



AN1895 APPLICATION NOTE

EVAL6562-375W, 375W FOT-CONTROLLED PFC PRE-REGULATOR WITH THE L6562

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This note describes an evaluation board based on the Transition-mode PFC controller L6562 (order code: EVAL6562-375W) and presents the results of its bench evaluation. The board implements a 375W, wide-range mains input, PFC pre-regulator, e.g. suitable for a 300/350W ATX12V PSU. To enable the use of a low-cost device like the L6562 at this power level, usually prohibitive for this device, the chip is operated with Fixed-Off-Time control. This allows Continuous Conduction Mode operation, normally achievable with more expensive control chips and more complex control architectures.

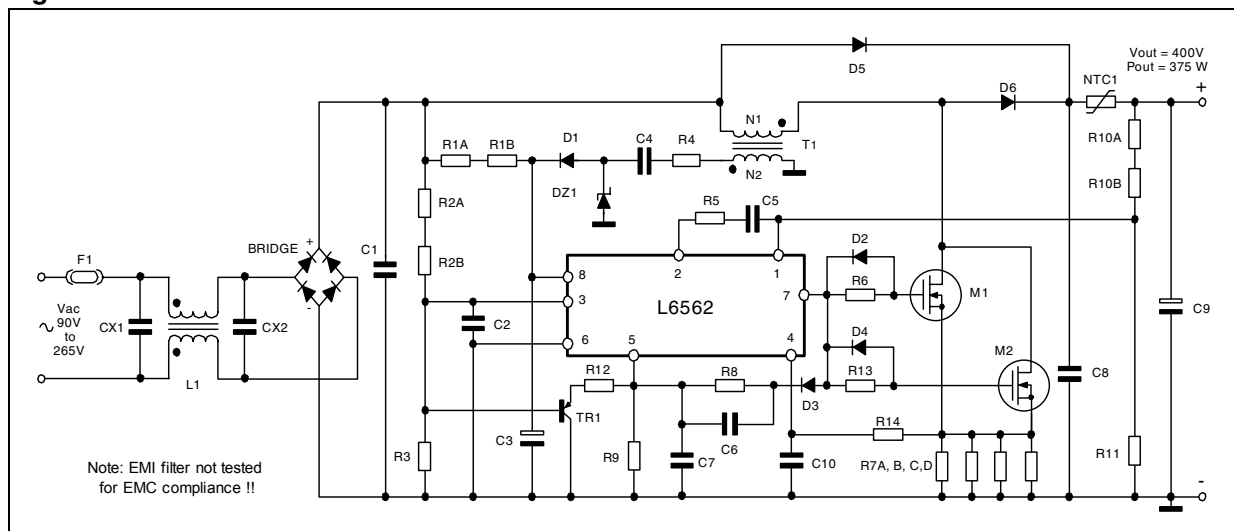
Design Specification

Table 1 summarizes the electrical specification of the application, table 2 provides the BOM and table 3 lists transformer's spec. The electrical schematic is shown in figure 1 and the PCB layout in figure 2.

Table 1. EVAL6562-375W evaluation board: electrical specification

Parameter	Value
Line voltage range	90 to 265 Vac
Minimum Line frequency (f_L)	47 Hz
Regulated output voltage	400V
Rated output power	375 W
Maximum $2f_L$ output voltage ripple	20V pk-pk
Hold-up time	17 ms
Maximum switching frequency (@ $V_{in}=90Vac$, $P_{out}=375W$)	100 kHz
Minimum estimated efficiency (@ $V_{in}=90Vac$, $P_{out}=375W$)	90%
Maximum ambient temperature	50 °C

Figure 1. EVAL6562-375W evaluation board: electrical schematic



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The electrical specification is typical of a PFC pre-regulator for a 300W ATX12V PSU: it is able to deliver 375W continuous power on a regulated 400V rail from a wide range mains. This rail will be the input for the cascaded isolated DC-DC converter (typically a forward converter) that will provide the output rails of the silver box. Although the ATX specification envisages air cooling, typically realized with a fan capable of an airflow in the range of 25-35 CFM, this is not allowed for in the design of this demo board. Enough heat sinking will be provided to allow full-load operation in still air. With an appropriate airflow and without any change in the circuit the demo board can easily deliver up to 400-420W.

