*Application Report*
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# *An Improved Line Regulation Solution Used In LM3444/ LM3445 Nonisolated LED Lighting Application*

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## ABSTRACT

This paper details the full operation principle based on the traditional nonisolated solution with LM3445. The targeted line regulation formula is derived and analyzed. The result has been verified from the results of a practical experiment, and they matched very closely. To evaluate the feasibility in mass production, the output current tolerance is fully investigated and analyzed. The result proves that it is difficult for the traditional solution to meet the total mass production current tolerance, especially in the higher output application as required by the current market tendency.

To solve this problem, a simple line regulation compensation circuit is proposed. This proposed solution is verified both from theoretical calculation and experiment measurement results. Based on the formula of output current and line regulation rate derived, the final total current tolerance is analyzed for the practical mass production requirement. From the result, we find there is a great improvement toward meeting the practical requirement. Finally, the test result and calculation result are compared based on the prototype; it is proven that they matched well.

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# 1 Introduction

With the increasing growth in LED indoor lighting, the nonisolated scheme, along with the isolated scheme, has become more popular. Specifically, the scheme of higher PF and precise constant current mode with high line regulation has become the dominant issue on the market. However, with output voltage becoming higher and wider, the traditional LM3444/L3445 nonisolated application cannot achieve this requirement with enough margin, which may further limit the application of LM3445/LM3445.

In view of the above-mentioned issue, the major objective of this paper focuses on the higher output application with precise line regulation requirement. In this paper, the general operation principle is illustrated through the formulas in Chapter 2, with which the final output current can be solved. To evaluate the result, Chapter 3 provides the uniform formula into which the output current is simplified; Chapter 3 also gives and further detailed current tolerance analysis. Chapter 4 gives the design example based on the prototype. The calculation result, together with simulation result, is provided to make the contrast with the experiment result; it is proven they match very well. However, with further investigation, it is still difficult to meet the current tolerance for mass production.

To solve this problem, the proposed compensation circuit is presented in chapter 5. This compensation circuit is verified both through calculation and simulation and experimentation. Ultimately, experiments demonstrate that the circuit greatly improves the line regulation and current tolerance performance, with which the improved line regulation will become more competitive in the practical application, especially in the LED R30/PAR30/A19/E27 LED lighting applications.

# 2 The Principle of Traditional Nonisolated LM3444/LM3445 Solution

Figure 1 is presented as the traditional nonisolated solution with higher PF achievement. To convenient the operation principle, the parameters are defined as follows:

- Vout: Output voltage of LED
- I: Equivalent value of time within a single period
- $K_{feed}$: Feed ward coefficient of input AC voltage
- Rs: Resistor for current sense
- $R_{up}$: Charge resistor for $t_{off}$
- $C_{char}$: Charge capacitor for $t_{off}$
- Vinmin: Minimum of AC input voltage
- Vinmax: Maximum of AC input voltage
- Vinac: AC input voltage
- _noimp: Functions with no improved line regulation circuit

_imp: Functions with improved line regulation circuit

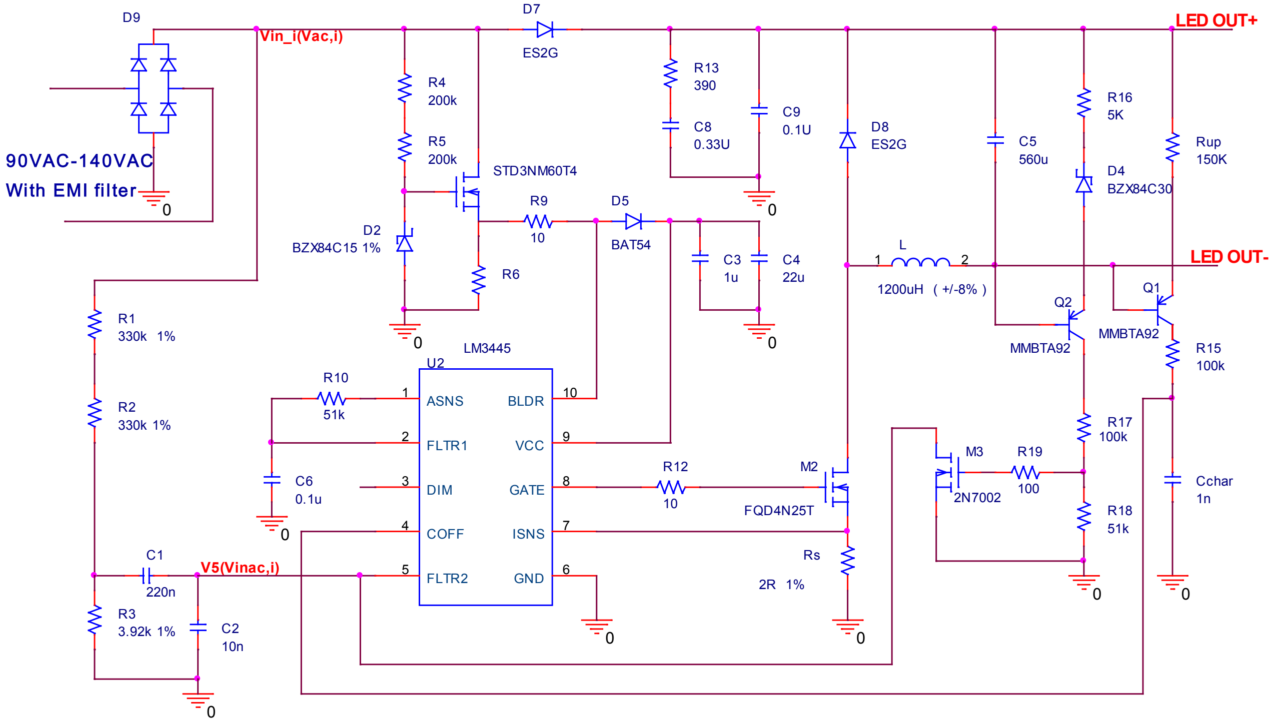


**Figure 1. Traditional Proposed Nonisolated Solution With High PF**

This is typically the application without feedback loop, but it can achieve the following characteristic:

1. Higher PF. This is achieved through input feed forward circuit.
2. Constant current. This is achieved through the $t_{off}$ circuit sensed through LED output voltage.

The AC input voltage can be expressed as follows:

$$Vin(t) = \sqrt{2}\cdot Vinac\cdot\left|\sin(\omega t)\right| \tag{1}$$

As shown as Figure 1, C1 is bigger than C2 in order to achieve higher PF value, for example: C1/C2 = 220n/10n. The voltage for pin 5 on the LM3444 or LM3445 can be expressed as:

$$V_5(t) = \sqrt{2}\cdot Vinac\cdot\left|\sin(\omega t)\right|\cdot k_{feed} - \frac{2\sqrt{2}\cdot Vinac\cdot k_{feed}}{\pi} + 0.75 \tag{2}$$

$$k_{feed} = \frac{R3}{R1+R2+R3}$$

The charge current for $t_{off}$ can be obtained as follows:

$$I_{char\_noimp}(t) = \frac{Vout - V_{eb\_Q1}}{R_{up}} \tag{3}$$

On practical calculation, Veb_Q1 can choose 0.6 as the reference design.

