

Low cost power supplies using VIPer12A in non-isolated off-line applications

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Abstract

Not isolated off-line power supplies for low cost applications are becoming more and more common in the industrial field as well as in home appliances. Since the size of the power supply is a key factor, the industry is looking for viable new solutions without bulky 50/60Hz transformers. Moreover the smart power approach is getting diffused thanks to its simplicity and easy using. STMicroelectronics VIPer12A is a low cost monolithic smart power with an integrated 60kHz PWM controller and a high voltage Power MOSFET with 730V breakdown voltage. The smart power IC performs high efficient power conversion with reduced space and cost compared to discrete counterpart.

In this paper several not isolated topologies using the power IC are analyzed, such as the standard Buck and Buck-boost configurations, a two-output topology and a novel topology with double complementary outputs. The considered topologies are suitable to cover the major part of the low power applications in the industrial as well as in the home appliances market.

Design tips and applications examples are given showing how simple is to build small power supplies thanks to the power IC features, such as start-up capability, integrated thermal and overcurrent protections, and feedback circuit.

1. Introduction

In the last years new a migration from linear to switch mode power supply has been taking place in industrial market as well as in the home appliances market in order to reduce size and cost of the converter. Moreover energy efficient solutions are preferred and almost mandatory because of international standard, recommendations and marketing look. As a consequence old projects have to be updated shifting from the 50/60Hz transformer plus linear regulator to high frequency power converter. Moreover cost optimi-

zation of new designs suggests developing worldwide suitable applications, considering wide range input voltage. Switch mode approach makes this possible since it is based on the modulation of the conduction time of a power semiconductor switch. In the industrial and home appliances markets the specifications are pretty standard, since the system usually consists in microcontroller, relays, LEDs, displays, triacs for low power motor control or gate drivers for isolated gate devices. Thus the required DC voltages are usually +15V for gate drivers, +5 for microcontroller and LEDs, +24V or +12V for relays, etc. What makes the difference between different applications is the complexity of the system and then the power required to feed all the components.

Smart power approach further simplify the design and development of such power supplies simplifying design procedure, since controller and power device are on-board coupled, no power device driving issue has to be managed as well as layout issues related to the core block of the power supply.

In the paper an overview of not isolated topologies is carried out and some typical applications are analyzed using the smart power integrated approach using VIPer12A.

2. Off-line low power topology overview

Off-line not isolated topologies convert the mains to regulated dc voltage with no need of any isolation transformer, adjusting the duty cycle of a power switch. The energy is transferred from input to output by a low cost inductor.

Two topologies are used to generate either positive or negative voltage with respect to the common terminal of the input voltage, "step down" (or "buck") and "step-down/up" (or buck-boost") topology respectively, shown in Fig. 1.

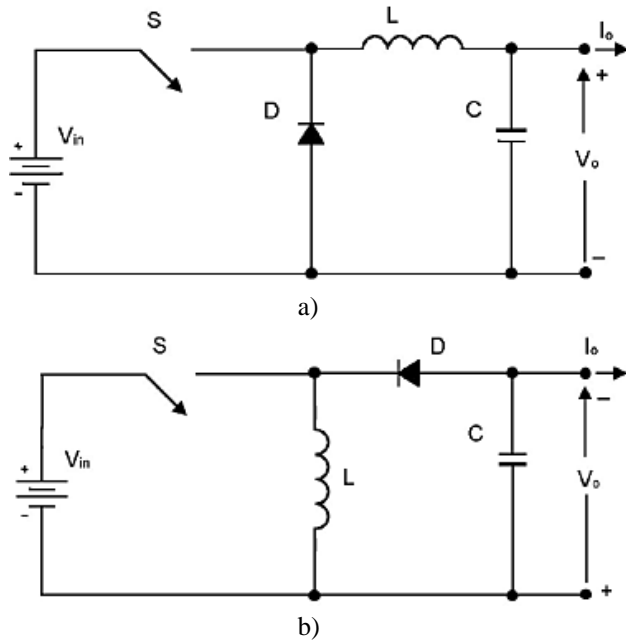


Fig. 1 - Not isolated power converters: a) Buck, b) Buck-boost

Both topologies use an inductor for energy storage, charged during the turn-on of the power switch. The inductor current waveform defines the mode of operation of the converter, i.e. “continuous” and “discontinuous”. In continuous mode, the inductor current never goes to zero, while in discontinuous mode such a current is zero for a given time period. A “boundary mode” is also defined, referring to a single zero point of the inductor current.

In continuous mode, both converters operates like a transformer with a voltage ratio continuously controlled electronically by means of duty cycle of the switch, \$D\$, defined by the ratio between the turn on time, \$t_{on}\$, and the switching period \$T_s\$, according to (1) and (2):

$$\frac{V_o}{V_i} = D \quad \text{buck converter} \quad (1)$$

$$\frac{V_o}{V_i} = \frac{D}{1-D} \quad \text{buck-boost converter} \quad (2)$$

When the switch is on, there is a constant voltage across the output inductor (\$V_i - V_o\$), making the current in it rising linearly at a rate, \$di/dt\$, given by (3).

$$\frac{di}{dt} = \frac{V_i - V_o}{L} \quad (3)$$

As the switch is turned off, the voltage polarity across the inductor immediately reverses trying to maintain the same current as just before turn off. The diode turns on and clamps the inductor voltage to ideally zero. The voltage across \$L\$ is \$V_o\$ and its current ramps down linearly at a rate given by (4).

$$\frac{di}{dt} = -\frac{V_o}{L} \quad (4)$$

Once the switch turns on again the current in \$L\$ is diverted from \$D\$ to the switch \$S\$, back biasing the diode. The current in \$L\$ consists of the switch current when it is on and of the diode current when the switch is off. The inductor

current ramps up and down around the DC value \$I_o\$ with a ripple determined by the value of \$L\$.