Table 2. EVAL6562-375W evaluation board: Bill Of Material

Symbol	Value	Note
R1A, R1B	120 k Ω	
R2A, R2B	620 k Ω	
R3	10 k Ω	
R4	47 Ω	
R5	6.8 k Ω	
R6, R13	6.8 Ω	
R7A, R7B, R7C, R7D	0.68 Ω	Metal film, 1W
R8, R12	1.5 k Ω	
R9	12 k Ω	
R10A, R10B	499 k Ω	
R11	6.34 k Ω	
R14	330 Ω	
CX1, CX2	330 nF	EPCOS B81131 or equivalent
C1	1 μ F	400V, EPCOS B32653 or equivalent
C2, C4	10 nF	
C3	47 μ F	25V electrolytic
C5	1 μ F	
C6, C10	330 pF	
C7	560 pF	
C8	470 nF	630V, EPCOS B32653 or equivalent
C9	220 μ F	450V, Electrolytic Nichicon LS or equivalent
C14	56 nF	400V, polyester
C15	100 pF	1kV, Y5P, Panasonic or equivalent
L1	TOR73	3.9 mH / 6A, supplied by ITACOIL s.r.l.
T1	E4218	Boost inductor. See spec on table 3. Supplied by ITACOIL s.r.l.
BRIDGE	KBU8M	8A / 1000V, GI or equivalent
D1, D2, D3, D4	1N4148	0.3A / 75V, glass case, Vishay or equivalent
D5	1N5406	3A / 600V, D0201, ON Semiconductor or equivalent
D6	STTH806DTI	8A / 600V, Tandem Hyperfast, TO220, ST
DZ1	1N5248B	18V / 500mW Zener, ON Semiconductor or equivalent
U1	L6562	TM PFC controller, DIP8, ST
M1, M2	STP12NM50FP	0.3 Ω / 500V, MDmesh™, TO220FP, ST
TR1	BC557	PNP, 0.1A / 45V, TO92, On Semiconductor or equivalent
NTC1	BS237	NTC 2.5 Ω , EPCOS or equivalent
F1	---	8A, 250V
PCB	---	FR-4, Cu single layer 35 μ m, 150 x 81.5 mm
Heat sink	OS512	2.12 $^{\circ}$ C/W, Extrusion Profile, Aavid Thermalloy
Notes: if not otherwise specified, all resistors are 1%, 1/4 W, all capacitors are ceramic or plastic film BRIDGE, M1, M2 and D6, all share the same heat sink		

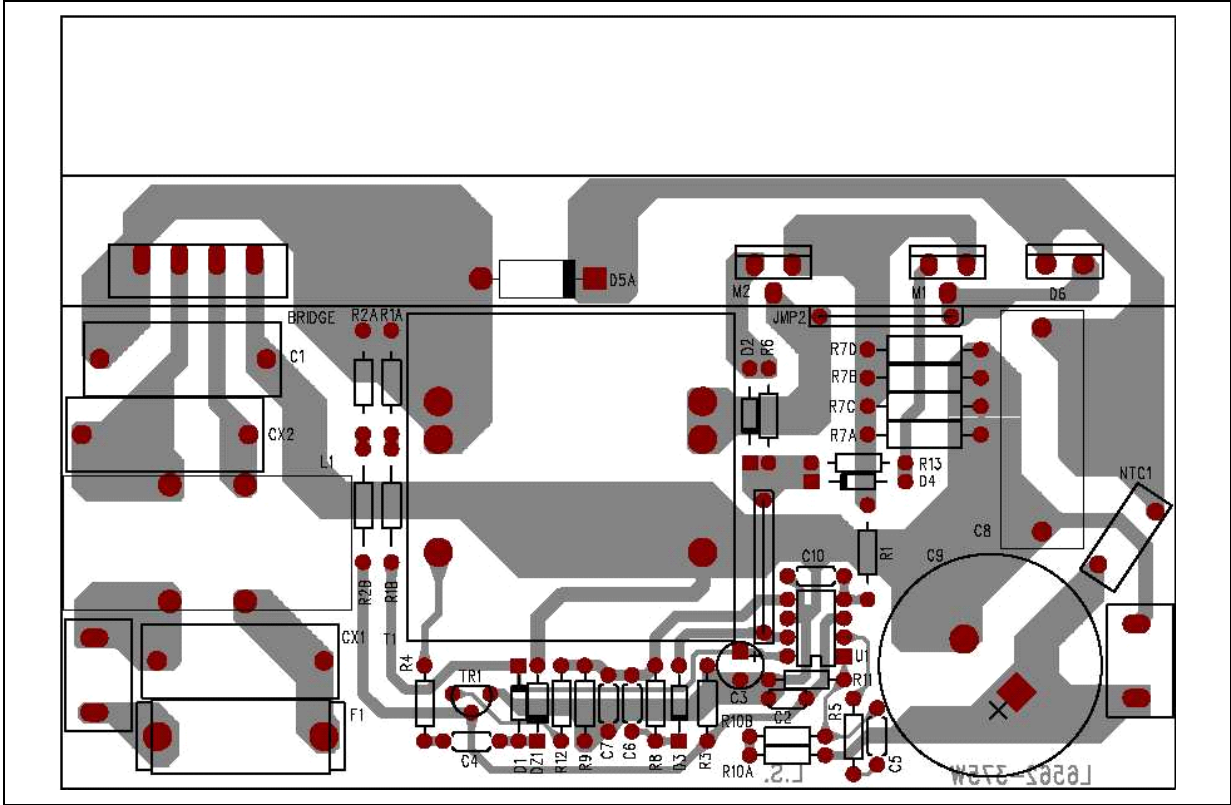
The controller chip is the L6562 [1]. This device is designed for Transition-Mode (TM) operation, where the boost inductor works next to the boundary between Continuous (CCM) and Discontinuous Conduction Mode (DCM). However, with a slightly different usage, the chip can be operated so that the boost inductor works in CCM, hence surpassing the limitations of TM operation in terms of power handling capability. The gate-drive capability of the L6562 ($\pm 0.8A$ min.) is also adequate to drive the MOSFET's used at higher power levels.