So, $t_{off}$ can be written as:

$$T_{off\_noimp}(t) = \frac{C_{char} \cdot 1.276}{I_{char\_noimp}(t)} \tag{4}$$

.

The frequency can be expressed as follows

$$F_{sw\_noimp}(t) = \frac{1 - \dfrac{Vout}{Vin(t)}}{T_{off\_noimp}(t)} \tag{5}$$

$$\left(Vout \le Vin(t)\right)$$

The ripple current through the inductor is obtained as:

$$\Delta i\_noimp(t) = \frac{T_{off\_noimp}(t) \cdot Vout}{L} \tag{6}$$

So, the maximum current and average inductor current formula can be written as:

$$IL\_\max(t) = \frac{V_5(t)}{Rs} \tag{7}$$

$$(Vout \le Vin(t))$$

$$Iavg\_noimp(t) = \frac{V_5(t)}{Rs} - 0.5 \cdot \Delta i\_noimp(t) \tag{8}$$

$$(Vout \le Vin(t))$$

Then the LED output current can be obtained as follows:

$$\Delta I_{out\_noimp}(t) = \frac{1}{T_{rec}} \cdot \int_0^{T_{rec}} I_{avg\_noimp}(t) \cdot dt \tag{9}$$

## 3 Analysis of LED Current Line Regulation Based On the Traditional Solution

As the LED current is derived above, we can write the total formula as follows:

$$I_{out\_noimp}(Vinac) = \left( 0.75 - \frac{2\sqrt{2} \cdot Vinac \cdot k_{feed}}{\pi} - \frac{\dfrac{0.5Vout \cdot C_{char} \cdot 1.276 \cdot Rs}{L}}{\dfrac{Vout - V_{be\_Q1}}{Rup}} \right) \cdot \frac{\pi - 2\arcsin\left(\dfrac{Vout}{\sqrt{2}Vinac}\right)}{\pi \cdot Rs} +$$

$$2\sqrt{2}\cdot Vinac\cdot\frac{k_{feed}}{\pi\cdot Rs}\cdot\sqrt{1-\frac{Vout^{2}}{2\cdot Vinac^{2}}} \tag{10}$$

To derive the LED current variation per input voltage, formula (10) will be simplified because Vout is normally much smaller than Vinac, and Vout is much higher than Vbe_Q2. The simplification is obtained as follows:

$$I_{out\_noimp}(Vinac)=\left(0.75-\frac{2\sqrt{2}\cdot Vinac\cdot k_{feed}}{\pi}-\frac{0.5C_{char}\cdot 1.276\cdot Rs\cdot R_{up}}{L}\right)\cdot\frac{\pi-\frac{\sqrt{2}Vout}{Vinac}}{\pi\cdot Rs}+$$

$$2\sqrt{2}\cdot Vinac\cdot\frac{k_{feed}}{\pi\cdot Rs} \tag{11}$$

Then the LED current variation within the whole input range can be derived from formula (11).

$$\Delta I_{out\_noimp}=\left(0.75-\frac{0.5C_{char}\cdot 1.276\cdot Rs\cdot R_{up}}{L}\right)\cdot\frac{\sqrt{2}Vout}{\pi\cdot Rs}\cdot\left(\frac{1}{V_{ac\min}}-\frac{1}{V_{ac\max}}\right) \tag{12}$$

It can be seen that the LED current variation depends greatly on the Vout, which means that it can be with the higher line regulation when the LED voltage is low, in which case it is very suitable for GU10 application.

## 3.1 The Delta LED Current Variation Analysis During Mass Production

Because the LED current variation is derived as shown in formula (11) however, this variation is influenced by the tolerance of Rs, L, Cchar, and Rup during the whole input range. It has been investigated per the mass production requirement as follows:

1. The Delta LED current variation influenced by Rs (for example: 2% tolerance) when mass production is as follows:

$$\Delta(\Delta I_{out\_}Rs)=\frac{-\sqrt{2}\cdot 0.75\cdot V_{out}\cdot\Delta Rs}{\pi\cdot Rs^{2}}\cdot\left(\frac{1}{V_{ac\min}}-\frac{1}{V_{ac\max}}\right) \tag{13}$$

2. The Delta LED current variation influenced by $R_{up}$ (for example: 2% tolerance) when mass production is as follows:

$$\Delta(\Delta I_{out\_R_{up}})=\frac{-0.5\cdot C_{char}\cdot 1.276\cdot\Delta R_{up}}{L}\cdot\frac{\sqrt{2}\cdot V_{out}}{\pi}\cdot\left(\frac{1}{V_{ac\min}}-\frac{1}{V_{ac\max}}\right) \tag{14}$$

3. The Delta LED current variation influenced by Cchar (for example: 10% tolerance) when mass production is as follows:

$$\Delta(\Delta I_{out\_C_{char}})=\frac{-0.5\cdot\Delta C_{char}\cdot 1.276\cdot R_{up}}{L}\cdot\frac{\sqrt{2}\cdot V_{out}}{\pi}\cdot\left(\frac{1}{V_{ac\min}}-\frac{1}{V_{ac\max}}\right) \tag{15}$$

4. The Delta LED current variation by L (for example: 16% tolerance) when mass production is as follows:

$$\Delta(\Delta I_{out\_L}) = \frac{0.5\cdot C_{char}\cdot \Delta L\cdot 1.276\cdot R_{up}}{L^2}\cdot\frac{\sqrt{2}\cdot V_{out}}{\pi}\cdot\left(\frac{1}{V_{ac\min}}-\frac{1}{V_{ac\max}}\right) \tag{16}$$

5. The worst case Delta LED current variation under a certain Vled when mass production is as follows:

$$\Delta(\Delta I_{out\_total}) = \left|\Delta(\Delta I_{out\_Rs})\right| + \left|\Delta(\Delta I_{out\_R_{up}})\right| + \left|\Delta(\Delta I_{out\_C_{char}})\right| + \left|\Delta(\Delta I_{out\_L})\right| \tag{17}$$

Normally, this total variation is very small compared to the LED current variation.

## 3.2 The LED Current Tolerance Analysis During Mass Production

In mass production, the LED current is specified. It is normally required to be within ±5% regardless of the tolerance of Vled, kfeed, L, Cchar, and Rup during the whole input range.

From formula (9), we can see that the LED current variation is influenced by these parameters. The following details this analysis.