Starting from the basic topologies, double output converters can be obtained with low cost components, as shown in Fig. 2. In particular they are referred to Buck converter, but Buck-Boost topology applies as well. The topology in Fig. 2a) uses an output inductor with two windings coupled in flyback mode with a proper turns ratio \$n\$. The second topology represents a novel configuration and is suitable to supply double complementary output. The main advantage is the cost optimization due to the standard single winding inductor. The second complementary output is generated charging a capacitor during the free-wheeling of the inductor current. The voltage across the capacitor is regulated by means of a zener diode of suitable value.

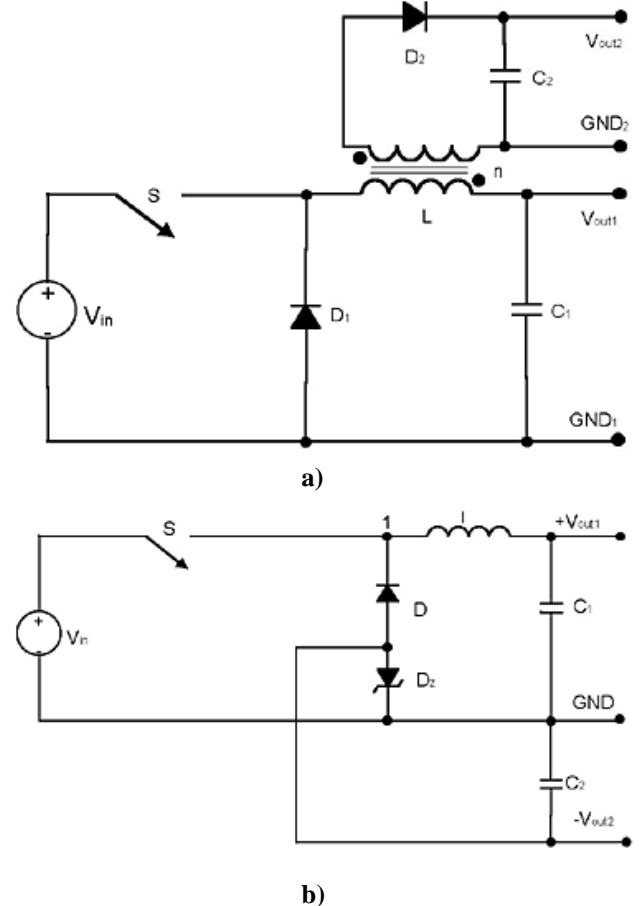


Fig. 2 - Two output Buck converter: a) coupled inductor, b) complementary.

In the standard Buck topology the voltage of the node 1, in Fig. 3, is clamped by the diode \$D\$, allowing the free-wheeling of the inductor current. In the considered solution, the zener diode, \$D_z\$, clamps such a voltage to \$(V_d + V_z)\$, where \$V_d\$ is the voltage drop across the diode and \$V_z\$ the zener voltage. If a capacitor is connected across the zener and the ground, a negative voltage source is generated. Of course, due to the principle of operation, the second output cannot supplies more current than the first one. The switching cycle can be basically divided in two periods as shown in Fig. 3. Considering discontinuous conduction mode, DCM, during the conduction of the switch \$S\$, \$t_{on}\$, the input DC bus is connected to the output and supplies the load, as shown in Fig. 3a). Once the switch is turned off, the inductor current

free-wheels through the diode D_1 , as shown in Fig. 3b), until it reaches zero and the output capacitor C_1 feeds the load.

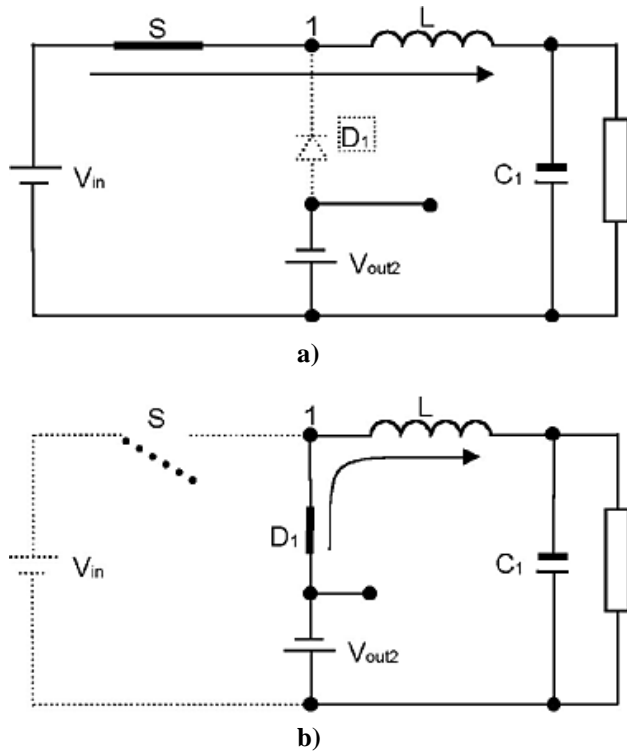


Fig. 3 - Functional circuit of the proposed Buck converter: a) t_{on} , b) t_{off} .

The presence of the zener diode in the free-wheeling path does not affect the basic operation of the converter but it could impact the efficiency. In order to understand how the zener diode affects the efficiency of the converter, Fig. 4 can be considered. If there is no load on OUT2, the free-wheeling current flows through both diodes, D_1 and D_z .