This approach, which couples the simplicity and cost-effectiveness of TM operation with the high-current capability of CCM operation is the Fixed-Off-Time (FOT) control: the control modulates the ON-time of the power switch, while its OFF-time is kept constant. More precisely, it will be used the Line-Modulated FOT (LM-FOT) where the OFF-time of the power switch is not rigorously constant but is modulated by the instantaneous mains voltage. Please refer to [2] for a detailed description of this technique.

Table 3. EVAL6562-375W: boost inductor specification (part# E4218, made by ITACOIL s.r.l.)

Core	E42/21/7, N67 Material or equivalent				
Bobbin	Horizontal mounting, 10 pins				
Air gap	≈ 1.9 mm for an inductance 1-10 of $550 \mu H$				
Windings Spec & Build	Pin Start/End	Winding	Wire	Turns	Notes
	1/10	Main	20xAWG32	58 (N1)	Pins 1 & 2, pins 10 & 9 are shorted on the PCB
	6/5	Aux	AWG32	6 (N2)	Evenly spaced

Figure 2. EVAL6562-375W: PCB layout, silk + bottom layer (top view); size: 150 x 81.5mm



Power stage design procedure

The step-by-step procedure of an LM-FOT controlled PFC pre-regulator outlined in [2] will be followed. The design will be done on the basis of a ripple factor (the ratio of the maximum current ripple amplitude to the inductor peak current at minimum line voltage) $K_r=0.3$.

- 1)The range of k ($k_{min} \div k_{max}$) associated to the line voltage range is:

$$k_{\min} = \sqrt{2} \frac{V_{in(RMS)\min}}{V_{out}} = \sqrt{2} \frac{90}{400} = 0.318, \quad k_{\max} = \sqrt{2} \frac{V_{in(RMS)\min}}{V_{out}} = \sqrt{2} \frac{265}{400} = 0.937.$$

2) The required $T_{OFF\min}$ is derived from the specification on the maximum switching frequency (on the top of the line voltage sinusoid) $f_{sw\max}$ at minimum line voltage:

$$T_{OFF\min} = \frac{k_{\min}}{f_{sw\max}} = \frac{0.318}{100 \cdot 10^3} = 3.18 \mu s$$

3) The maximum expected input power $P_{in0} = P_{out0}/\eta$ and the maximum line peak current, $I_{pk\max}$ are:

$$P_{in0} = \frac{375}{0.9} = 417W; \quad I_{pk\max} = \frac{2P_{in0}}{k_{\min} V_{out}} = \frac{2 \cdot 417}{0.318 \cdot 400} = 6.56A.$$

4) The ripple amplitude on the top of the sinusoid at minimum line voltage, assuming it is 75% of the maximum specified, will be:

$$\Delta I_{Lpk} = \frac{6Kr}{8-3Kr} I_{pk\max} = \frac{6 \cdot 0.3}{8-3 \cdot 0.3} \cdot 6.56 = 1.66A$$

5) The required inductance L of the boost inductor is:

$$L = (1 - k_{\min}) \frac{V_{out}}{\Delta I_{Lpk}} T_{OFF\min} = (1 - 0.318) \cdot \frac{400}{1.66} \cdot 3.18 \cdot 10^{-6} = 523 \mu H$$

This value will be rounded up to 550 μH ; the resulting value of Kr will be slightly smaller than 0.3, but we will go on using the target value, this will give some additional margin.

6) The maximum inductor peak current, $I_{Lpk\max}$, is calculated:

$$I_{Lpk\max} = \frac{8}{8-3Kr} I_{pk\max} = \frac{8}{8-3 \cdot 0.3} \cdot 6.56 = 7.39A$$

7) The maximum sense resistor $R_{sense\max}$ is:

$$R_{sense\max} = \frac{1.6}{I_{Lpk\max}} = \frac{1.6}{7.39} = 0.216 \Omega$$

(1.6V is the minimum value of the pulse-by-pulse current limiting threshold on the current sense pin of the L6562). It will be realized with four 0.68 Ω , 1W-rated paralleled resistors, for a total resistance of 0.17 Ω . This provides some extra power capability. The inductor peak current that the inductor must be able to carry without saturating will be:

$$I_{Lpk\text{sat}} = \frac{1.8}{0.17} = 10.6A$$

8) From the formulae in [2], table 4, the MOSFET RMS current is:

$$I_{Q(rms)} = \frac{P_{in0}}{k_{\min} V_{out}} \sqrt{2 - \frac{16k_{\min}}{3 \cdot \pi}} = \frac{417}{0.318 \cdot 400} \sqrt{2 - \frac{16 \cdot 0.318}{3 \cdot \pi}} = 3.96A;$$

the diode RMS current is:

$$I_{Q(rms)} = \frac{P_{in0}}{k_{\min} V_{out}} \sqrt{\frac{16k_{\min}}{3 \cdot \pi}} = \frac{417}{0.318 \cdot 400} \sqrt{\frac{16 \cdot 0.318}{3 \cdot \pi}} = 2.41A$$

the dissipation on the sense resistor will be $0.17 \cdot 3.96^2 = 2.7W$, which justifies the use of four resistors; the selected MOSFET is the STP12NM50, a 0.3 Ω /500V MDmesh™ type from STMicroelectronics, housed in a TO220 package; two of them will be paralleled to handle the rated power; the selected diode is an STTH806DTI, an 8A/600V Tandem diode, again from STMicroelectronics,

housed in a TO220 package. All of them must be dissipated to keep their temperature within safe limits.