1. The LED current variation influenced by Rs (for example: 2% tolerance) when mass production is as follows:

$$\Delta I_{out\_Rs\_noimp}(Vinac) = \left(0.75-\frac{2\sqrt{2}\cdot Vinac\cdot k_{feed}}{\pi}\right)\cdot\frac{0.02\left(\pi-2\arcsin\left(\frac{Vout}{\sqrt{2}Vinac}\right)\right)}{\pi\cdot Rs}+2\sqrt{2}\cdot Vinac\cdot\frac{0.02\cdot k_{feed}}{\pi\cdot Rs} \tag{18}$$

2. The LED current variation influenced by Rup (for example: 2% tolerance) when mass production is as follows:

$$\Delta I_{out\_Rup\_noimp}(Vinac) = \frac{0.5C_{char}\cdot 1.276Rs\cdot R_{up}}{L}\cdot\frac{0.02\left(\pi-2\arcsin\left(\frac{Vout}{\sqrt{2}Vinac}\right)\right)}{\pi\cdot Rs} \tag{19}$$

3. The LED current variation influenced by Cchar (for example: 10% tolerance) when mass production is as follows:

$$\Delta I_{out\_Cchar\_noimp}(Vinac) = \frac{0.5C_{char}\cdot 1.276Rs\cdot R_{up}}{L}\cdot\frac{0.1\left(\pi-2\arcsin\left(\frac{Vout}{\sqrt{2}Vinac}\right)\right)}{\pi\cdot Rs} \tag{20}$$

4. The total LED current variation by L (for example: 16% tolerance) when mass production is as follows:

$$\Delta I_{out\_L\_noimp}(Vinac) = \frac{0.5C_{char}\cdot 1.276Rs\cdot R_{up}}{L}\cdot\frac{0.16\left(\pi-2\arcsin\left(\frac{Vout}{\sqrt{2}Vinac}\right)\right)}{\pi\cdot Rs} \tag{21}$$

5. The total LED current variation by kfeed (for example: 2% tolerance) when mass production is as follows:

$$\Delta I_{out\_kfeed\_noimp}(Vinac) = \frac{-2\sqrt{2}\cdot Vinac\cdot k_{feed}}{\pi}\cdot\frac{0.02\left(\pi - 2\arcsin\left(\frac{Vout}{\sqrt{2Vinac}}\right)\right)}{\pi\cdot Rs} +$$

$$+2\sqrt{2}\cdot Vinac\cdot\frac{0.02\cdot k_{feed}\cdot\sqrt{1-\frac{Vout^{2}}{2\cdot Vinac^{2}}}}{\pi\cdot Rs} \qquad (22)$$

6. The worst-case LED current variation under a certain Vled when mass production is as follows:

$$\Delta I_{out\_total\_noimp} = \Delta I_{out\_Rs\_noimp}(Vinac) + \Delta I_{out\_Rup\_noimp}(Vinac) + \Delta I_{out\_Cchar\_noimp}(Vinac) + \qquad (23)$$

$$\Delta I_{out\_L\_noimp}(Vinac) + \Delta I_{out\_kfeed\_noimp}(Vinac)$$

Then the total LED current tolerance can be expressed as follows as mass production requirement:

$$\Delta I\%_{out\_noimp}(Vinac) = \frac{\Delta I_{out\_total\_noimp} + \Delta I_{out\_noimp} + \Delta\left(\Delta I_{out\_total}\right)}{I_{out\_noimp}(Vinac)} \qquad (24)$$

## 4 Design Example Verification On the Line Regulation and Mass Production Current Tolerance Based On the Traditional Solution

To verify the validation of above derived calculation result, a prototype is made as the parameters listed in Table 1.

| Parameters | Value | Parameters | Value |
|---|---|---|---|
| Rs | 2.2 | k1 | 0.098 |
| L | 1.1 mh | Kfeed | 3.939 m |
| Rup | 270K | Cchar | 470 p |
| Vled | 30 | R1 comp | 600 K |

**Table 1. Parameters for the Prototype**

Using formula (5) in Chapter 2, obtain the frequency curve as shown in Figure 2:

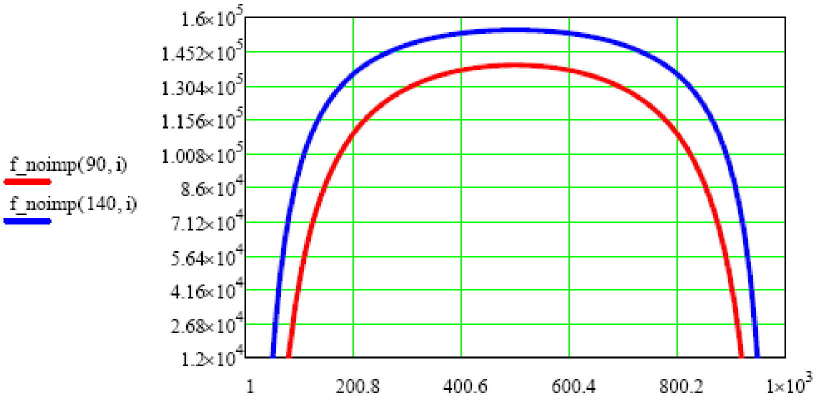


**Figure 2. Frequency of No Improved Solution With Less Than 90 Vac and 140 Vac**

Using formulas (7) and (8) in Chapter 2, obtain the maximum current and average current through the inductor (see Figure 3):

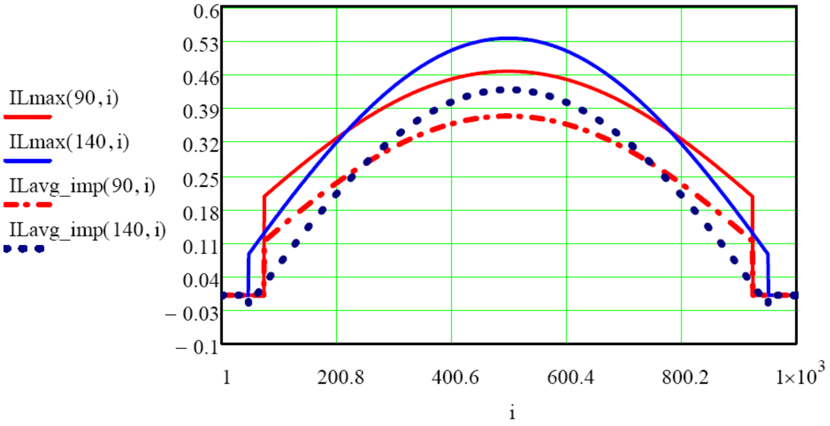


**Figure 3. Output Current of No Improved Solution Less Than 90 Vac and 140 Vac**

Figure 4 and Figure 5 show the simulation and experiment results less than 90 Vac and 140 Vac.

