

# **Challenges of Dimming LED Loads on ELV and MLV Transformers**

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# 1 Introduction

LEDs (Light Emitting Diodes), also known as Solid State Lighting (SSL), are replacing traditional light sources in nearly every lighting application imaginable. Based on the number of LED lighting companies and products launched over the last few years, low-voltage MR16s are a popular source being targeted for replacement by LEDs. Additionally, LED strips or “tape” are increasingly used to add indirect accent, under counter, or cove light to a space where incandescent or low-voltage halogen festoon lights may have previously been used. Dimmers are often used to enhance the user experience—switching to LEDs should not change this experience.

Anyone who has used LED loads with low-voltage magnetic or electronic transformers in dimming applications has likely experienced confusion, frustration, and even disappointment. Some may blame the dimmer as the cause of the problem, when the real issue is compatibility among all three components in the system. Why do LEDs that run at the same 12 or 24 volt low voltages as traditional incandescent low-voltage loads cause so many problems? This paper will explain the technical difficulties with dimming low-voltage LED lamps on magnetic and electronic transformers, and provide some design tips to improve the situation and avoid problems.

## 1.1 Low Voltage Transformers

MR16 lamps, whether they are traditional halogen or LED, are predominantly low-voltage devices. LED strip or tape lights, or their halogen predecessors, are also low-voltage (12V or 24V). A device is required to convert line-voltage (120, 230, or 277V) power into low-voltage needed for the lighting load. This device is either a magnetic low-voltage (MLV) transformer or an electronic low-voltage (ELV) transformer.



Figure 1: E-I MLV (left), toroidal MLV (center) and ELV (right) transformers

Basic MLV transformers are simple in their construction: they are made from windings of copper wire around an iron core. The core may take one of a few shapes, such as an E-core or toroid (see Figure 1), but the basic operation is the same: voltage is stepped-down via magnetic coupling through the core. Magnetic transformers have the advantage of being relatively inexpensive, simple, and reliable. However, they operate at a low line frequency (60 Hz in the United States) making them large and

heavy, especially for control of higher wattage loads. Their efficiencies can vary from 75% to 90%, based on construction and loading, resulting from losses through the large amount of copper wire in the coil and magnetic field losses.

The output AC sinusoid waveform of a MLV transformer looks identical to the input waveform, merely with lower amplitude (see Figure 2). Some transformers may contain filtering or safety components on their outputs, creating AC rectified or DC waveforms, or protecting against over-current or over-temperature conditions.

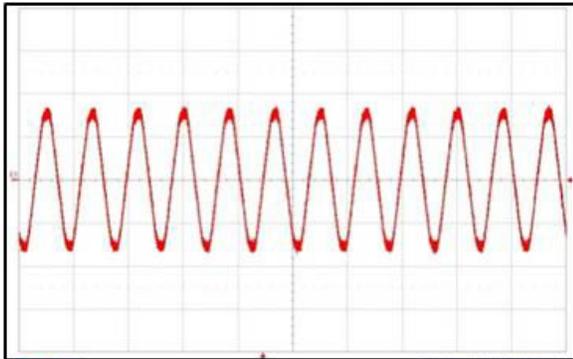


Figure 2: Output voltage of an MLV transformer

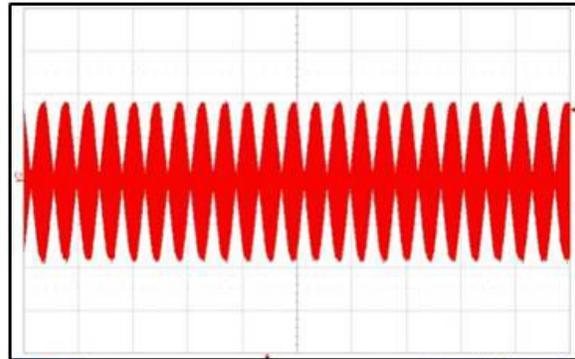


Figure 3: Output voltage of an ELV transformer

In contrast, ELV transformers have internal circuitry which operates at a much higher frequency. ELV transformers generally have higher efficiency and can convert the same amount of power in a smaller, lighter footprint. This is achieved by using a self-oscillating circuit which drives a high-frequency transformer, providing the step-down function as well as necessary isolation. The output of an ELV transformer is a high-frequency waveform contained within an envelope representing the input line frequency (see Figure 3).

