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AN-4190

Improve Flicker Performance of Direct AC Driven LED Fixtures with Self Valley Fill

Introduction

To provide power to LED loads from AC input, Switch-Mode Power Supplies (SMPS) are generally used since LED need to be driven by regulated current. Consequently, LED lighting solution have to inherit the design complexity of a typical SMPS which includes designing the magnetic component, handling of Electromagnetic Interferences (EMI) as well as implementing Power Factor Correction (PFC). Direct-AC Drivers (DACD) for LEDs provides a new way to drive the LED load from an AC input with much simpler system architecture while satisfying EMI and power factor (PF) requirements with minimal effort. However, its drawback is flickering of light output at the zero crossing of AC line voltage due to loss of current to the LED load.

Though flicker is not always obvious, it can still cause headaches for a small percentage of people exposed to flickering lights for long periods [1]. This is a major issue for offices, schools, stores and other brightly lit commercial and industrial spaces where people spend a lot of time.

While there are currently no official standards governing flicker, most manufacturers and customers accept the US Energy Star recommended method for calculating Flicker Index. [2] [3]

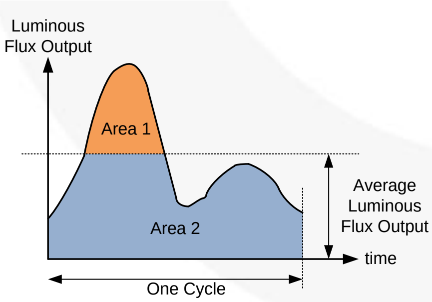


Figure 1. Definition of Flicker Index

For a periodic variation in luminous flux output as shown in Figure 1, the definition of Flicker Index (F.I.) is:

$$F.I. \equiv \frac{\text{Area 1}}{\text{Area 1} + \text{Area 2}} \qquad (1)$$

In practice, F.I. below 0.15 is considered imperceptible so, naturally, lighting manufacturers aim to achieve or surpass this.

To deal with flickering, energy-storage devices are required. Capacitor is a kind of energy-storage device. A straight-forward idea of applying capacitors in DACD systems is adding a valley-fill circuit to its front end, as shown in Figure 2. But, the drawback of this architecture is that input current will be distorted, which leads to degraded PF and Total Harmonic Distortion (THD). Reason of the distortion is that charging and discharging of the capacitors in valley-fill circuit change shape of input-current waveform, which is originally very close to a sinusoidal wave in-phase with input voltage for DACD systems. For example, the waveform in Figure 3 comes with THD of 21.77%. Without the valley-fill front end, THD could be as low as 11.36%.

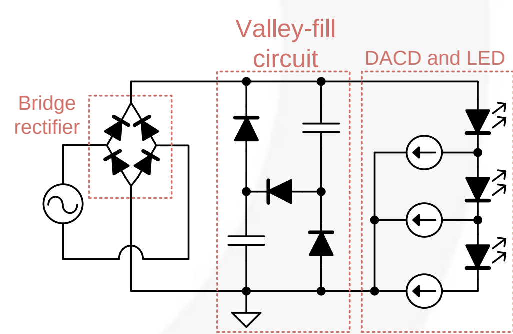


Figure 2. Traditional Valley-fill Circuitry with a DACD System

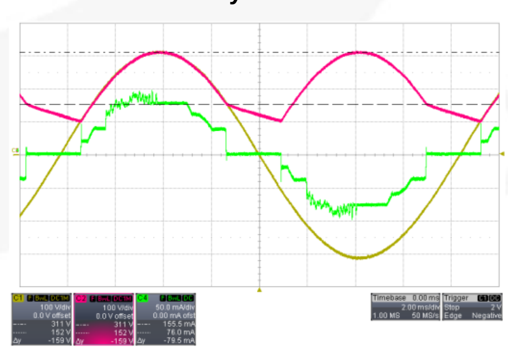


Figure 3. Waveform of DACD System with Traiditional Valley-Fill Circuit (Ch1: AC Input Voltage, Ch2: Output of Valley-Fill Circuit, Ch4: AC Input Current)

This application note now proposes a new proprietary method called Self Valley Fill (SVF) which achieves low flicker, high PF and low THD at the same time, as well as outlines its practical design considerations.