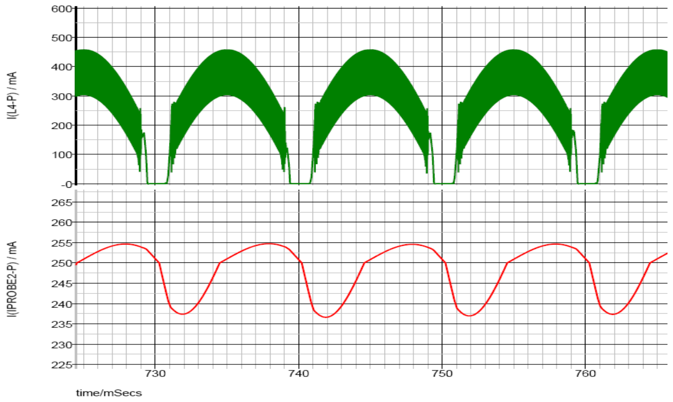


**Figure 4. Simulation Result of Inductor Current and Output Current Less Than 90 Vac**

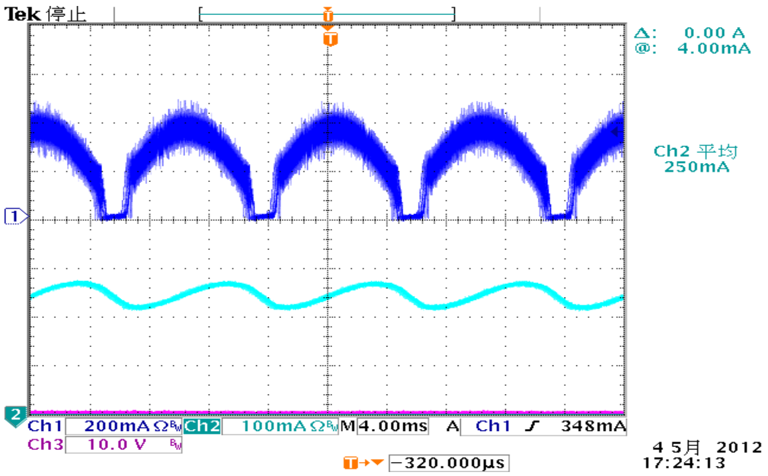


**Figure 5. Test Result of Inductor Current and Output Current Less Than 90 Vac**

The measured and simulated current waveforms (see Figure 4 and Figure 5) are nearly identical; the output ripple has shown a small difference due to the difference between LED simulation model and practical testing LED load.

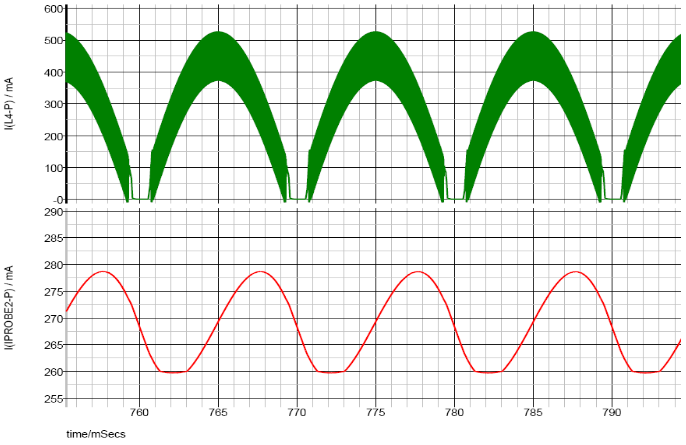


**Figure 6. Simulation Result of Inductor Current and Output Current Less Than 140 Vac**

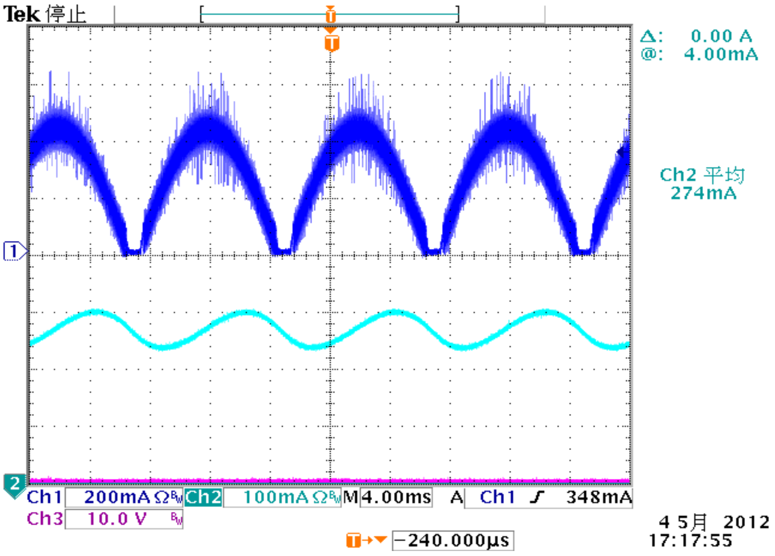


**Figure 7. Test Result of Inductor Current and Output Current Less Than 140 Vac**

From the results in Figure 6 and Figure 7, it seems that the calculation results closely match the simulation results and practical measured results. This finding provides the strong theoretical support for the following tolerance analysis.

Using formula 9 in Chapter 2, calculate the normal output current; obtain the maximum and the minimum output current, after considering the parameters tolerance, during mass production as follows:

$$\Delta I_{o\_noimp\_\max}(Vinac) = I_{out\_noimp}(Vinac) + 0.5\Delta I_{out\_total\_noimp}(Vinac) \tag{25}$$

$$\Delta I_{o\_noimp\_\min}(Vinac) = I_{out\_noimp}(Vinac) - 0.5\Delta I_{out\_total\_noimp}(Vinac) \tag{26}$$

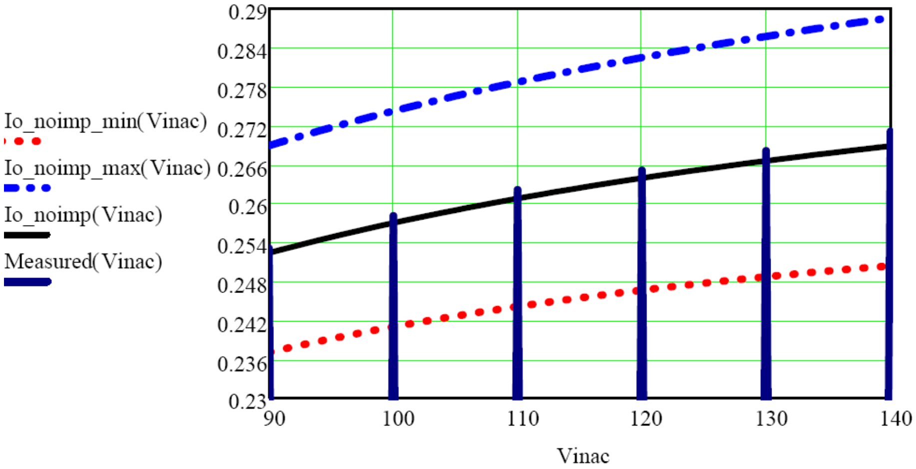


**Figure 8. Output Current of No Improved Solution Less Than 90 Vac and 140 Vac**

Using formula (23) in Section 3.2, obtain the worst-case LED current variation after considering the parameters tolerance during mass production (see Figure 9).