## 1.2 Dimming Low-Voltage Transformers

Each transformer type, MLV or ELV, has always required its own specific dimming technology. Dimmers designed and tested for the highly inductive MLV transformers use a forward-phase (also called leading-edge) waveform (see Figure 4). Brightness is determined by the ratio of “on” time to “off” time: the higher the ratio, the brighter the output. The amount of “off” time represents the energy saved by dimming.

While the vast majority of incandescent triac dimmers installed today create forward-phase waveforms, those dimmers designed specifically for MLV loads also have to maintain voltage symmetry: identical wave shapes in both the positive and negative half-cycles of the sine wave.

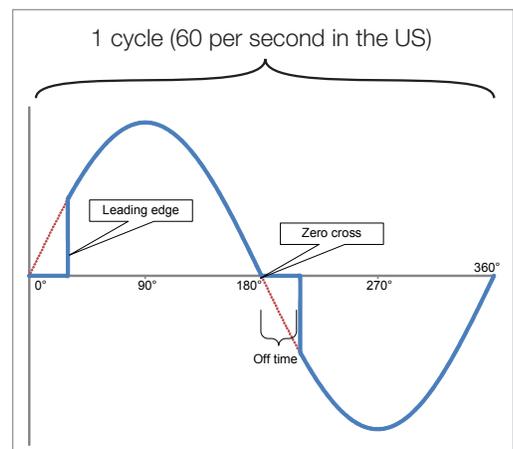


Figure 4: Forward Phase Waveform

Deviations from symmetry in positive and negative half-cycles can cause a voltage imbalance when feeding the MLV transformer. An imbalance of even a few volts can cause significant heating within the transformer, leading to an unsafe condition or transformer failure.

In contrast to forward-phase dimmers, those designed, tested, and approved for ELV transformers create reverse-phase (also called trailing-edge) waveforms (see Figure 5). Like forward-phase dimmers, brightness is determined by the ratio of “on” time to “off” time.

Since the input characteristics of an ELV transformer are highly capacitive, combining an ELV load with an incandescent or MLV forward phase dimmer creates an instantaneous spike of current due to the rapid switch-on of voltage that occurs every half-cycle when a forward-phase dimmer starts conducting. This spike, also called repetitive peak current, can cause stress and acoustic noise in both the dimmer and the transformer, leading to potential premature failure of either device. To avoid this repetitive peak current, ELV dimmers begin conducting at the zero cross of the sine wave, and the voltage slowly increases at the (slow) rate of the line voltage waveform.

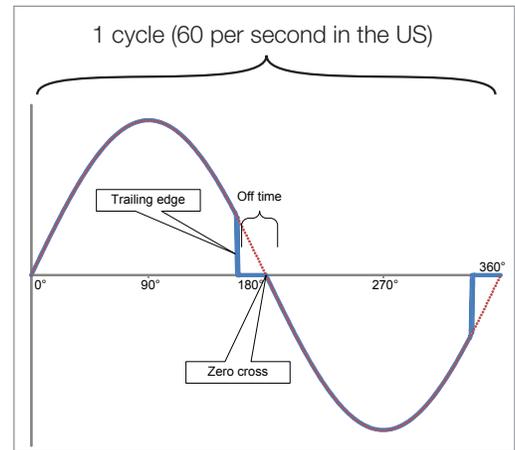


Figure 5: Reverse Phase Waveform

Not only are problems caused by using forward-phase dimmers on capacitive ELV loads, but the opposite is also true. Reverse-phase dimmers have a rapid turn-off of voltage when the dimmer stops conducting every half-cycle. If this waveform is applied to an MLV load, the sudden change of voltage causes the magnetic field in the inductive transformer to suddenly collapse, creating a large voltage spike that can damage the dimmer. This voltage spike can also pass through the transformer to the LED load, which can exceed the design voltage of the LEDs or associated driver circuitry, potentially damaging the light source as well as the dimmer. Proper pairing of the dimmer type and low-voltage transformer is essential to performance.