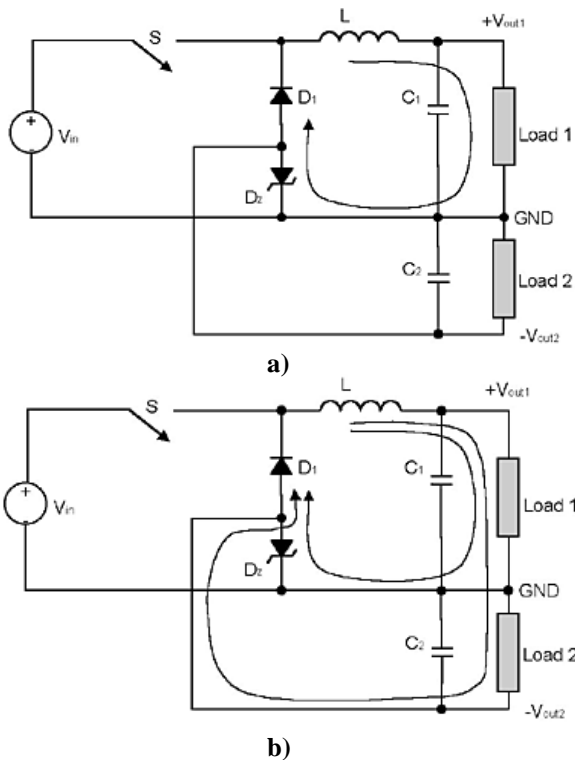


Fig. 4 - Effect of zener diode on power conversion: a) $I_{load2}=0$, b) $I_{load2} \neq 0$.

As the current drawn from OUT2 increases, the free-wheeling current flows through a different path, splitting in two components as shown in Fig. 4b). In this way the power dissipation in D_z is reduced and the efficiency is increased accordingly. Thus, the converter performs better if the complementary output is loaded, for a given output current I_{out1} . The selection of both the output capacitors depends on the output ripple specification. A proper C_2 selection has to be made taking into account that the complementary output is somehow related to the main output. If decoupled outputs are required, a suitable control circuit has to be used, as shown in Fig. 5. This circuit works like a dummy load and can be easily implemented with very low cost components. The circuit consists in two transistors, Q_1 and Q_2 , e.g. a pnp and a npn BJT, a resistor R_1 and a zener diode D_{z1} . The transistor Q_1 , driven by Q_2 and D_{z1} , assures a given current in L regardless of the load supplied by V_{out1} . Doing so, I_{out2} can be varied regardless of I_{out1} and is only limited by the maximum allowable I_{out1} .

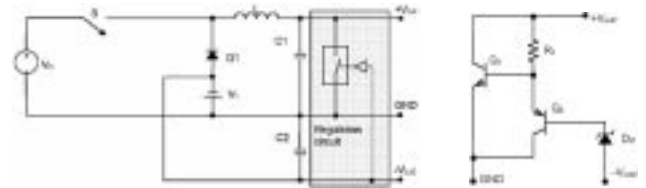


Fig. 5 - Double-output regulated converter in Buck configuration.

3. Designing a not isolated converter using a VIPer12A

The design of a Buck converter using a VIPer12A is straightforward thanks to the device features. The circuit schematic is shown in Fig. 6a. The supply voltage for VIPer12A can be easily obtained through the output of the converter by means of a diode and a capacitor on V_{dd} pin, D_1 and C_1 . The diode voltage rating depends on the input voltage, e.g. for European voltage range 185-265Vac a 400V diode can be used. C_1 value is chosen according to the start-up time and the short circuit behavior of the converter. In fact, during short circuit the V_{dd} voltage falls down below the minimum required value, enabling the internal high voltage current generator for a new start-up sequence. The charging and discharging time of the capacitor depends on its value, thus the time period during which the power switch is properly supplied changes accordingly. Moreover, if current pulses heat considerably the device, the over temperature protection shut off the circuit. Typical values range from 300nF to 10uF, while the voltage rating is 25-50V, depending on the output voltage. The regulation circuit simply consists in a zener diode D_z across FB and V_{dd} pins. To perform a better regulation, a filter capacitor C_2 can be connected across FB and S pins. C_2 value is in the order of some tens of nF. If the output voltage is lower than 15V the circuit has to be slightly modified in order to allow the start up of VIPer12A. In such a case the regulation circuit has to be decoupled from the supply circuit, using separate diode and capacitor to supply the zener diode on FB pin, D_2 and C_3 in Fig. 6b. The diode D_2 is a low voltage diode, e.g. 1N4148, and allows the voltage on Vdd to reach the start-up value. Since D_2 and C_3 realize a peak detector of the output voltage, C_3

value influences the precision of the regulation circuit. If high precision is not an issue it can be as low as 100nF