As for the inductor, the core size will be determined by saturation since the ripple is relatively low. Assuming a peak flux density $B_{max}=0.3T$, the minimum required Area-Product is:

$$AP_{min} \approx 186 \left(\frac{1 - k_{min} K_r P i n_0 T_{OFF}}{k_{min} K_r B_{max}} \right)^{1.31} = 186 \left(\frac{1 - 0.318 \cdot 0.3 \cdot 417 \cdot 3.18 \cdot 10^{-6}}{0.318 \cdot 0.3} \right)^{1.31} = 2.92 [cm^4]$$

An E42 core ($AP = 3.15 cm^4$) has been chosen. See table 3 for the complete inductor spec.

The output capacitor is determined by the hold-up time requirement. Assuming a minimum voltage of 300V after the line drop, a minimum of 180 μF is needed and a 220 μF /450V capacitor will be used.

9)The peak multiplier bias voltage V_{MULT} @90V mains must meet the condition:

$$\frac{I_{Lpkmax} R_{sense}}{1.65} \leq V_{MULTpk} \leq 3 \frac{V_{in(RMS)min}}{V_{in(RMS)max}},$$

where 1.65 is the minimum slope of the multiplier characteristic associated to the error amplifier saturated high (see figure 9 in [1]). With the selected value for R_{sense} (0.17 Ω):

$$\frac{7.39 \cdot 0.17}{1.65} = 0.761 \leq V_{MULTpk} \leq 3 \cdot \frac{90}{265} = 1.02$$

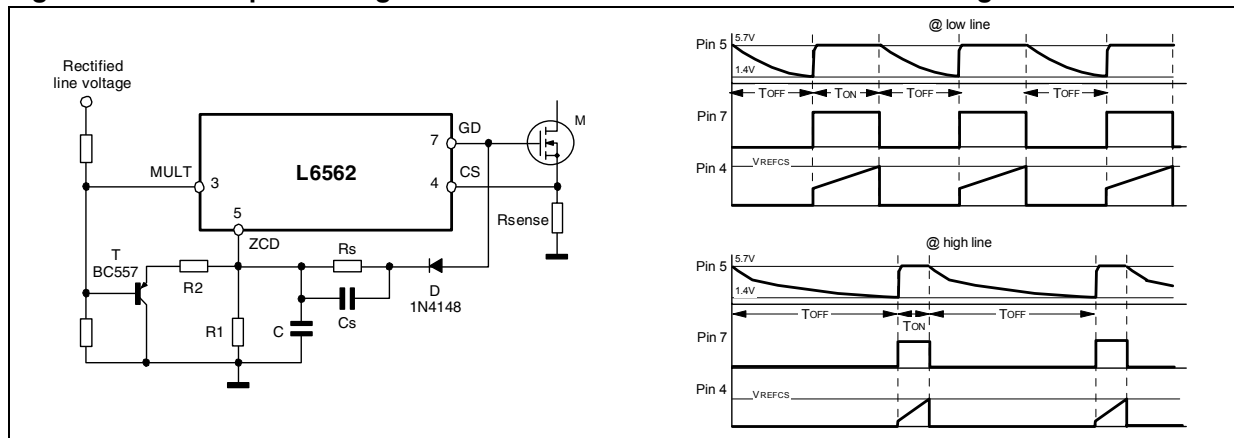
Choosing the ratio of the resistor divider that biases the multiplier input (pin 3, MULT) $K_P=8 \cdot 10^{-3}$ lets the peak voltage on the multiplier pin will go from 1V to 3V, thus meeting the above condition. The high-side resistor of the output divider that sets the output voltage is chosen on the basis of the maximum allowed overvoltage on the output. Considering 40V overvoltage, the high-side resistor must be 1M Ω (see [3] for details, in this respect the L6561 and the L6562 are exactly equal). The low-side resistor will then be 1M $\Omega \cdot (400/2.5 - 1) = 6.29k\Omega$; the 6.34k Ω standard value will be used.

Based on the model given in [2], a compensation network made with an RC series ($R=6.8 k\Omega$, $C=1\mu F$) guarantees a minimum of 25° phase margin (with 9 Hz bandwidth) at minimum line and a bandwidth not exceeding 20 Hz (with 50° phase margin) at maximum line.