Concept of Self Valley Fill (SVF)

A typical SVF circuitry is shown in Figure 4. Originally the driver IC regulates input current to drive the LEDs. With added capacitors in the SVF circuit, the input current charges capacitor and drives LEDs simultaneously. The charged capacitors also supply LEDs when regulated driving current is cut off. Thus, LED currents get smoothed without distorting the AC input current shape. As a result, flickering of light output is reduced while maintaining high PF and THD performance.

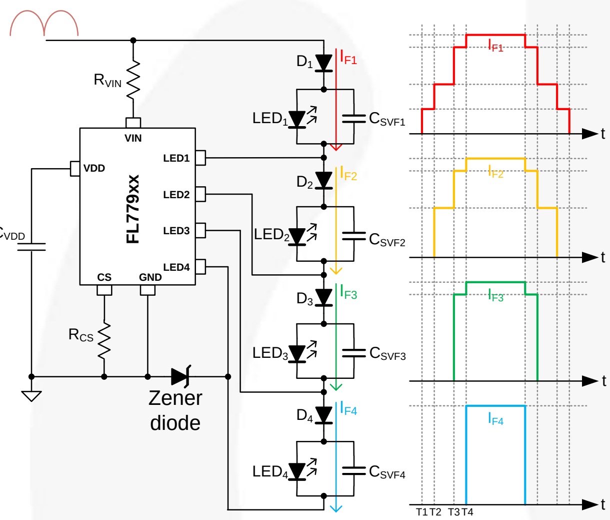


Figure 4. Self Valley Fill in a DACD System

For simplicity, the operation of the Self Valley Fill circuit is explained using one of the LED segments as an example as shown in Figure 5. Before the SVF capacitor, C_{SVFi}, is applied, the circuitry is no difference than general DACD system. When anode voltage of LEDi, V_{Ai}, is higher than forward-voltage summation of D_i and LED_i, I_{DRVi} starts conducting a regulated current until V_{Ai} drops below the summation of forward voltages.

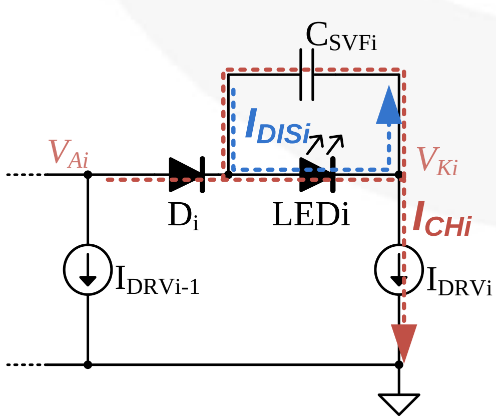


Figure 5. Self Valley Fill In One LED Segment

When the SVF capacitor is applied in the circuitry, I_{DRVi} not only drives LEDi but also charges C_{SVFi} simultaneously. Current flowing through LEDi is less than I_{DRVi} since part of the current is used to charge C_{SVFi}. C_{SVFi} will be charged up to around forward voltage of LEDi, $V_{F\text{-}LEDi}$, since the LED clamps voltage on the capacitor. Once I_{DRVi} is cut off, voltage accumulated on C_{SVFi} supplies LEDi until V_{CSVFi} is discharged to threshold forward voltage of LEDi. The threshold forward voltage means the forward voltage of the LED when its forward current is extremely close to zero.

From the description above, two facts can be concluded. First, since voltage on the SVF capacitor is kept around forward voltage of its parallel-connected LED, behavior of the driving current (I_{DRVi}) will be the same. That is, when anode voltage of the LED group exceeds the LED group's forward voltage, current starts to flow. The current ceases when the anode voltage decreases to lower than the forward voltage. As a result, input current will be almost identical to the without-SVF case. Second, LED current will be smoothed since driving current is shared to charge the capacitor and the capacitor supplies LED when driving current is absent.