There are also “universal” or “adaptive” dimmers, that are capable of creating both forward-phase and reverse-phase waveforms, either through manual configuration or by automatically detecting whether the load is inductive or capacitive. Universal dimmers can be extremely useful, as they can be selected without prior knowledge of the type of transformer that will ultimately be installed.

### 1.3 LEDs with Transformers

Since traditional halogen MR16 lamps are simple resistors, their electrical characteristics and performance are easy to model, regardless of whether they are fed from an ELV or MLV transformer. Power consumed is simply related to the amount of applied RMS voltage, independent of waveform shape [Power = (Voltage)<sup>2</sup>/Resistance].

However, several problems are introduced when LEDs are used:

- LEDs require Direct Current (DC), and cannot inherently handle Alternating Current (AC)
- LED performance may be different if LEDs are supplied with a low-frequency (MLV) or high-frequency (ELV) electrical waveform
- Since LEDs require regulation of current (not voltage) for proper operation, and transformers regulate voltage (not current), additional circuitry is required between the transformer and LEDs. This additional circuitry can be considered a “driver” and is located in the low-voltage fixture housing or the base of the MR16 lamp (similar to other LED fixtures and lamps).
- While all halogen MR16 lamps are inherently dimmable, not all drivers used with low-voltage LED loads are designed to be dimmed

Simple LED applications, such as tape or strip LEDs, usually consist of a number of LEDs in series with a current-limiting component, such as a resistor, being used as the “driver”. The number of LEDs, as well as the series resistor value, is determined by the operating voltage the LED product designers are targeting for their application (typically 12 V or 24 V). Minimizing the resistor value maximizes efficiency, but also narrows the tolerances of the LED components the manufacturer of the LED load can use.

LEDs only conduct current in a single direction, and only produce light when current is flowing. Thus, the AC output of a transformer must be rectified into DC or a second set of LEDs has to be installed in reverse-parallel (similar to how line-voltage AC LEDs operate). Otherwise, the LEDs will be completely dark for one half of the sine wave. Even when fully rectified, the voltage output of the transformer alternates between values that are above the forward voltage of the LEDs and values that are below the forward voltage of the LEDs (see Figure 6).

Since the LED only conducts current when the voltage is above the forward voltage of the LEDs, the LEDs are alternately conducting and not conducting at twice the line frequency ( $2 \times 60 \text{ Hz} = 120\text{Hz}$  in the United States). Due to the extremely fast response of LEDs, they are only emitting light when conducting current. Simple LED loads driven with a full-wave rectified waveform can appear to “shimmer” (also called “stroboscopic” effect). This is especially noticeable if there is relative motion between the LEDs and the observer (this effect can often be observed when driving or walking past LED holiday light strings). This is true for any LED load designed in this manner—**whether or not a dimmer is used**. Traditional low-voltage halogen lamps, when fed a similar waveform, do not fluctuate noticeably in their light output due to the high thermal mass of the filament which remains hot and provides light even during the low portions of the AC half-cycle.

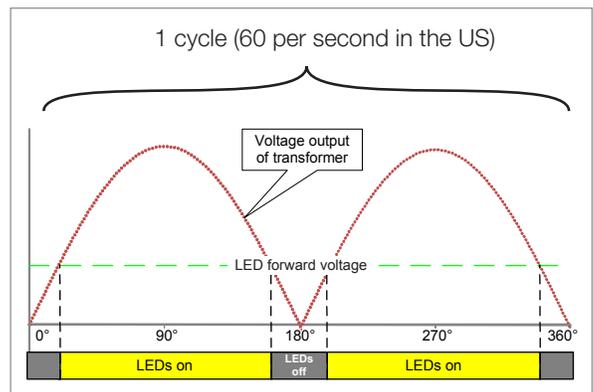


Figure 6: Rectified voltage with LEDs

## 2 Dimming LEDs with Magnetic (MLV) Transformers

### 2.1 Background

Wave form symmetry is particularly important to the performance of MLV systems. If the dimmer does not feed the transformer a perfectly symmetrical forward-phase signal, or the output rectifier does not provide a perfectly-symmetrical output, or the LED driver circuit doesn't draw current symmetrically, the MLV transformer may begin to saturate due to the imbalance, and/or the light may become visibly unstable.