Setting up FOT control with the L6562

FOT control is implemented with the L6562 with the circuit shown in figure 3, which shows some significant waveforms as well. Before starting the design the desired value of T_{OFF} at maximum line voltage has to be specified. In [2] it is shown that to reduce high-voltage distortion it must be $T_{OFF} > 7\mu s$, hence we choose $T_{OFF} = 8\mu s$.

Figure 3. Circuit implementing FOT control with the L6562 and relevant timing waveforms.



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Following the design procedure given in [2], with the aid of the diagram of figure 4:

1)The ratio of the maximum T_{OFF} value to the minimum T_{OFF} value is:

$$\rho = \frac{8 \cdot 10^{-6}}{3.18 \cdot 10^{-6}} = 2.52$$

2)Consider the value of V_{MULTpk} at minimum line voltage ($V_{MULTpk} = 1V$), in figure 4 draw an horizontal line located at $\rho = 2.52$ (on the left vertical axis) as long as it intercepts the ρ curve relevant to the value $V_{MULTpk}=1V$ in P1. The abscissa of P1 gives the value $K1=0.891$.

3)From P1 draw a vertical line as long as it intercepts the K2 curve relevant to $V_{MULTpk}=1$ in P2. The ordinate of P2 (on the right vertical axis) gives the value $K2=4.17$.

4)The required time constant is:

$$\tau = \frac{T_{OFFmin}}{K2} = \frac{3.18 \cdot 10^{-6}}{4.17} = 0.76 \cdot 10^{-6} \text{ s.}$$

5)A capacitor $C=560$ pF is selected, then the associated resistance value will be:

$$R' = \frac{\tau}{C} = \frac{0.76 \cdot 10^{-6}}{560 \cdot 10^{-12}} = 1357 \Omega.$$

6)R1 and R2 will be respectively:

$$R1 = \frac{R'}{1 - K1} = \frac{1357}{1 - 0.891} = 12450 \Omega \quad R2 = \frac{R'}{K1} = \frac{1357}{0.891} = 1523 \Omega$$

the standard values $R1=12k\Omega$ and $R2=1.5k\Omega$ will be chosen.

7)Assuming that the V_{CC} voltage never falls below 14-15V, the limiting resistor R_s can be selected according to:

$$R_s > \frac{V_{GDx} - V_{ZCDclamp} - V_F}{I_{ZCDx} + \frac{V_{ZCDclamp} R2 + (V_{ZCDclamp} - V_{MULTpkmax} - V_{BE}) R1}{R1 R2}}$$

where $V_{GDx}=15V$ is the maximum clamp value of the gate drive voltage, $V_{ZCDclamp} \approx 5.7V$ is the clamp value of the ZCD pin voltage, $V_F \approx 0.5V$ the forward drop on the diode, $I_{ZCDx}=10mA$ the maximum ZCD clamp current D and $V_{BE} \approx 0.55V$ the emitter-to-base forward drop of T . Substituting:

$$R_s > \frac{15 - 5.7 - 0.5}{10 \cdot 10^{-3} + \frac{5.7 \cdot 1500 + (5.7 - 3 - 0.55) \cdot 12000}{1500 \cdot 12000}} = 739 \Omega$$

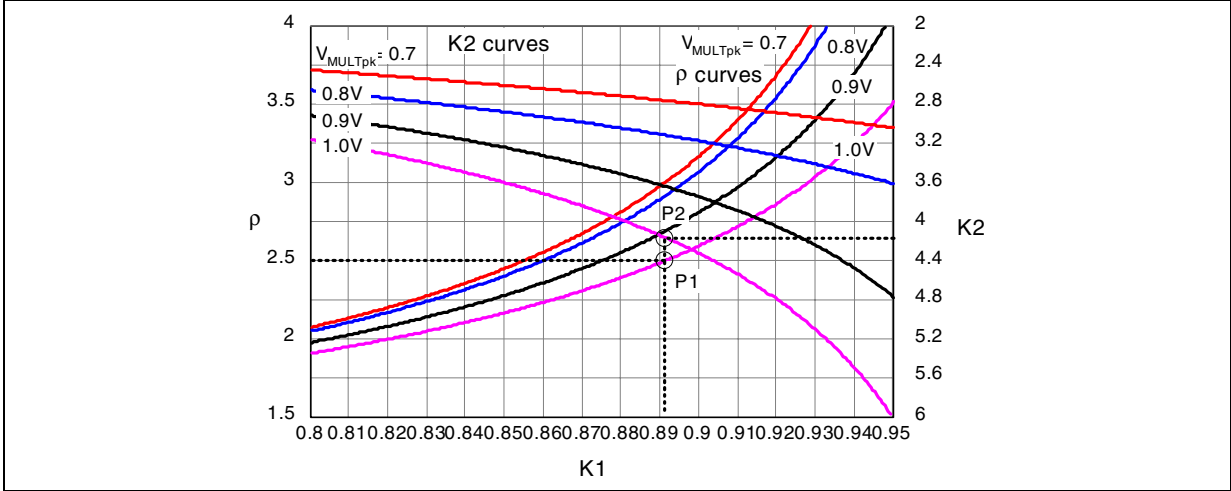
in this case a 1.5k Ω resistor will be chosen

8)Cs will be selected according to the relationship:

$$C_s < C \frac{V_{ZCDclamp}}{V_{GDx} - V_{ZCDclamp} - V_F} = 560 \cdot 10^{-12} \frac{5.7}{15 - 5.7 - 0.5} = 363 \text{ pF};$$

a standard value $C_s=330$ pF will be used.