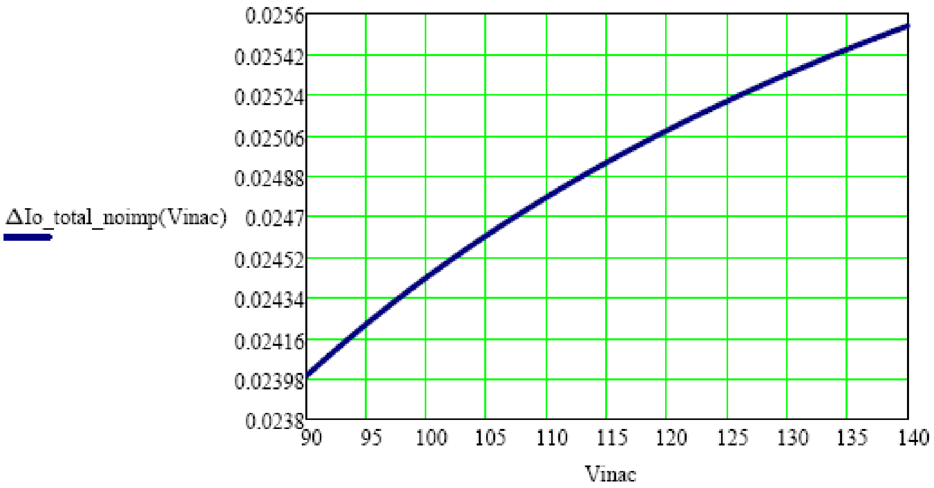


**Figure 9. LED Output Current Variation Influenced by the Components Tolerance of No Improved Solution Less Than 90 Vac to 140 Vac**

Using formula (24) of 3.2, obtain the total LED current tolerance during mass production (see Figure 10):

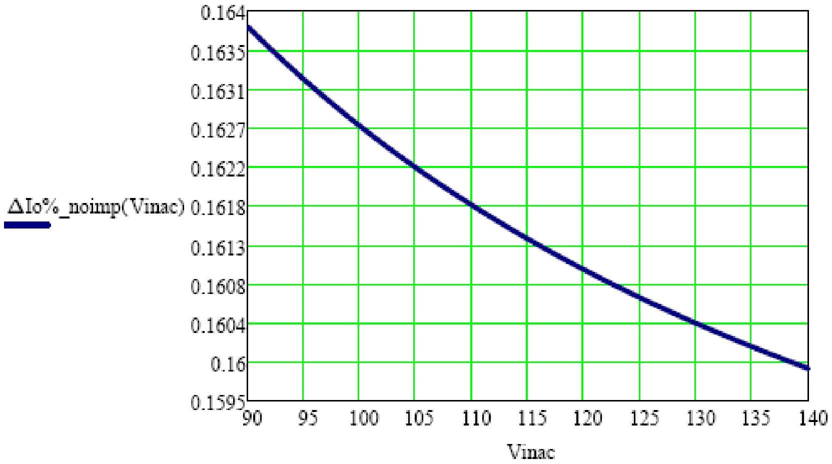


**Figure 10. Total LED Current Tolerance of No Improved Solution Less Than 90 Vac to 140 Vac When Mass Production**

From formula (24), we can see the normal LED current variation above 90 Vac to 140 Vac is17 mA, the line regulation is ±3.3%, it is acceptable for the single unit. The primary concern in practical engineering, however, is the total regulation feasibility, namely the total LED current tolerance after the component tolerance is considered. From Figure 8, it can be seen that the output current variation influenced by the components tolerance is about 32 mA. So the total LED current tolerance when mass production is above ±8%, as shown as Figure 10. This is also hard to implement in practical production. From above analysis, we know the line regulation is the key to improve the total tolerance during the input range.

## 5 Principle of Improved Nonisolated LM3444/LM3445 Solution

To improve the line regulation, the line compensation shown in Figure 11 is proposed.

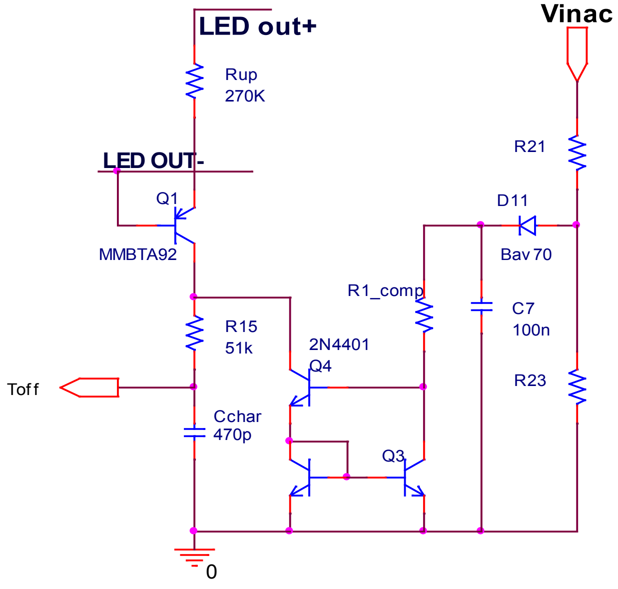


**Figure 11. Improved Line Compensation Circuit**

To reduce the latched current tolerance as the circuit shown in Figure 11, the higher precise resistors R21, R23, and R1_comp are used. To reduce the effect of forward voltage of D11, Q3, and Q4, the voltage on C7 is proposed to be a little high (for example, 20 Vdc). To know the current tolerance under a different temperature, the spice-based temperature sweep simulation is conducted when defining V_C7 as 20 V, V_c of Q4 as 20 V, and R_comp as 300K. Figure 12 shows the result.

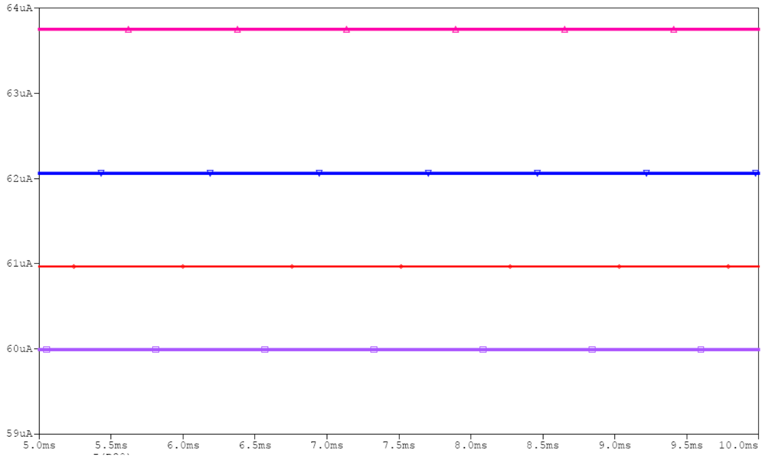


**Figure 12. Temperature Sweep Simulation Result Less Than 0°C, 25°C, 50°C, 85°C**

From the result, the temperature tolerance is seen as ±3%, so it is feasible to put it into the practical design.