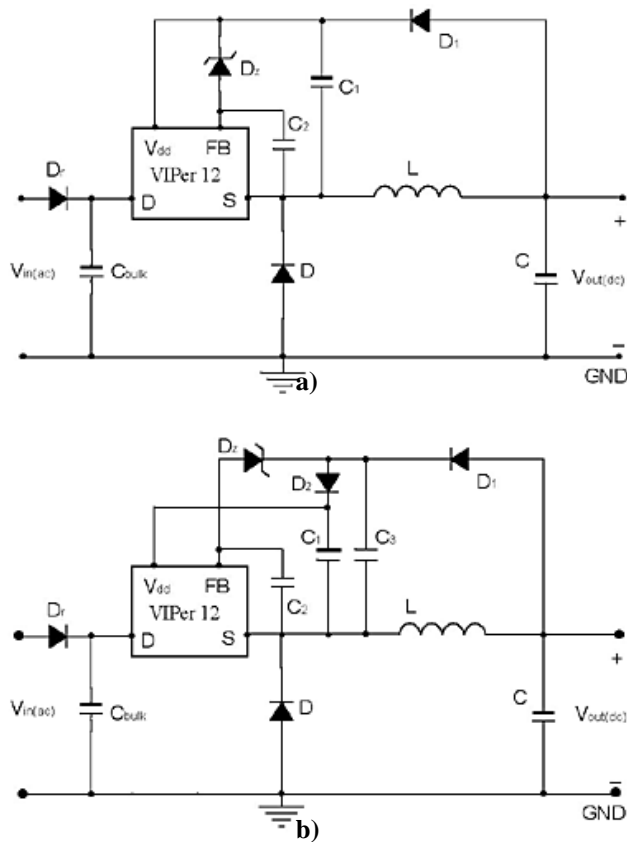


Fig. 6 - Buck converter: a) $V_{out} > 15V$, b) $V_{out} < 15V$.

If the required output voltage is lower than 8V, a different solution has to be used. In fact, although the control feedback path and supply circuit are separated, since the output voltage is lower than the minimum voltage on V_{dd} pin, the device would not start anyway and would work in start up mode with no voltage regulation and high peak current. A patented approach is introduced that allows supplying the power IC. As shown in Fig. 8a the proposed circuit needs one more inductor compared to the standard Buck topology to generate the supply voltage. It stores the required energy in an auxiliary capacitor through a low voltage diode by means of a voltage divider. The capacitor C_4 is charged during the turn-on time of the power switch through D_3 and then is discharged during the turn-off time through D_1 transferring energy to C_1 . D_3 is a low voltage diode, i.e. 1N4148, and C_4 is a low voltage capacitor which value ranges from 10nF to 1uF. In particular., such a capacitor has to be calculated in order to store the charge required by the VIPer12A and supply the proper voltage depending on output inductors ratio L_1/L_2 and ac input voltage. Due to inductor ESR, the voltage across C_4 may depend on the output current too. The capacitor C_1 is calculated following the standard procedure. In Fig. 7 are shown the schematics for Buck-Boost converter with output voltage lower than $(-15V) < V_{out}$ and for $(-15V) < V_{out} < (-8V)$. If the required output voltage is higher than $(-8V)$, i.e. $(-5V)$, a different solution has to be used as shown in Fig. 8b. The diode D_4 is a low voltage diode, e.g. 1N4148, and the value

of C_4 is about 100nF in order to store the energy required by the VIPer12A. The capacitor C_1 is calculated following the standard procedure. The capacitor C_2 is connected between FB and S pins to improve the regulation.

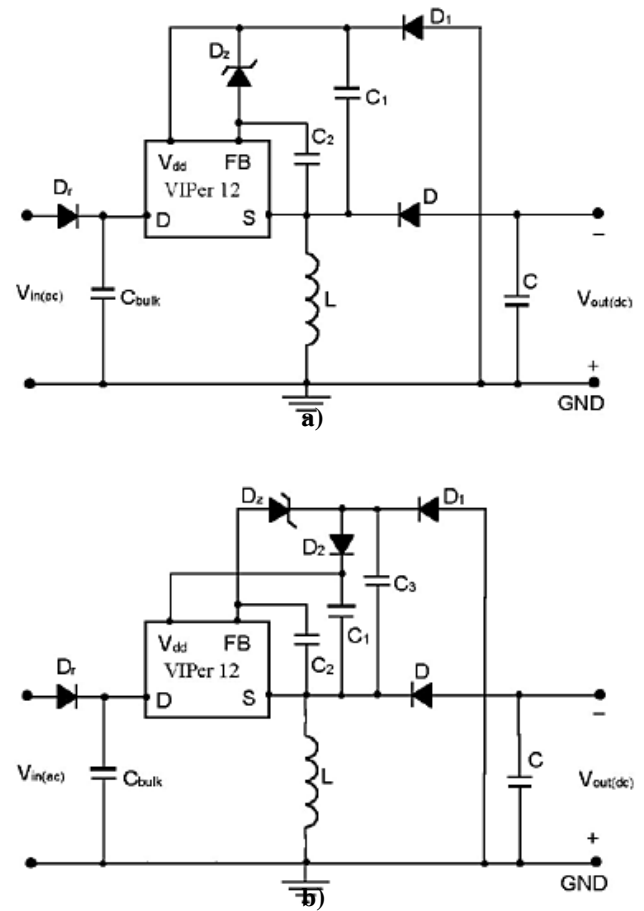
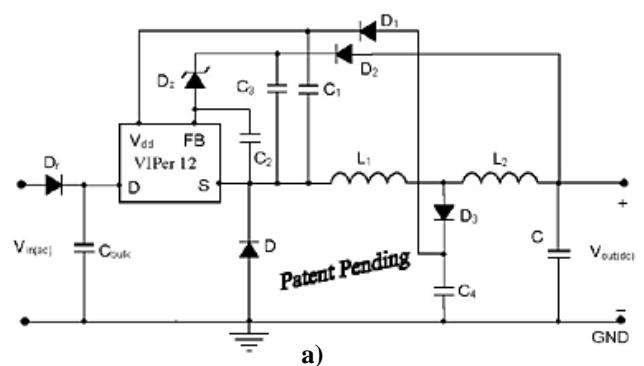


Fig. 7 - Buck-boost converter: a) $V_{out} < -15V$, $(-15V) < V_{out} < (-8V)$.