Figure 4. Diagrams for the design of the circuit of figure 3 (valid for wide-range mains operation).



Board evaluation: getting started

The AC voltage, generated by an AC source ranging from 90 Vac to 265 Vac, will be applied to the input connector, located close to the bottom left-hand corner.

The 400 VDC output is located close to the bottom right-hand corner and will be connected to the load. If an electronic load is going to be used pay attention to the right polarity: the (+) output terminal is that located closer to the corner.

Like in any offline circuit, extreme caution must be used when working with the application board because it contains dangerous and lethal potentials. The application must be tested with an isolation transformer connected between the AC mains and the input of the board to avoid any risk of electrical shock.

Board evaluation: bench results and significant waveforms

In the following diagrams the results of some bench evaluations are summarized. A number of waveforms under different load and line conditions are shown for user's reference.

Figure 5. EVAL6562-375W: evaluation data.

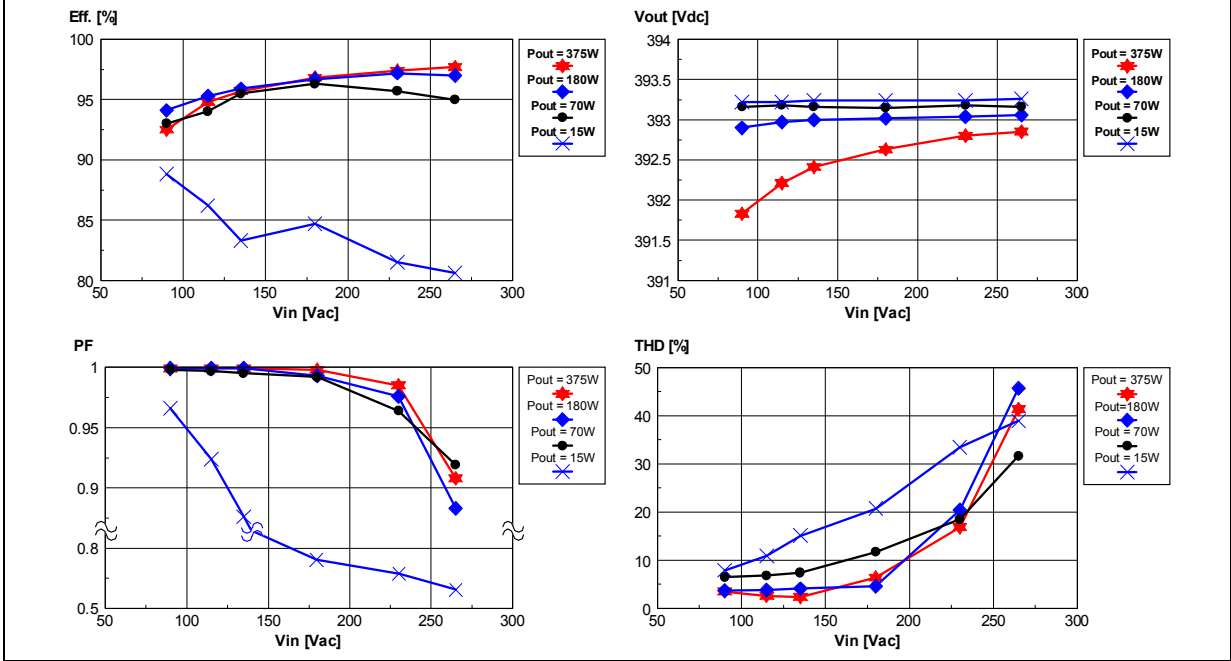


Figure 6. EVAL6562-375W: conformity to JEIDA-MITI & EN61000-3-2 standards.

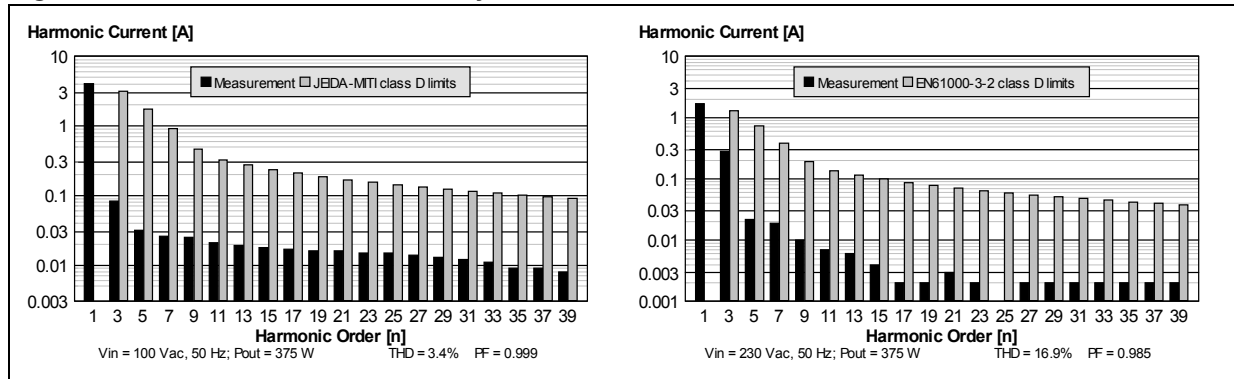


Figure 7. EVAL6562-375W: harmonic emissions at light load (70W).