The purpose of the additional diode D_i is to avoid charges on C_{SVFi} is wrongly discharged by driving current of its previous tap, I_{DRVi-1}. Note that D_i can also be an LED.

Evaluate Required Capacitance of Self Valley Fill in a Simplified System

In this section, we try to show an analytical estimation of how effective the SVF will be with a specific capacitance, so that we can evaluate how big the capacitance should be. To simplify the system, let's focus on a circuit like shown in Figure 5, which is redrawn in Figure 6 with its driving current waveform. The driving current has a periodic rectangular waveform with amplitude I_{DRV} and on-time t_{ON} in each period.

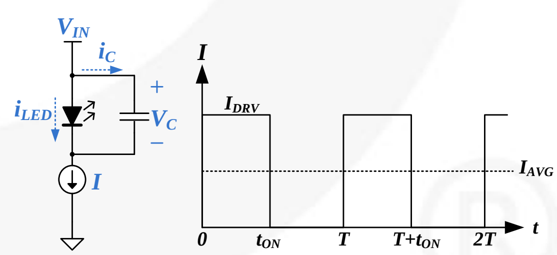


Figure 6. Simplified Schematic of SVF In One LED Segment

Without the capacitor, the driving current is equal to LED current. Average driving current in this case is:

$$I_{AVG} = \frac{I_{DRV} \cdot t_{ON}}{T} \tag{2}$$

Assume luminous flux is proportional driving current. Based on the definition, flicker index in this situation is:

$$F.I.\big|_{\text{no SVF}} = \frac{(I_{DRV} - I_{AVG})\cdot t_{ON}}{I_{DRV}\cdot t_{ON}} \tag{3}$$

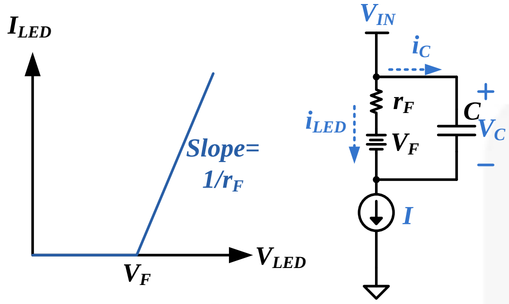


Figure 7. Simplified LED Model with SVF Circuit

When the SVF capacitor is added, actual LED current depends on V-I characteristics of the LED. Assume the LED can be modeled as a fixed voltage drop with a series resistor as shown in Figure 7. Assuming voltage on the SVF capacitor is always higher than V_F, LED current over one period can be calculated through circuit analysis.

$$i_{LED}(t) = \begin{cases} -\dfrac{1-e^{-\frac{T-T_{ON}}{r_F\cdot C}}}{1-e^{-\frac{T}{r_F\cdot C}}}\cdot I_{DRV}\cdot e^{-\frac{t}{r_F\cdot C}} + I_{DRV} & \text{for } t\in[0, t_{ON}] \\[2ex] \dfrac{1-e^{-\frac{T_{ON}}{r_F\cdot C}}}{1-e^{-\frac{T}{r_F\cdot C}}}\cdot I_{DRV}\cdot e^{-\frac{t-t_{ON}}{r_F\cdot C}} & \text{for } t\in[t_{ON}, T] \end{cases} \tag{4}$$

Based on same assumption as in (3), flicker index of this condition can be calculated as:

$$F.I.\big|_{\text{SVF}} = \frac{(I_{DRV} - I_{AVG})\cdot t_{ON}}{I_{DRV}\cdot t_{ON}} + \frac{r_F\cdot C}{t_{ON}}\cdot \ln\left(\frac{T-t_{ON}}{T}\cdot\frac{1-e^{-\frac{T}{r_F\cdot C}}}{1-e^{-\frac{T-t_{ON}}{r_F\cdot C}}}\right) - \frac{r_F\cdot C}{T}\ln\left(\frac{T-t_{ON}}{t_{ON}}\cdot\frac{1-e^{-\frac{t_{ON}}{r_F\cdot C}}}{1-e^{-\frac{T-T_{ON}}{r_F\cdot C}}}\right) \tag{5}$$