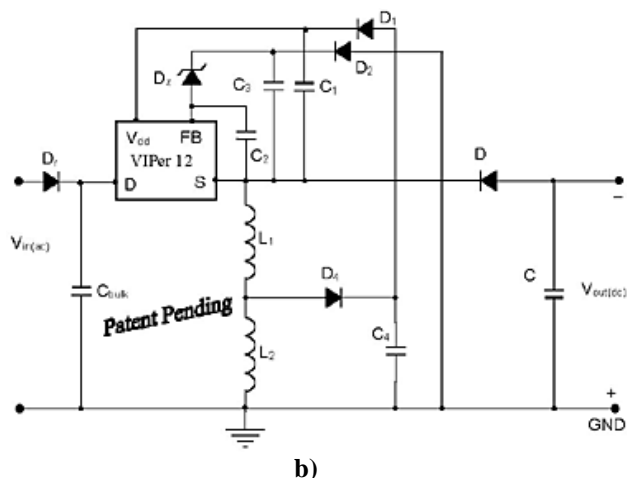


Fig. 8 - Buck-boost converter with $(-8V) < V_{out} < 0$.

4. Application examples

In this section three application examples using VIPer12A are introduced and fully analyzed. The first application example is a 16V-100mA off-line power supply. Converter specifications are $V_{in} = 185-265V_{ac}$, $V_{out} = 15V$ and $I_{out} = 100mA$. In order to have a regulated output in open load condition a burden resistor R_{burden} is connected to the output providing a minimum output current of less than 2mA. The schematic of the circuit is shown in Fig. 6a. Single wave rectifier is used in order to have the ground connected to the neutral of the mains. In this case to improve the reverse voltage robustness a second rectifier diode can be connected on the neutral wire. Moreover the input bulk capacitor can be split into two capacitors and an inductor inserted in between, realizing a low cost EMI filter. The part list is given in Tab I. The proposed power supply can be successfully applied in microcontroller-based low power motor drive systems. Such an application requires two regulated output voltage: 15V for power switch gate driver and 5V for microcontroller. In Fig. 9 is shown the circuit schematic, using a 5V linear regulator with reset for proper system operation. The size of the board is 3.5x4 mm as shown in Fig. 10 and can be further reduced using SMD components.

Typical waveforms of the 15V power supply are shown in Fig. 11a with $I_{out} = 100mA$ (boundary condition). In Fig. 11b are shown the output voltage and the source voltage in open load condition. In such a case the VIPer12A operates in burst mode, decreasing the effective switching frequency and reducing the power consumption to less than 100mW.

Part	Value	Part type
R1	10Ω / 1/2W	Resistor
R _{burden}	15kΩ / 50mW	Resistor
C _{in1}	1μF / 400V	Elec. Capacitor
C _{in2}	1μF / 400V	Elec. Capacitor
C1	10μF / 25V	Elec. Capacitor
C2	22nF / 25V	Cer. Capacitor
C _{out}	10μF / 25V	Elec. Capacitor
D1	1A - 600V	Diode STTA106
D2	1A - 600V	Diode STTA106
D3	1A - 1000V	Diode 1N4007
D4	15 V	Zener Diode
L	1.5mH	Inductor
L1	600μH	Inductor
IC1		VIPer12A - D8P8

Table I. Part list

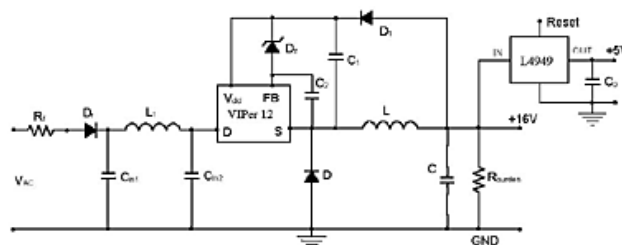


Fig. 9 - Application example: double output converter for microcontroller supply.

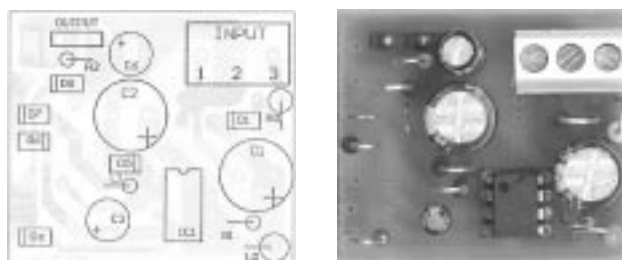
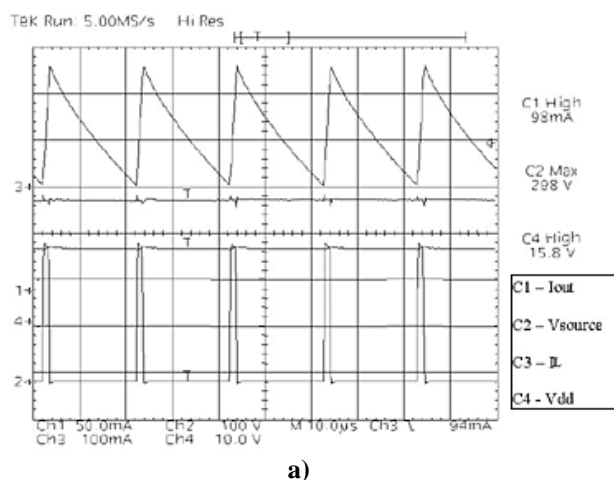
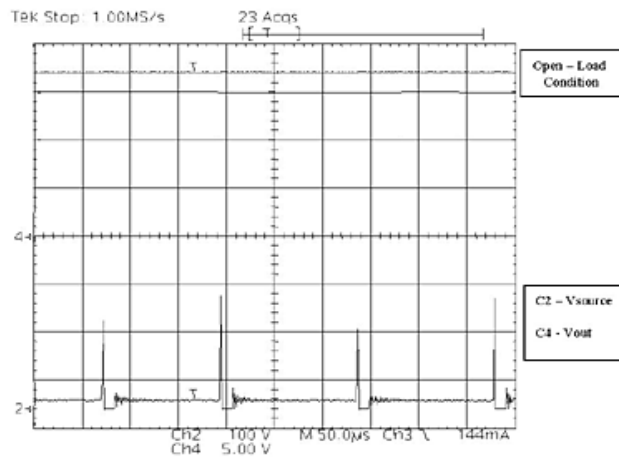