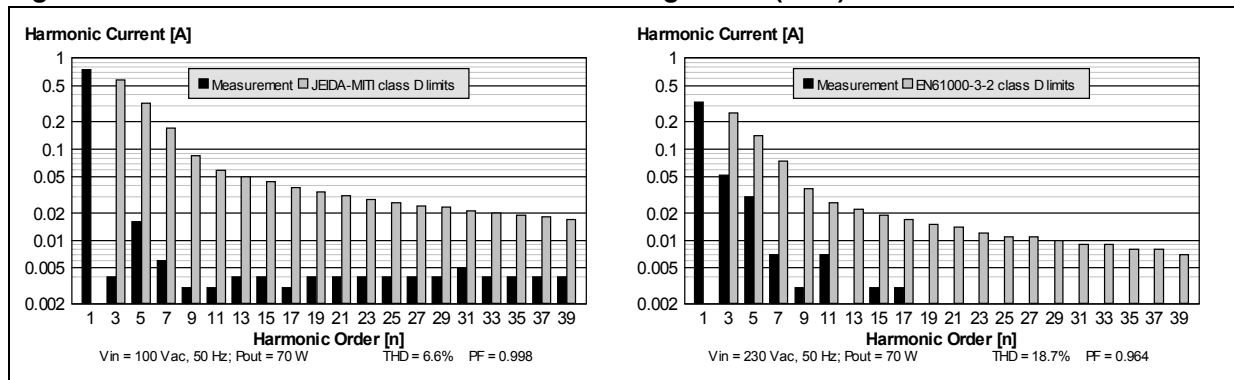


Figure 8. EVAL6562-375W: line current waveforms @ Pout = 375W.

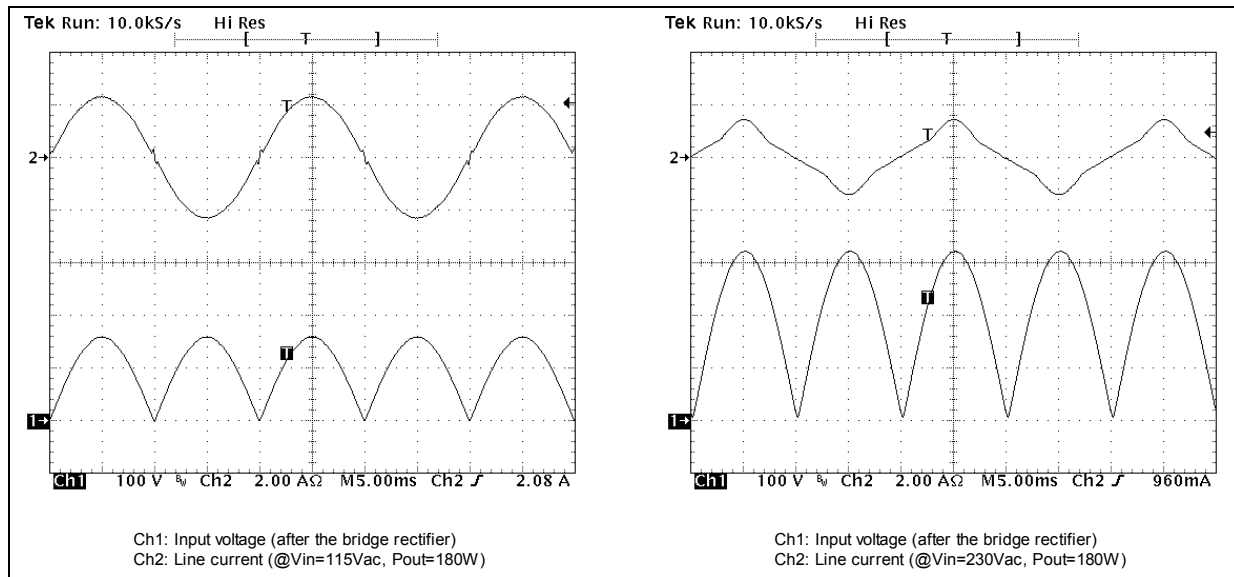


Figure 9. EVAL6562-375W: line current waveforms @ Pout=180W.