The equation is a little bit complicated to interpret. Let assume a case with r_F = 150 Ω, T = 8.33 ms, t_{ON} = 0.56T, I_{DRV} = 71 mA. Flicker Index can be represented as a function of the SVF capacitance as in Figure 8. Figure 8 shows that if SVF capacitance is larger, Flicker Index will be lowered. When there is no SVF capacitor, Flicker Index is 0.44 according to (3). While 47-µF SVF capacitor is implemented in this case, F.I. can be as low as 0.06. Driving current and LED current under 47-µF SVF capacitance are shown in Figure 9.

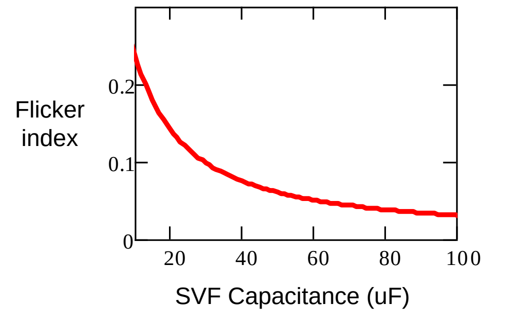


Figure 8. Flicker Index vs. SVF Capacitance

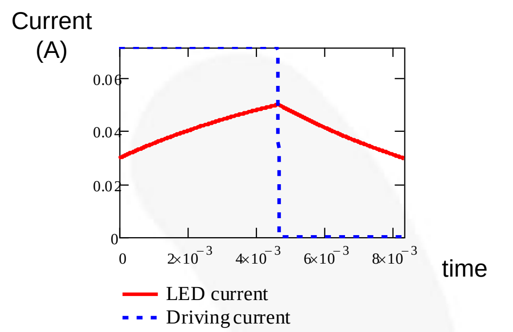


Figure 9. Driving Current and LED Current of Simplified SVF Circuit with 100-µF Capacitance

Evaluation and Measurement of a Practical DACD system with SVF

Figure 10 shows a schematic of a DACD system with SVF for reduction of flickering. It is actually schematic of the evaluation board "FEBFL77944_L80H012B" [4].

Calculation process of current and timing parameters of the same system without SVF can be referred to design example in FL77944's application note [5]. It is a system designed for 220 V_{AC} input and input wattage is 12 W. Key parameters used in this section are listed in Table 1.