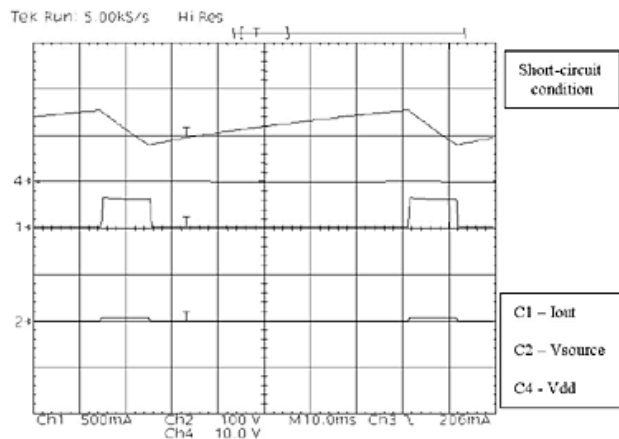
Fig. 10 - PCB Layout.



a)



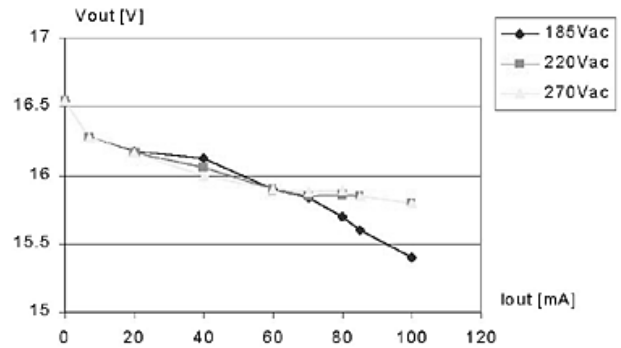
b)



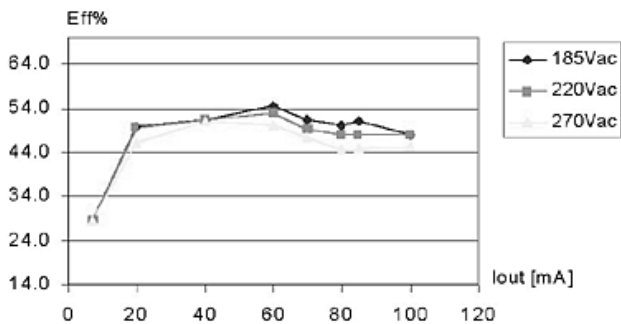
c)

Fig. 11 - Buck converter with $V_{out}=15V$: a) $I_{out}=100mA$, b) open load, c) short circuit

In short circuit condition VIPer12A limits the short circuit current, as shown in Fig. 11c, thanks to three main features: start-up sequence due to low Vdd voltage, current limit function and thermal shut down. In this way the power dissipation is strongly reduced and the converter is safely protected. The performance of the circuit has been evaluated and fully characterized, as shown in Fig. 12. In particular, the circuit features a good line and load regulation. The worst regulation at low input voltage and high output current is basically related to the value of the input capacitors, a trade off between performance, size and cost. The efficiency of the power supply is higher than 50%, considerably affected by the parasitic resistor of the components. High quality components could be used to improve the efficiency, but a trade off between cost and performance has to be done for such a low cost application.



a)



b)

Fig. 12 - Buck converter with $V_{out}=15V$: a) regulation, b) efficiency.

The EMI behavior of VIPer12A-based power supply is shown in Fig. 13. Conducted emission measurements have been performed according to the standard EN55022 using a 50(LISN (Line Impedance Stabilization Network), with a peak detector, in the frequency range 0.15-30 MHz.

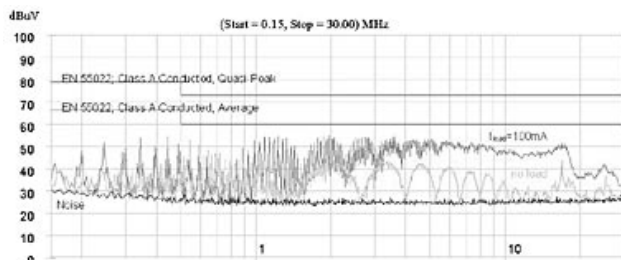


Fig. 13 - Buck converter with $V_{out}=16V$: EMI behavior with low cost EMI filter.

The second application example is based on Buck topology with two complementary outputs, i.e. $V_{out1}=12V-100mA$ and $V_{out2}=-5V$, as shown in Fig. 14. The power supply operates with wide range input voltage, i.e. 85-265Vac, and is designed to operate in DCM. A single diode rectification is used to limit the cost and the input fuse is replaced with a suitable resistor. A simple input CLC EMI filter is connected but it could be removed thanks to the low emission related to the power level. In Tab. II is given the part list of the considered power supply. The VIPer12A makes the power supply short circuit protected. In fact if a short circuit appears on OUT1 the restart mode is entered, limiting the power dissipation. On the other hand, if a short circuit appears on OUT2, the converter operates as a conventional Buck converter with V_{out1} given by D_z . Some experimental waveforms are shown and a performance evaluation is carried out in terms of line and load regulation as

well as efficiency. In Fig. 15 typical waveforms of the Buck based converter are shown: the voltage across the power device, V_{DS}, the output current, the inductor and the diode currents with $V_{in(ac)} = 220V_{rms}$. The static performance of the power supply can be evaluated from Fig. 15c that shows OUT1 voltage ripple, limited to $50mV_{pp}$, i.e. less than 0.5%, with a small and low cost output capacitor. Regulation and efficiency diagrams are shown in Fig. 16. The maximum current that can be supplied by the negative output current is related to the current of the positive output. If more current is required, the regulation circuit described previously has to be used.