If a dimmer does not create a perfectly symmetrical output, the current imbalances between positive and negative half-cycles can begin to saturate a transformer, especially if it is already operating near its design limits. Because toroidal transformers do not have an air-gap which inherently helps prevent saturation, they are especially sensitive to saturation. In addition, toroidal transformers are typically designed to operate near their maximum flux levels to minimize their manufacturing costs. If a toroidal transformer saturates, it causes an increase in input peak current which leads to acoustic noise and an increase in input RMS current, which increases transformer losses and heat. This heat quickly becomes significant; for example, a 40% percent increase in RMS current doubles the temperature rise because power losses are proportional to the square of the current [power = (current)<sup>2</sup>/resistance]. Excessive rise in temperature can cause premature failure of the transformer.

Voltage imbalances may also cause the LED load to appear brighter (or conduct current for longer) during one half cycle than during the opposite half cycle, leading to perceptible shimmer, occurring at the line frequency (60 Hz in the United States, 50 Hz in most other countries).

Voltage imbalances and shimmer may also occur as a result of line voltage noise or disturbances from external sources, which can pass unimpeded through the transformer and become a visible disturbance due to the fast response of LEDs. It is also possible for line noise to cause small disturbances when the dimmer turns on and off each cycle, further exacerbating light level instability.

### 2.2 Output Capacitors

To overcome the challenges of dimming low-voltage LEDs, some manufacturers add a filtering capacitor to the output of the transformer at the input of the LEDs, or within the LED lamp itself. While this reduces the noticeable shimmer of the LEDs, it can lead to problems when used with a dimmer.

The first potential problem when using an output filtering capacitor occurs as a result of the peak-detecting nature of the capacitor. The capacitor must be properly sized to maintain its output above the forward voltage of the LEDs (to keep them from turning off) between line half-cycles. At the same time, current will only flow from the transformer into the capacitor when the transformer's output voltage is above the capacitor's voltage. However, as described previously, dimmers designed for MLV transformers are forward-phase, meaning they "chop off" the front portion of the line voltage sine wave. If this chopped portion occurs before the output voltage exceeds the voltage on the capacitor (generally around the peak of line), then chopping the front off the sine wave will have no perceivable effect on the output voltage or light level. This means that if the output capacitor is large enough (compared to the size of the load) that its voltage doesn't drop much below the peak of the transformer's output, then no dimming may be observed until the chopped dimming edge reaches the middle of the line cycle (peak of line), or later.

This phenomenon of changing the dimming phase angle (also known as adjusting the dimmer travel) without a corresponding light level change is called “dead travel,” and is one flaw that gives the end user a negative impression of dimming performance (see Figure 7).

The second potential problem with using output capacitors on MLV transformers occurs at the leading edge where the dimmer begins conducting current. If the output capacitor's voltage is significantly below the instantaneous transformer output voltage when the dimmer starts to conduct, this can cause a large amount of current to flow momentarily until the capacitor is charged. This repetitive peak current, which happens at twice the line frequency, can cause stress on the dimmer, transformer, and capacitor, in the worst case leading to the premature failure of any of those components. Large amounts of repetitive peak current can cause acoustic noise in the transformer or dimmer, leading to end user dissatisfaction.

Finally, recovery from these high peak currents can cause current to momentarily drop below zero, which can in turn cause the triac to prematurely turn off in pulse-fired dimmers (those that apply a “pulse” to the gate of the triac, typical of most simple wall box dimmers). This premature turn-off can lead to flicker, as the dimmer will be unable to provide a constant amount of power to the transformer. System-based or panel-mounted dimmers do not usually use pulse-fired triacs, and are less prone to flicker.