After incorporating the compensation circuit (see Figure 11), the charge current for the improved $t_{off}$ can be obtained as follows:

$$I_{char\_imp}(t)=\frac{V_{out}-V_{eb\_Q1}}{R_{up}}-\frac{\sqrt{2}\cdot k\cdot Vinac\text{ - }2V_{be}}{R_{1\_comp}} \tag{27}$$

To decrease the effect of $V_{be}$ of Q3 and Q4 (shown in Figure 11), it is advised that the coefficient k in formula (27) is as high as possible so that we can ignore the $V_{be}$ in the design.

The maximum current and average inductor current formulas are the same as formulas (7) and (8) in Chapter 2.The final LED current formula can be obtained as follows:

If no other component tolerance is considered, the normalized formula for the output LED current can be expressed as follows:

$$I_{out\_imp}(Vinac)=\left(0.75-\frac{2\sqrt{2}\cdot Vinac\cdot k_{feed}}{\pi}-\frac{\frac{0.5Vout\cdot C_{char}\cdot 1.276\cdot Rs}{L}}{\frac{Vout-V_{eb}\_Q1}{Rup}-\frac{\sqrt{2}\cdot k\cdot Vinac}{R_{1\_comp}}}\right)\cdot\frac{\pi-2\arcsin\left(\frac{Vout}{\sqrt{2}Vinac}\right)}{\pi\cdot Rs}+$$
$$+2\sqrt{2}\cdot Vinac\cdot\frac{k_{feed}}{\pi\cdot Rs}\cdot\sqrt{1-\frac{Vout^2}{2\cdot Vinac^2}} \tag{28}$$

In practical calculation, we can define the 0.95 Char, 0.99 Rs, 0.99 Rup, 1.08 L, 0.99 kfeed to obtain the maxim LED output current. The formula is as follows:

$$I_{out\_imp\_\max}(Vinac)=\left(0.75-\frac{2\sqrt{2}\cdot Vinac\cdot 0.99\cdot k_{feed}}{\pi}-\frac{\frac{0.5Vout\cdot C_{char}\cdot 0.95\cdot 0.99\cdot 1.276\cdot Rs}{1.08L}}{\frac{Vout-0.6}{0.99Rup}-\frac{\sqrt{2}\cdot k\cdot 0.99Vinac}{R_{1\_comp}}}\right)\cdot\frac{\pi-2\arcsin\left(\frac{Vout}{\sqrt{2}Vinac}\right)}{\pi\cdot 0.99Rs}$$
$$+2\sqrt{2}\cdot Vinac\cdot\frac{k_{feed}}{\pi\cdot Rs}\cdot\sqrt{1-\frac{Vout^2}{2\cdot Vinac^2}} \tag{29}$$

Using the same analysis, we can define the 1.05 Char, 1.01 Rs, 1.01 Rup, 0.92 L, 1.01 kfeed to obtain the minim LED output current. The formula is as follows:

$$I_{out\_imp\_\min}(Vinac)=\left(0.75-\frac{2\sqrt{2}\cdot Vinac\cdot 1.01\cdot k_{feed}}{\pi}-\frac{\frac{0.5Vout\cdot C_{char}\cdot 1.05\cdot 1.01\cdot 1.276\cdot Rs}{0.92L}}{\frac{Vout-0.6}{1.01Rup}-\frac{\sqrt{2}\cdot k\cdot 1.01Vinac}{R_{1\_comp}}}\right)\cdot\frac{\pi-2\arcsin\left(\frac{Vout}{\sqrt{2}Vinac}\right)}{\pi\cdot 1.01Rs}$$
$$+2\sqrt{2}\cdot Vinac\cdot\frac{k_{feed}}{\pi\cdot Rs}\cdot\sqrt{1-\frac{Vout^2}{2\cdot Vinac^2}} \tag{30}$$

Then we can obtain the following calculation regarding the frequency range and inductor current waveform.