Part	Value	Part type
R _i	10Ω / 50W	Resistor
C _{in}	1μF / 400V	Elec. Capacitor
C _{in2}	1μF / 400V	Elec. Capacitor
C ₁	10μF / 25V	Elec. Capacitor
C ₂	22nF / 25V	Cer. Capacitor
C _{out1}	33μF / 25V	Elec. Capacitor
C _{out2}	10μF / 25V	Elec. Capacitor
D ₁	1A - 1000V	Diode 1N4007
D ₂	1A - 600V	Diode STTA108
D ₃	1A - 600V	Diode STTA108
D ₄	18 V	Zener Diode
D ₅	18 V	Zener Diode
D ₆	5.1 V	Zener Diode
L	1.5mH	Inductor
L ₁	470μH	Inductor
IC1		VIPer12A

Table II. Part list

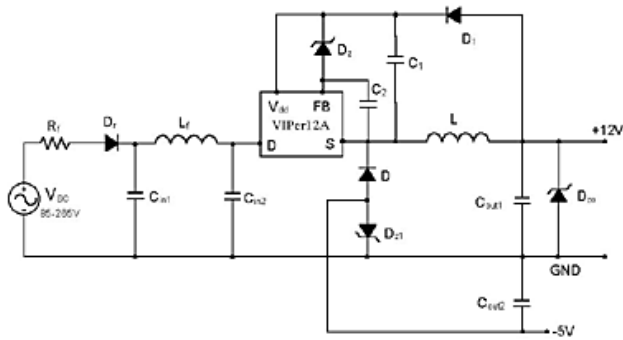
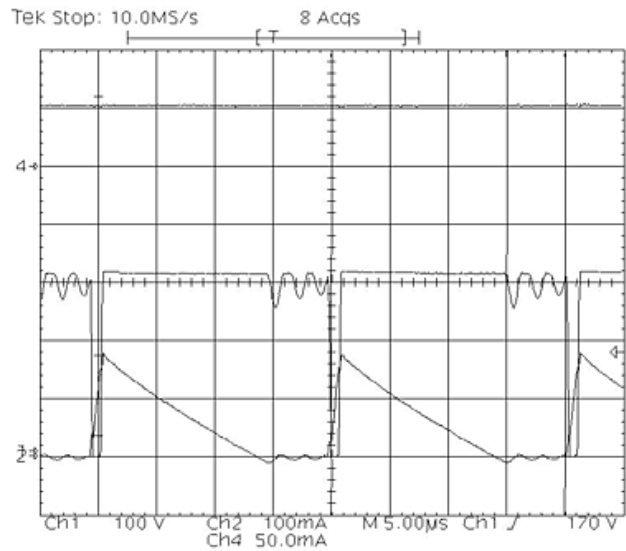
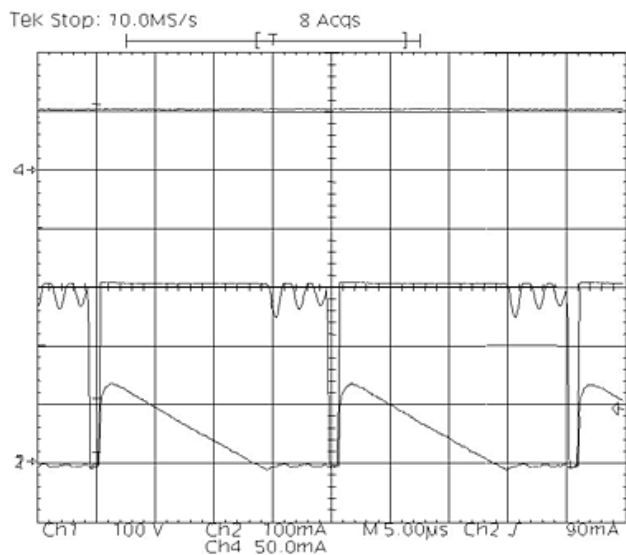


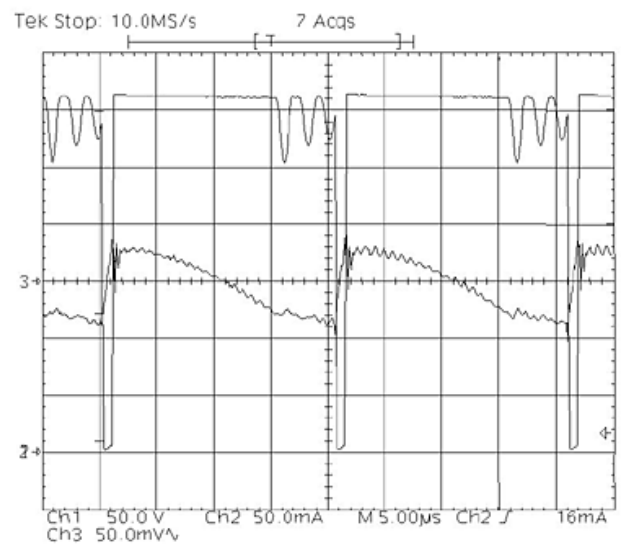
Fig. 14 - Double output converter: 12V-100mA, -5V.



a)



b)



c)

Fig. 15 - Double output converter: a) $I_{out1}=50mA$ (Ch 4): V_{ds} (Ch 1) @ $220V_{ac}$ and I_o (Ch 2), b) $I_{out1}=50mA$ (Ch 4): V_{ds} (Ch 1) @ $220V_{ac}$ and I_o (Ch 2), $I_{out1}=50mA$: V_{ds} (Ch 2) @ $220V_{ac}$ and ripple on V_{out1} (Ch 3).