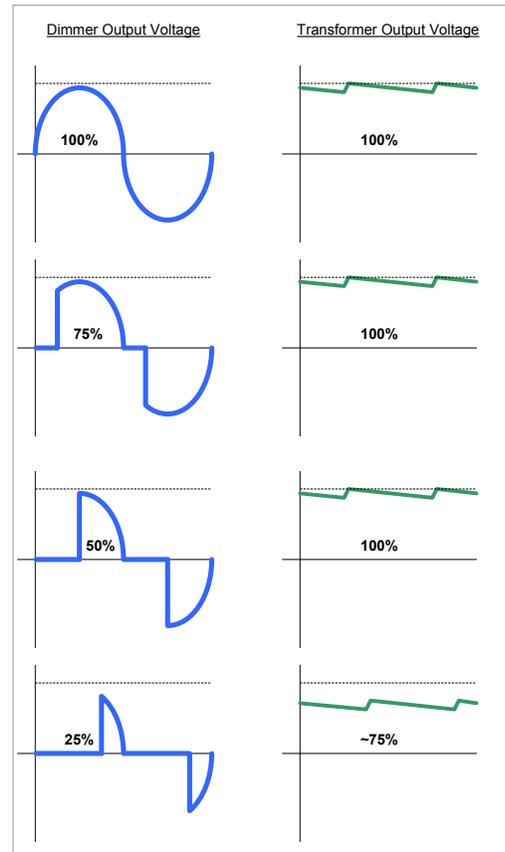


Figure 7: Dimmer output versus MLV transformer output with capacitor, illustrating dead travel

### 2.3 Finding Zero Cross

Another challenge is that many dimmers for MLV transformers are constructed as two-wire devices, meaning they have no reference to neutral (ground wires are usually present for safety reasons, but are not required for proper dimmer operation). The dimmer must determine the zero cross location (the point on the sine wave where the dimmer begins conducting; see Figure 4 and Figure 5), by “viewing” the line voltage through the impedance of the load. This impedance will be reflected through the transformer, and therefore influenced by the output load of the transformer.

If the impedance of the load is changing, due to non-resistive loads (like LEDs), then the dimmer may be unable to determine a stable zero-cross location, leading to possible movement of the leading edge, which would be observed in the light output as flicker. Dimmers which require a neutral wire for proper operation (which is often not available for retrofit installations) are less prone to this problem. They “view” the line voltage between hot and neutral directly.

## 2.4 Under Loaded Magnetic Transformers

A final challenge with using MLV transformers with LED loads has to do with the amount of load (in Watts) connected to the output of the transformer. All MLV transformers have a maximum wattage rating, indicating how much load they are capable of safely and reliably handling. LEDs have much lower power ratings than their halogen equivalents (commonly, 10 Watts for LED loads compared to

50 Watts for halogen loads). MLV transformers with LED loads are often loaded well below their maximum wattage rating. When some MLV transformers are lightly loaded, their high inductance, combined with the non-linear nature of the LED load, can cause the output to “ring-up” higher than would be expected merely from the turns ratio of the input to output (see Figure 8). Ring-up voltage is defined as a momentary spike of voltage which exceeds the nominally expected value, typically caused by the discharge of energy-storing components such as inductors (this is not to be confused with repetitive peak *current*, discussed previously). With enough ring-up, the **transformer may exceed the maximum voltage rating of any components** at its output, including bridge diodes, driver circuitry, or the LED load itself potentially causing premature failure.