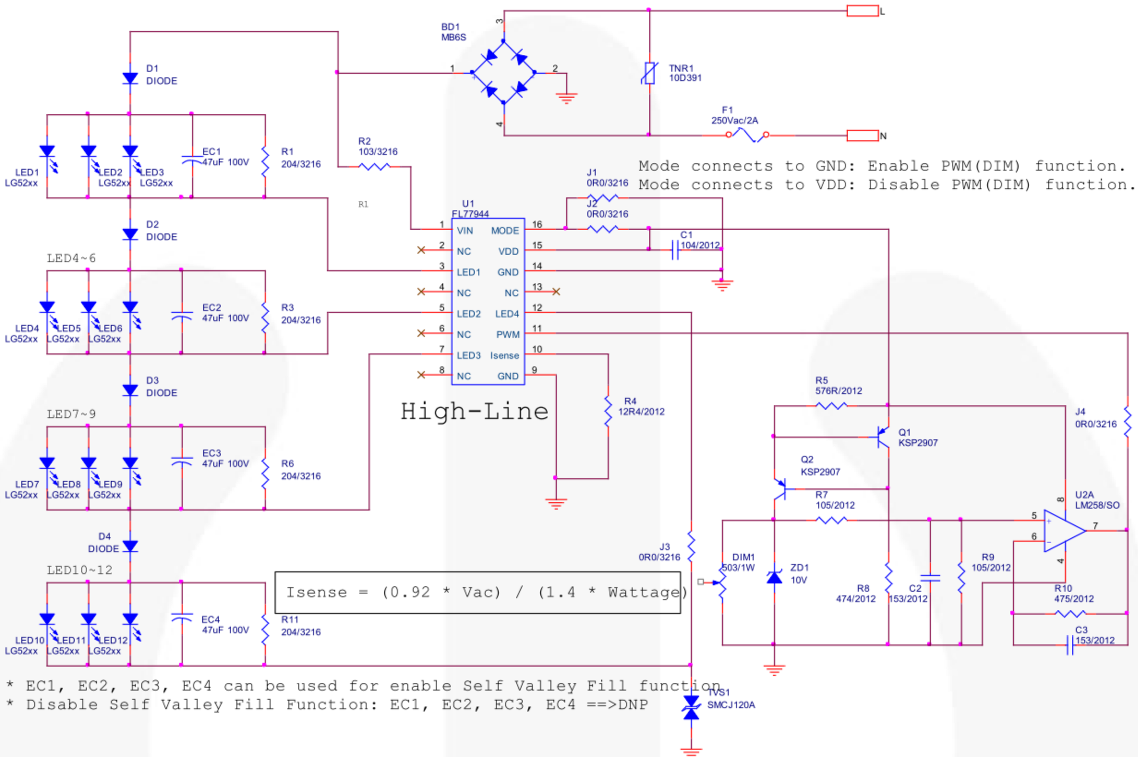


Figure 10. Schematic of FL77944 Evaluation Board with SVF

Table 1. Key Parameters of the Design Example

Parameter	Number	Unit
T	1/120	ms
I_{LED1}	14.5	mA
I_{LED2}	29.8	mA
I_{LED3}	66.9	mA
I_{LED4}	74.1	mA
T1	0.51	ms
T2	1.08	ms
T3	1.84	ms
T4	2.75	ms
$I_{F1,AVG}$	47.22	mA
$I_{F2,AVG}$	45.24	mA
$I_{F3,AVG}$	39.8	mA
$I_{F4,AVG}$	25.2	mA

To apply the equations derived above, the current waveforms $I_{F1\sim4}$ are simplified as in Figure 11. Average values of the original and simplified waveforms are the same. The t_{ON} of the simplified waveform is equal to time duration that its original waveform is higher than its average value. Turning-on moment of the simplified waveforms is aligned to $t=0$. t_{ON} and I_{DRV} of each group are listed in Table 2.

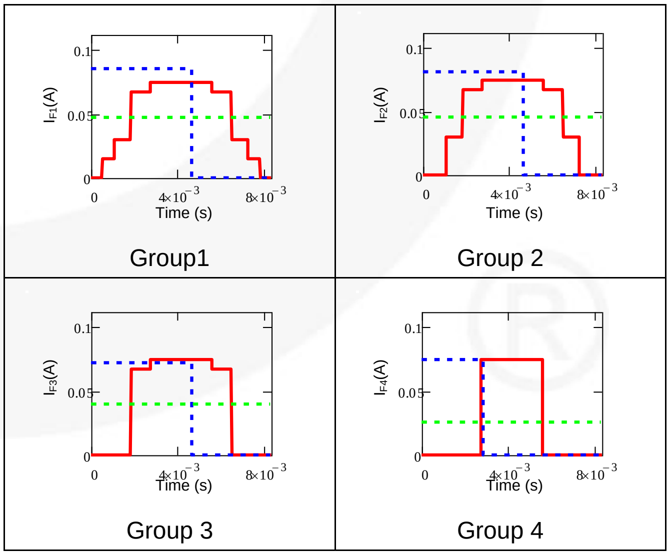


Figure 11. LED Group Current in Half AC Period (RED: Original, Blue: Simplified, Green: Average)

Table 2. Parameters of the Simplified Current Waveform

Parameter	Number	Unit
t_{ON1}	4.65	ms
t_{ON2}	4.65	ms
t_{ON3}	4.65	ms
t_{ON4}	2.83	ms
I_{DRV1}	85	mA
I_{DRV2}	81	mA
I_{DRV3}	71	mA
I_{DRV4}	74	mA

The LEDs implemented in this system has V-I curve as shown in Figure 12. It can be modeled as a fixed 55.56-V voltage drop plus a series 450-Ω resistor. Since there are three LEDs put in parallel for each LED group, the effective resistance is 150 Ω.