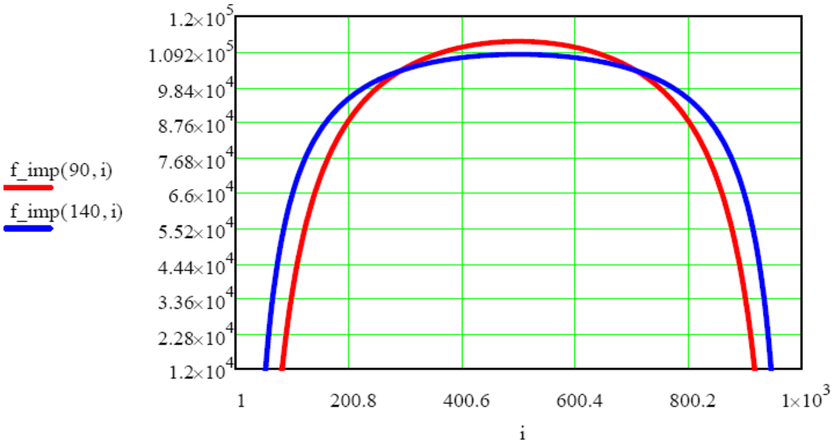


Figure 13. Frequency Less Than 90 Vac and 140 Vac

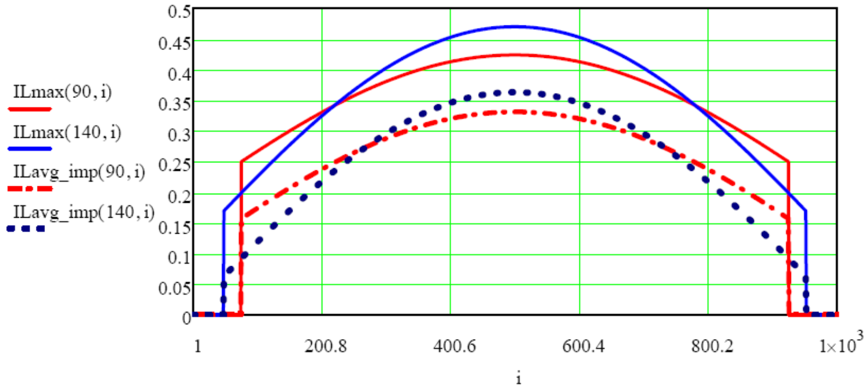


Figure 14. Inductor Current Less Than 90 Vac and 140 Vac

Figure 15 and Figure 16 show the experiment results less than 90 Vac and 140 Vac

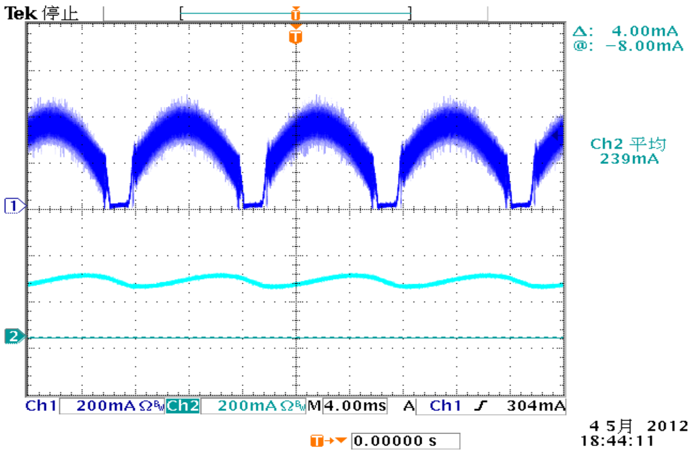


Figure 15. Test Result of Inductor Current and Output Current Less Than 90 Vac

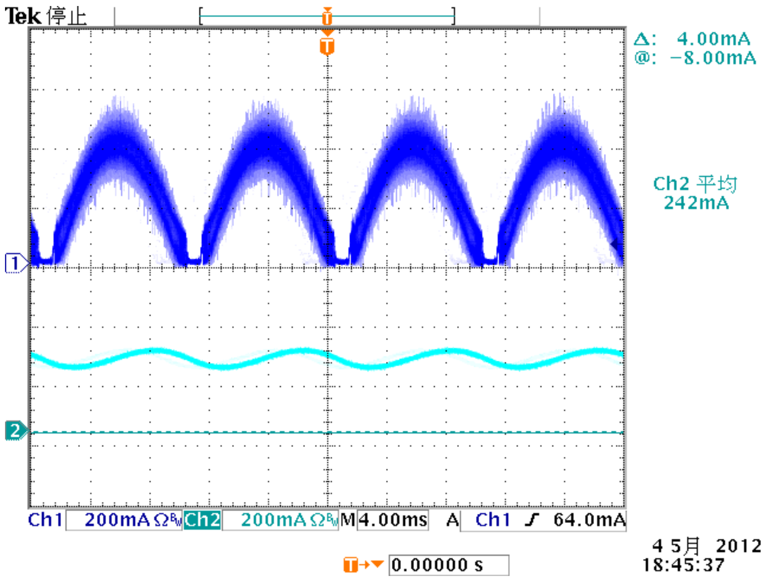


**Figure 16. Test Result of Inductor Current and Output Current Less Than 140 Vac**

Figure 17 shows the line regulation calculation result:

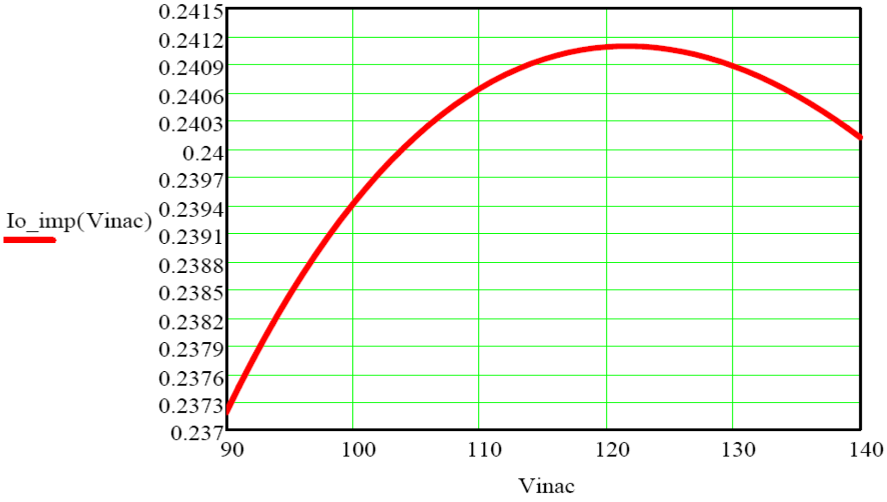
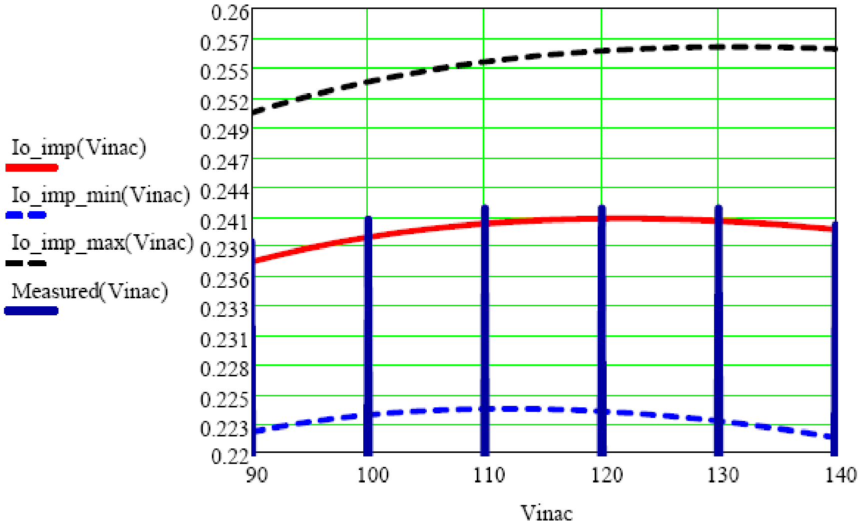


**Figure 17. Line Regulation Calculation Has Been Improved to Less Than ±1%**

The output current is a nonlinear curve with the input voltage, not a linear curve. The compensation parameters greatly influence the curve. In practical design, engineers can optimize the curve by adjusting the line compensation parameters.

To verify the result, use the measurement results shown in Figure 18 make the contrast with the calculation results.



**current tolerance:**

$$\Delta Io\%\_imp := \frac{Io\_imp\_max(130) - Io\_imp\_min(90)}{Io\_noimp(120)\cdot 2}$$

$$\Delta Io\%\_imp = 0.066$$

**Figure 18. Calculation of worst-case Current Tolerance Has Been Improved to ± 6.6%**

From Figure 18, it is seen that the worst-case current tolerance has also been improved due to the improved line regulation circuit. To meet the very stringent worst-case current tolerance, our solution must be improved more for some special users.

If the current tolerance under 90 Vac is considered, the following is obtained:

$$\Delta Io\%\_imp90 = \frac{Io\_imp\_max(90) - Io\_imp\_min(90)}{Io\_noimp(120)\cdot 2}$$

$$\Delta Io\%\_imp90 = 0.056$$

This target is attainable if the tolerance above 90 Vac is nearly the same; therefore, an optional method is proposed in Figure 19.