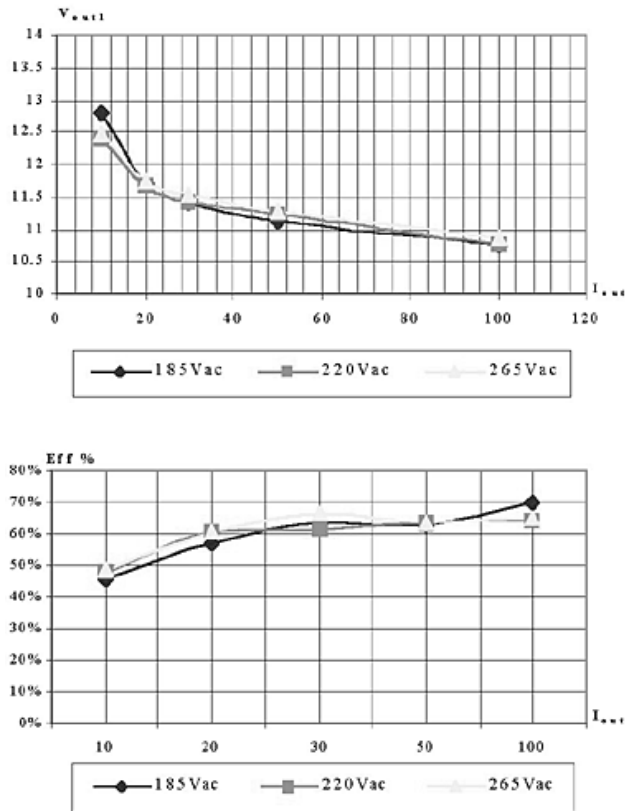


Fig. 16 - a) Regulation, b) Efficiency Vs. I_{out1} @ $I_{out2}=I_{out2(max)}$.

The last application example regards two outputs converter using a coupled inductor. The converter is based on a Buck topology, as shown in Fig. 17. The power supply is operated in off-line mode with an extended wide range of the input voltage, from 80 to 285Vac, and supplies $V_{out1}=24V@30mA$ and $V_{out2}=5V@50mA$. The input section consists in a resistor as a fuse, a single diode rectifier, and an input LC filter. Such a filter provides both DC voltage stabilization and improved EMI performance (compliant with EN55022 Class B standard). The capacitor C_{in1} could be connected to provide a further reduction of conducted EMI, if required. The regulation feedback is connected to “ V_{out1} ” as well as the supply circuit of the Viper12A. Doing so, only one high voltage diode and one capacitor are needed, i.e. D3 and C3 in Fig. 17, reducing the complexity and the cost of the circuit.

The output inductor, L, has two coupled windings on the same ferrite core, with a proper turn ratio and coupling factor in order to get the correct output voltage. In particular, 1.5mH inductor is used, with $N1=200t$ - wound on the ferrite core of “PANASONIC ELC10D152E” inductor - and $N2=60t$. Both outputs are protected against overvoltage by Zener diodes, D_{z1} and D_{z2} respectively. A burden resistor is connected across V_{out1} in order to perform the regulation on V_{out2} when V_{out1} is in open load condition. Such a resistor greatly improves the regulation with a slight impact on the efficiency.

The output rectifier diodes are both fast diodes: D1 is a high voltage diode since it has to sustain a reverse voltage given by the input DC bus voltage while D2 is a low voltage diode. The part list of the proposed circuit is given in Table III.

Part	Value	Parttype
Rf	10 Ω 1/2W	Resistor
Rfuse	4.7 k Ω 1W	Resistor
Cin	4.7 μ F, 450V	Elec. Cap
C1	33 μ F, 50V	Elec. Cap
C2	100 μ F, 16V	Elec. Cap
C3	1 μ F, 25V	Elec. Cap
C4	22 nF	Ceramic cap
D1		Diode 1N4007
D2		Diode BA159
D3		Diode 1N4148
Dz		Zener 22V
Dz1		Zener 27V
Dz2		Zener 5.6V
L	1.5 mH	
Lc	470 μ H	Inductor
IC1		VIPer12A

Table III. Part List

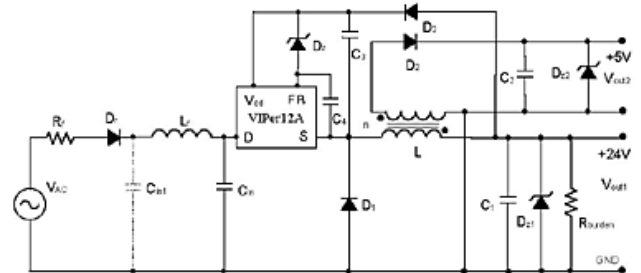


Fig. 17 - Two output converter.

5. Conclusion

Several configurations have been introduced in Buck, Buck-boost and modified configuration exploiting the main features of STMicroelectronics VIPer12A to realize low power and low cost not isolated power supplies for industrial and appliances applications. The inherent advantages of high frequency switched mode power conversion allow off line power supplies to operate with high efficiency and reduced cost and size. Viper12A smart power IC, integrating a PWM controller and a power device in a single chip, maximizes such advantages in the power range up to few watts.

Finally, smart power approach make the innovation possible in terms of cost and size even in such applications where the added value of the power supply is usually not considered.

6. References

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