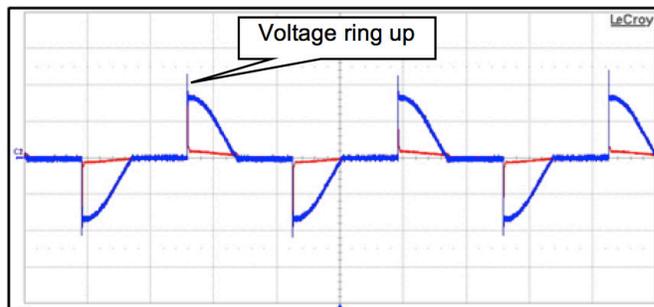


Figure 8: Forward-phase waveform showing ring-up

## 2.5 MLV Conclusion

Improper pairing of dimmers, MLV transformers, drivers, and LED loads can lead to any or all of the following problems:

- Visual light shimmer can occur when the rectified output voltage of a transformer momentarily falls below the forward voltage of the LEDs, causing them to turn off.
- Shimmer can also occur from asymmetry, due to either a slight difference in light level output between positive and negative half cycles, or the overshoot in voltage after the zero cross due to transformer saturation.
- MLV transformers that use simple bridge rectifiers and a large capacitor at their output to minimize shimmer may be very difficult to dim well, and may require a dimmer with a neutral wire in order to allow stable zero-cross detection and dimmer timing. If the capacitor is large enough, however, even a neutral wire may not solve the issue. The low power factor (“leading current”) resulting from such a setup may cause the dimmer’s triac to improperly conduct into the next half cycle, leading to flicker.
- Using ELV reverse phase dimmer controls on MLV transformers can result in an overvoltage spike across either the input or output of the transformer; damage to the transformer, driver, LED, or dimming control may result.

## 2.6 Dimming MLV Best Practices

For dimmers to properly operate LED loads on MLV transformers, the load should meet all of the following criteria:

- The load should present some resistive impedance all the way to the zero cross.
- The load must be resistive (or inductive) at all operating points, but not capacitive.
- Current draw from the load on the output of the transformer should be symmetrical in the positive and negative half-cycles.
- Extra voltage margin should be considered in the design of the LED load, to account for excessive voltage ring-up on minimally-loaded transformers.
- The transformer should be loaded to 50% of its maximum rating or higher.

While the first four criteria are dependent on the design of the LED load, the final one is application specific. One design solution that has a high likelihood of success is, somewhat paradoxically, for the manufacturer to select a transformer with a lower efficiency. Such transformers usually have a higher leakage inductance (which makes the load look less capacitive) and higher losses (which provides sufficient load for proper dimmer operation).

An alternate approach is to add additional resistive load on the output, because it shifts the perceived power factor of the system closer to 1.0. Typically, this “dummy load” can be sized as low as 5 to 10 Watts; however, such a resistive load will lower the overall efficiency of the system, reducing the benefit of using LEDs.

Finally, ensure the proper dimmer is selected. Use dimmers rated for MLV loads and consider additional useful features including an adjustable low-end trim, and selecting a dimmer with a neutral wire.

All of these criteria may be achievable with a new design or installation, but may be difficult or impossible to meet in retrofit installations (where the transformer characteristics are unknown), or in situations when the transformer and LED load are supplied by different sources.

## 3 Dimming LEDs with Electronic (ELV) Transformers

### 3.1 Background

ELV transformers offer benefits of reduced size, lighter weight, higher efficiency, and lower costs and contain a self-oscillating circuit, that is used to generate an internal high frequency to drive their internal step-down circuitry. This oscillation only occurs during the portion of the line voltage sine wave during which the dimmer is conducting. The oscillation circuit is usually designed as simply as possible, and often relies on the expected resistive load of the halogen lamp at the output. In fact, most ELV transformers specify a minimum output load (usually around 10-20 Watts) to ensure that their internal oscillator is stable.

### 3.2 ELV Characteristics

Using LED loads on an ELV transformer designed for higher-wattage halogen lamps can easily lead to situations where the transformer's minimum specified load is not properly met. This can result in unstable operation, or even a complete lack of functionality. Even if the minimum specified load is met, the non-resistive nature of LEDs may not properly meet the needs of the oscillator in the ELV transformer. Furthermore, the ELV transformer may specify a different minimum load depending on whether the transformer is used with a dimmer or a switch. In recent years many manufacturers have introduced "LED compatible" or "Low Wattage" transformers which have a small, or even zero, minimum load requirements. These transformers are expected to provide stable output regardless of loading.

