity starts about 35 \( \mu \)s after pulling pin ON to ground: VIPer0P begins its soft-start phase (note its extremely short ON-times and its cycle skipping functionality to prevent current build-up due to the lack of demagnetization voltage at start-up) and \( V_{out1} \) starts rising (negative).
In the schematic of fig. 5 the ON/OFF pins appear to be operated by simple switches that pull those pins to the ground of the IC. The actual interface between the VIPer0P and the microcontroller powered by the SMPS that actually operates those pins must take some constraint into consideration.

The SMPS provides a -5V bus intended to enable triac driving in 4-quadrant operation to control the washing motor. On the other hand, an MCU requires a tightly regulated +5 V (or +3.3 V) supply voltage. Thus, not to generate an additional +5V bus, the MCU needs to be powered from the -5V. To do so, the ground of the MCU needs to be the -5V bus and the ground of the SMPS (and of the VIPer0P) its positive supply voltage.

This offset existing between the two grounds requires a form of level shifting. Fig. 10 shows possibly the simplest interface circuit, where the BJT and the resistor provide the necessary level shifting. The GPIO pin is assumed to be a push-pull type when operated as an output. The 220 pF capacitors connected between pins ON and OFF to the ground of the IC help reduce noise sensitivity and increase immunity to EFT tests.

4 Usage of an SMPS with Zero standby power consumption in household appliances

4.1 Appliances featuring a working cycle

There are a number of both major and small appliances that are characterized by a working cycle initiated by the user and that can be autonomously terminated, like that in fig. 1. Among major appliances, in addition to washing machines one could consider dishwashers and clothes dryers. Small appliances, such as microwave ovens and coffee makers, may have such a characteristic as well.

All of them may benefit from an SMPS with Zero-power standby consumption based on the VIPer0P, similar to that described in section 3. Needless to say, the SMPS will be tailored to the requirements of the specific appliance, so it may have a different number of outputs with different voltage and current ratings. The only constraint imposed by the VIPer0P is the maximum delivered power, which should not exceed about 7 W in wide-range mains applications and about 14 W in European mains applications.

However, the key to energy labelling is the standby consumption of the entire appliance and not just of its SMPS. Therefore targeting zero-power standby consumption of the appliance, there are two basic points to consider.

- Firstly, the appliance should be provided with a true “OFF-mode” state, i.e. with no indication given to the user; secondly, it is specified - or acceptable - that the appliance enters this mode once finished its working cycle, in case after staying in left-ON mode for a finite time to perform some additional actions (e.g. acoustic or visual signaling, automatic maintenance, etc.).

These appliances required/specified to provide some indications to the user at the end of their working cycle and, therefore, not provided with a true OFF-mode could still meet the zero-power target. To do so, the indication system should consume no more than few μA, as dictated by (1), or should not be electrically operated.

- In nearly all major appliances, this SMPS with Zero-power standby consumption is not the only functional block using electrical energy from the power line (e.g. the washing motor or the water pump in a washing machine). Therefore, the overall standby consumption of the appliance depends also on how the consumption of these parts during the OFF-mode is handled.

As to possible sources of standby power consumption other than the SMPS, not only active circuits should be taken into account but also passive circuits. EMI filters, for example, may consume significant standby power because of the current flowing through the X-capacitors (those connected across the power line). In view of achieving zero-power standby for the entire appliance, one might even consider disconnecting everything but the SMPS from the power line using a single side stable relay powered by the SMPS.

4.2 Remotely controlled appliances

There are a number of appliances that do not have a working cycle like that in fig. 1 and that might benefit from a VIPer0P-based SMPS with Zero-power standby consumption anyway. One group includes all those appliances that are switched on and off by the user via an RF or an IR remote control, such as air conditioners, TV sets, HI-FI and home cinema systems.
Again, the two previously mentioned points (acceptability of an OFF-mode with no indication given to the user and removal of all the sources of standby power consumption other than the SMPS) are a key to achieving zero standby consumption of the entire appliance.

Focusing on IR remote control, a system architecture like that depicted in fig. 11 may be used to meet the target. It exploits the Zero-power function of the VIPer0P, with the interface circuit in fig. 4b.

The functionality of this architecture resembles that described in [5], however, in this work a latching relay is still used, whereas the proposed solution gets rid of that. Additionally, while the system in [5] uses energy harvesting, this system relies on a more conventional approach based on a micropower transimpedance amplifier (TIA) and an appropriate signal conditioning circuit that provides good immunity to environmental disturbances (e.g. sunlight, fluorescent and incandescence lamps, etc.).

When the user switches off the appliance through the IR remote control, the SMPS enters ZPM and the MCU (STM32L151) a Standby Mode where its consumption is about 0.3 μA. This current is provided by the ON pin of the VIPer0P. Additionally, the VIPer0P supplies the IR diode and the downstream signal conditioning circuit through its OFF pin, delivering about 2 μA. According to (1), the worst-case overall current consumption in ZPM to stay within the 5 mW limit should be less than 2.46 μA, so the target is achievable.

The first experimental results on the prototype shown in fig. 12 are encouraging both in terms of electrical performance in ZPM and operability through a standard remote control. An optimization work is ongoing and is expected to result shortly in a fully compliant Zero-power standby consumption system.

4.3 Other appliances

Other household appliances, such as induction cookers, freezers and refrigerators, are normally switched on and off via an ac switch that opens and closes the physical connection of their electric and electronic systems to the power line.

The usage of an SMPS like the one described in section 3 in these appliances would turn true zero-power consumption into “legal” zero-power consumption in off-mode; however, the expensive ac switch could be replaced by a low-voltage pushbutton or tactile switch that, anyway, should guarantee safety isolation to the user. In this case only the removal of all the sources of standby power consumption other than the SMPS would be of concern to meet the zero-power target.

Conclusions and future work

An SMPS for electronic household equipment based on the VIPer0P, a high-voltage switcher IC featuring the so-called “Zero-power function”, has been presented along with its energy saving performance. This SMPS enables appliances to shut down automatically at the end of the working cycle and achieve zero standby power consumption (according to IEC62301 Clause 4.5) from the power line.

This SMPS, with the necessary changes, is applicable to other household equipment as well, in particular to remotely controlled appliances. The target of zero standby power consumption appears to be within easy reach also in these applications. This is the objective of the optimization work currently ongoing on a prototype for air conditioners and the final results of this work will be the subject of a future paper.

References