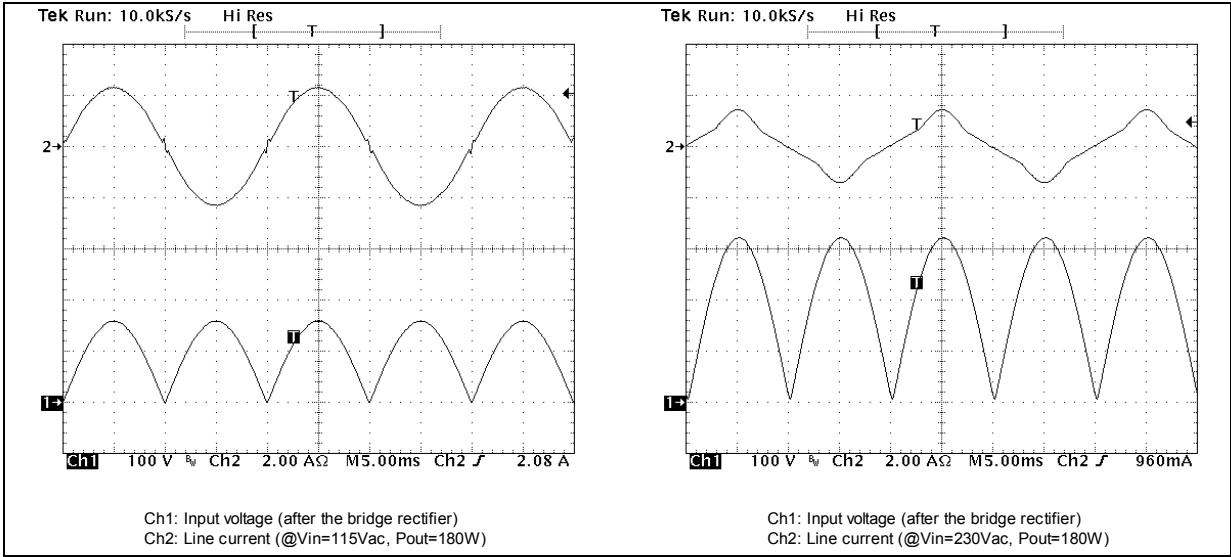
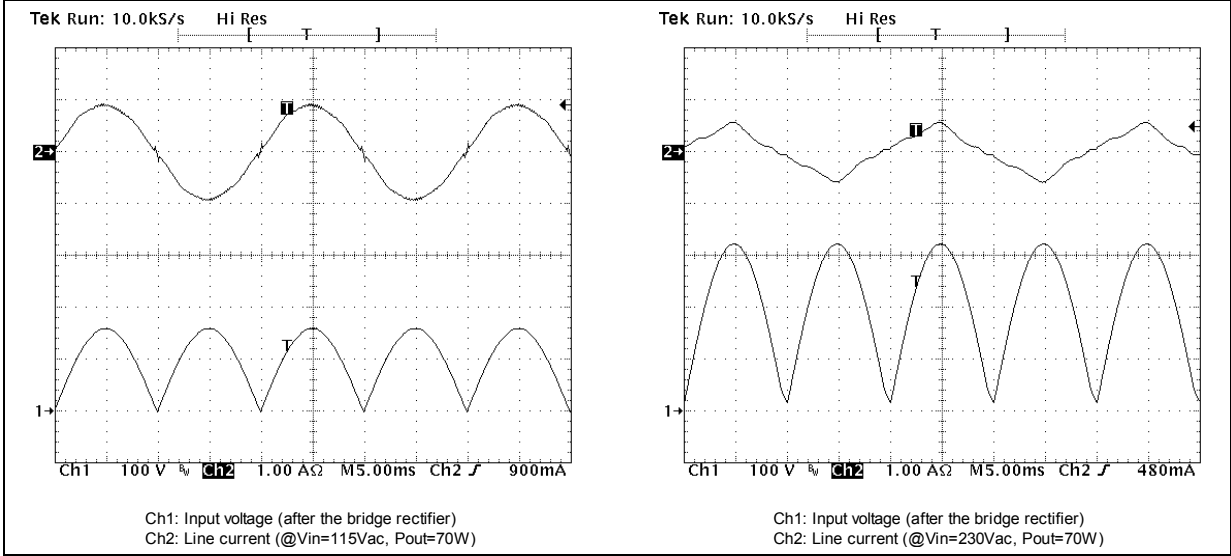


Figure 10. EVAL6562-375W: line current waveforms @ Pout=70W.



Note that input LC filter is provided only to clean the line current waveform enough to prevent the measurement system from being misled by an excessive noise level. The filter has not been designed nor tested for EMI compliance.

The board, as is, is able to handle properly an output load as low as 15 W. With lower load levels the system will not start up correctly at low line because the OVP generated at start-up lasts so long that the Vcc voltage drops below the UVLO of the L6562 (e.g. with 4W load the system would stop for 600 ms @ Vin=90Vac). Load transients from the maximum load to levels below 15W may cause the Vcc to be lost as well. Supplying the L6562 from an external source the minimum load that can be handled properly goes to virtually zero.

REFERENCES

- [1] "L6562 Power Factor Corrector" Datasheet
- [2] "Design of Fixed-Off-Time-Controlled PFC Pre-regulators with the L6562", AN1792
- [3] "L6561, Enhanced Transition-Mode Power Factor Corrector", AN966

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