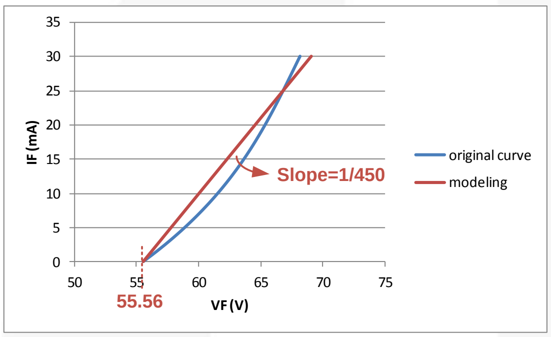


Figure 12. V-I Curve of the LED

t_{ON}, I_{DRV}, I_{AVG}, and r_F of each LED group are now calculated. So, we can have Flicker Index of each LED group according to (5). For Flicker Index of the whole system, we can simply evaluate it by weighted sum of each LED group's Flicker Index according to their average current.

$$I_{AVG,TOTAL} = I_{AVG,F1} + I_{AVG,F2} + I_{AVG,F3} + I_{AVG,F4} \tag{6}$$

$$\begin{aligned} F.I.|_{\text{wholesystem}} = {} & F.I.|_{\substack{SVF \\ I_{DRV2} \\ I_{AVG,F1} \\ T_{ON1}}} \cdot \frac{I_{AVG,F1}}{I_{AVG,TOTAL}} + F.I.|_{\substack{SVF \\ I_{DRV2} \\ I_{AVG,F2} \\ T_{ON2}}} \cdot \frac{I_{AVG,F2}}{I_{AVG,TOTAL}} \\ & + F.I.|_{\substack{SVF \\ I_{DRV3} \\ I_{AVG,F3} \\ T_{ON3}}} \cdot \frac{I_{AVG,F3}}{I_{AVG,TOTAL}} + F.I.|_{\substack{SVF \\ I_{DRV4} \\ I_{AVG,F4} \\ T_{ON4}}} \cdot \frac{I_{AVG,F4}}{I_{AVG,TOTAL}} \end{aligned} \tag{7}$$

Assuming same capacitance is applied in every LED group, Flicker Index versus the capacitance can be drawn as Figure 13. It indicates that Flicker Index is 0.069 when 47-μF capacitor is applied in each LED group.

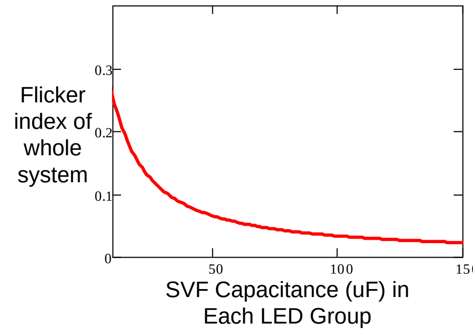
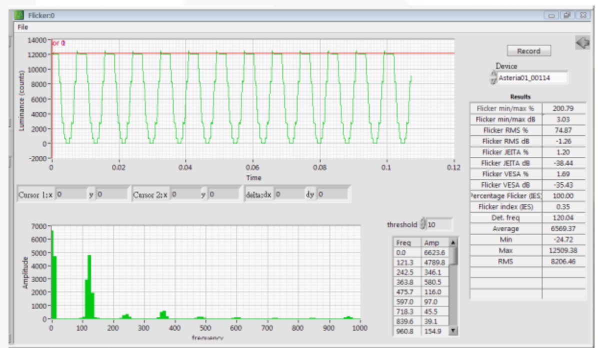
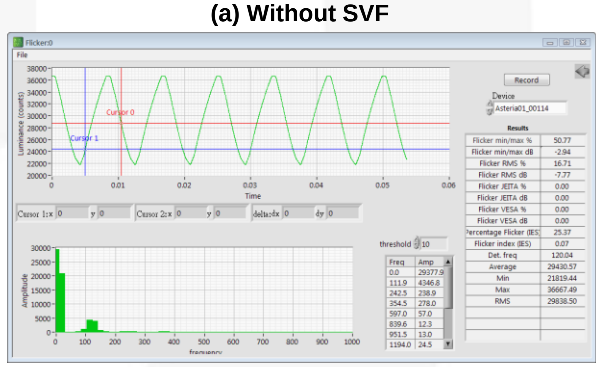