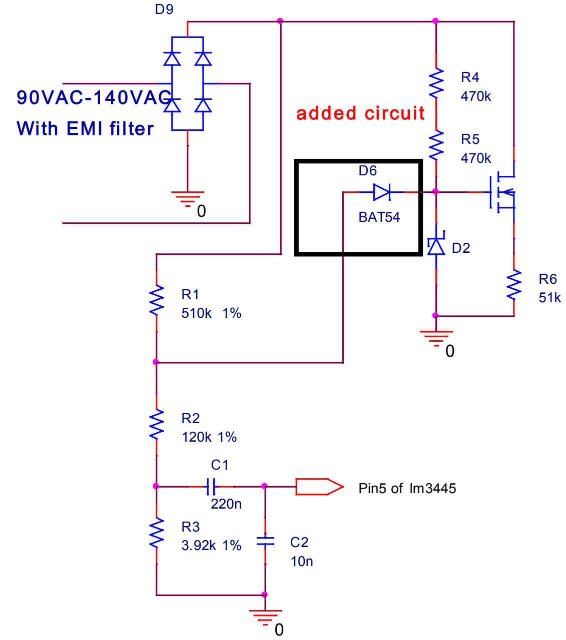


Figure 19. Circuit to Improve Line Regulation Less Than 120 Vac to 140 Vac

Then the pin 5 voltage of LM3445/LM3444 is calculated as shown in Figure 20 and Figure 21:

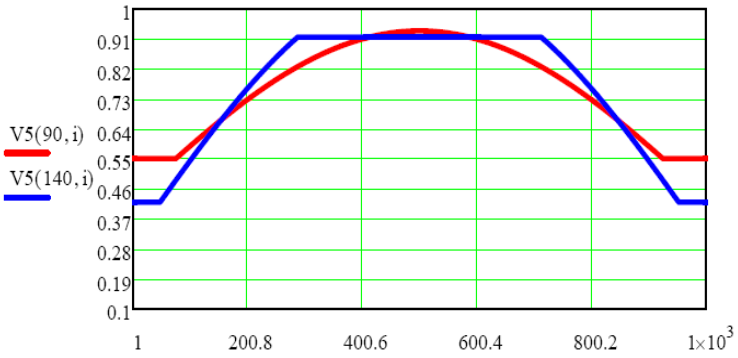


Figure 20. Voltage of Pin 5 on LM3445/LM3444 When Figure 20 Circuit is Added

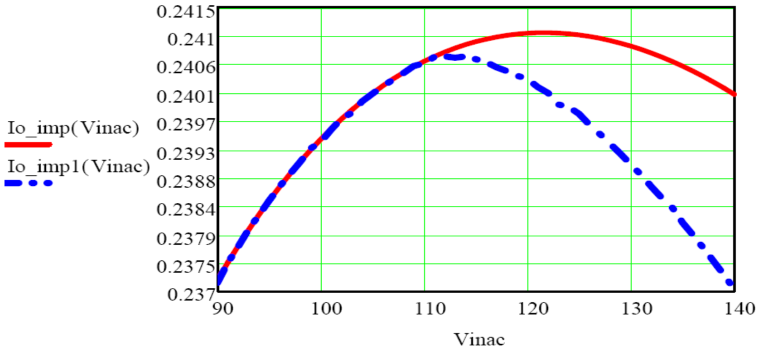


Figure 21. Line Regulation Has Been Improved More After Using Figure 19 circuit.

From the preceding analysis, it can be concluded that this circuit helps improve the line regulation. However, if the current tolerance using the line compensation circuit can meet the requirement during mass production, then the added diode circuit cannot be used. But TI still recommends using the added diode in the practical design schematic if there is room for PCB layout.

Finally, Figure 22 shows the total improved solution with the optional way.

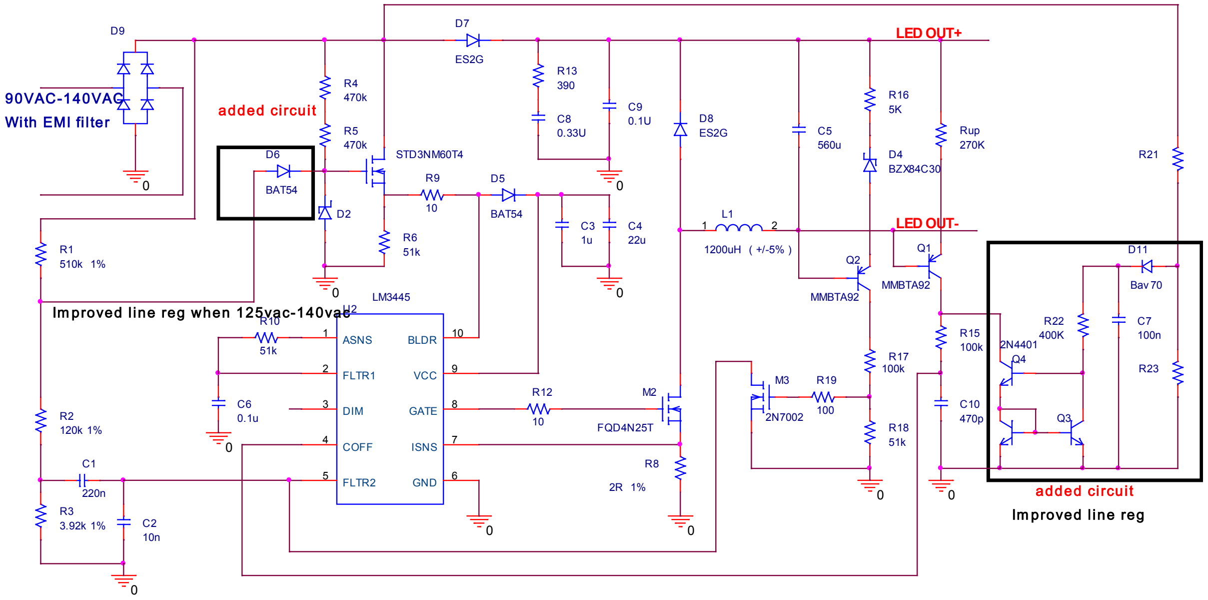


Figure 22. Total Solution With the Optional way to Improve the Line Regulation Greatly

## Conclusion

This paper thoroughly analyzes the line regulation of output current and current tolerance based on the traditional nonisolated LM3444/LM3445. It is determined that the line regulation is not good. To solve this problem, an improved solution is proposed. The line regulation and total current tolerance are also illustrated. The viability of the proposed solution is proved both from theoretical analysis and practical experimentation.

## References

[1] LM3445 Triac Dimmable Offline LED Driver Literature Number: SNVS570K.

[2] Application Note 2069 LM3445 - 230VAC, 6W- 15W Isolated Flyback LED Driver

[3] Application Note 2034 LM3445 -120VAC, 8W Isolated Flyback LED Driver (Rev. B)

[4] Application Note 2082 LM3444 -120VAC, 8W Isolated Flyback LED Driver (Rev. B)

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