Figure 13. Flicker Index vs. SVF Capacitance of the Design Example

Figure 14 shows measurement result from a light meter. The "without SVF" means to simply remove the capacitors from the circuit. It can be seen that SVF improves Flicker Index from 0.35 to 0.07 in this design.



(a) Without SVF



(b) With SVF

Figure 14. Measurement result of SVF with Light Meter

This section shows a design example and its experiment result. The equations derived in previous section are extended to a much complicated system. There are assumptions and approximations when applying the equations.

For more complicated designs or more accurate results, the assumptions and approximations of this section may not be appropriate. For example, the capacitor may not be large enough to make the LED current not cut off, or the first-order approximation of the LED model may not be accurate enough. Since currents in LED and capacitor depend on each other, the calculation process is complicated. Computer simulation or mathematical software may be required for design estimation. A Design Tool has been provided to assist in designing SVF capacitors [6].

If those kinds of tools are not available, the design can also be done through experimenting with different capacitances and measuring the Flicker Index directly with hardware.

Practical Design Considerations along with SVF

To Design by Trial

DACD system is generally designed as evenly separated LED groups, which means effective forward voltage of each LED group is identical. A simple way to design the SVF capacitance of this kind of system is to put identical capacitors to each LED group. While changing the capacitance value, replace all the capacitors at the same time.

Discharging Resistor

Due to existence of the SVF capacitors, when input power source is turned off, luminous flux decays to zero slowly. If it is considered too long for dimmed to black, resistors can be added in parallel with the SVF capacitors. Resistance value can be achieved through making R-C time constant equal to the desired response time.

$$\tau = R \times C_{SVF} \quad (8)$$

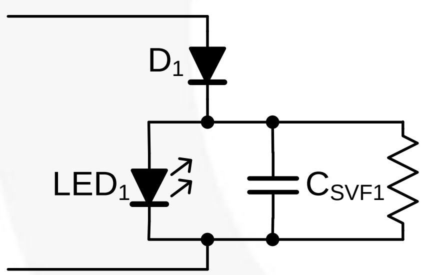


Figure 15. Adding Resistor to Discharge the SVF Capacitor

Applying Capacitors not in Every LED Group

In Figure 4, every LED group is with SVF capacitor. Designing in this way generally leads to good results in luminary and electrical characteristics of the system. If, in some cases, it is desired to design the system to have only some LED groups having the SVF capacitors, it is also doable. The driver can still work properly. Of course, only the LED groups with SVF capacitors get smoothed luminous output.

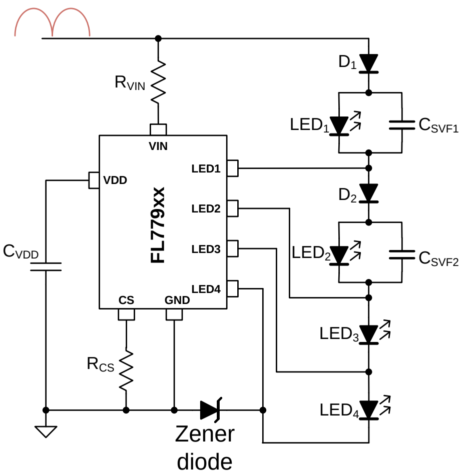


Figure 16. SVF Capacitors are only applied to some LED groups

Clamping the Inrush Voltage Spike

One more thing to be considered is transient voltage spike when turning on input voltage to a DACD system with SVF. Before powering on, initial voltage on the capacitors will be zero. Referring to Figure 17, assuming the input is turned on at its peak value, since initial voltage is zero for all the capacitors, the LED4 pin in Figure 17 will see directly the peak value of input voltage. If this voltage is beyond voltage rating of the LED4 pin, the driver IC is very likely to be damaged. In such cases, a Zener diode as shown in Figure 17 is required. For example, when the voltage rating of LED4 is 200 V and peak of input voltage is 310 V, a less than 200 V Zener diode is required to clamp the voltage spike. Since the transient time is not too short, power rating of the Zener diode needs to be high. SMCJ200A from Little Fuse is generally applied in our evaluation board. Its power rating is 1500 W. Also worth noting is that the Zener voltage should not be smaller than difference between maximum peak input voltage and LEDs' total effective forward voltage. If so, the Zener diode will be turned on at the peak input voltage region in every AC cycle. The circuit will not operate properly, consume lots of energy, and possibly be damaged.

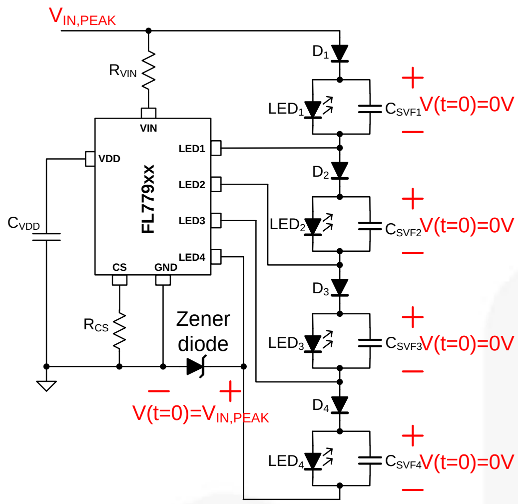


Figure 17. Voltage Spike on LED4 pin Before SVF Capacitors Get Charged

Another way to alleviate the impact of voltage spike and current inrush for charging the capacitors is to add inductors in front of bridge diode. Voltage spike and current inrush will be smoothed because that inductor takes time to get energized. This inductor can also be implemented with capacitors to form an L-C filter for enhancing immunity to lighting surge.

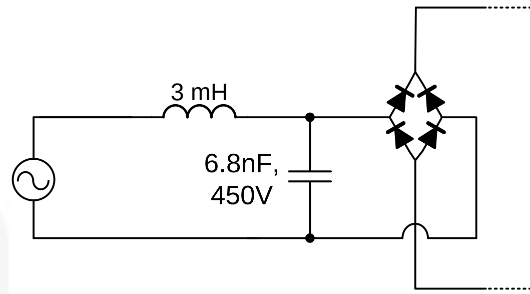


Figure 18. Example of Input L-C Filter

References

[1] *Wilkins, Arnold, Jennifer Veitch, and Brad Lehman. "LED lighting flicker and potential health concerns: IEEE standard PAR1789 update." 2010 IEEE Energy Conversion Congress and Exposition. IEEE, 2010.*

[2] *Kaufman, John E., H. Haynes, and Lighting Handbook IES. "Illuminating Engineering Society of North America." IES Lighting Handbook. New York, NY USA (1984).*

[3] *ENERGY STAR. "Recommended Practice - Light Source Flicker (Rev. December 2015)," ENERGY STAR (2015).*

[4] *"User Guide for FEBFL77944_L80L012B Evaluation board," Fairchild Semiconductor, April 2016.*

[5] *"AN-5088 Designing for High Performance Commercial and Industrial Lighting Solution Using FL77944 High Power LED Direct AC Driver," Fairchild Semiconductor, July 2016.*

[6] *"AN-4189 Guidance of Using Self Valley Fill Calculation Tool for FL77904/FL77944/FL77905," Fairchild Semiconductor, July 2016.*

Reference and Related Datasheets

FL77904 Phase-cut Dimmable Compact LED Direct AC Driver

FL77905 Analog/PWM/Phase-cut Dimmable Compact LED Direct AC Driver

FL77944 Analog/PWM Dimmable High Power LED Direct AC Driver

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