Unstable operation of an ELV transformer can often be observed on an oscilloscope. If the voltage waveform, as seen at the ELV transformer's output, changes slightly from half-cycle to half-cycle despite the input phase angle being constant, it indicates unstable operation (see Figure 9) and may result in flicker or shimmer when dimming, especially in LED loads. The light output of LED loads responds very quickly to changes in current, so any instability in transformer voltage output may be directly visible in the LED's light output. When using halogen lamps, the high thermal mass of their filaments masks minor voltage instability, but the instant response of today's LEDs may exhibit "shimmer" unless additional filtering techniques are incorporated by the LED or driver.

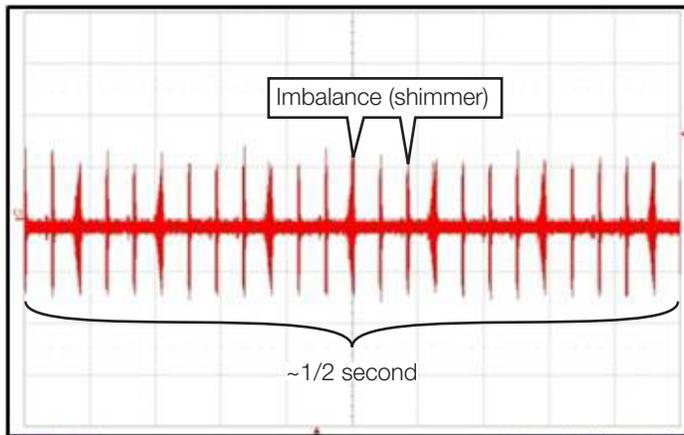


Figure 9: Fluctuating output voltage of an ELV transformer

Because ELV transformers appear capacitive to a dimmer, only reverse-phase (trailing-edge) "ELV dimmers" are typically recommended (note that a few ELV transformers are designed and rated to be controlled with forward-phase/leading-edge dimmers, as specified on the transformer datasheet). Improper pairing of LED loads on ELV transformers can exaggerate their capacitive qualities. In practice, multiple ELV transformers on a single dimmer, representing a large capacitive load, can actually "hold up" the line voltage output of the dimmer, even when it tries to switch off (the exact number of ELV transformers necessary to cause this phenomenon **is highly variable and depends largely on the transformer design**). The more capacitance, the slower the voltage decays at the trailing edge of the dimmer. This large amount of "slow decay" may affect how the ELV transformers recognize the phase angle, which leads to a poor dimming performance, including dead travel, poor minimum light level, "steps," or flicker when dimming.

Most ELV dimmers require a neutral wire for proper operation which helps the dimmer switch on and off properly, regardless of load characteristics. Using a dimmer with adjustable low-end trim can help to minimize areas of the dimming curve with poor performance.

### 3.3 ELV Conclusion

Improper pairing of dimmers, ELV transformers, drivers, and LED loads can lead to any or all of the following problems:

- Providing insufficient resistive-type load to the ELV transformer output can lead to output instability and light output shimmer.
- If the ELV transformer appears too capacitive to the dimmer, the result can be poor dimming curves or even flicker in the loads.
- Using forward phase controls on ELV transformers can lead to high repetitive peak currents, potentially damaging the ELV load or dimmer control.

### 3.4 ELV Best Practices

For ELV dimmers to operate on ELV transformers with LED loads, the LED load should meet all of the following criteria:

- Provide sufficient resistive-type load in the lamp to meet the minimum wattage requirements of ELV transformers.
- Minimize the use of integral capacitors on the input end of ELV transformers to prevent dimming curve problems.
- Minimize the input capacitance of the LED load as seen by the transformer. Large capacitance values may cause high repetitive peak current from the transformer to the load due to the high frequency switching of the transformer. These high currents can cause stress in the lamp, or falsely trip over-current protection mechanisms in the transformer.

Besides ensuring that the dimmer is properly rated for ELV loads, selecting a dimmer with adjustable low end and high end trim can help minimize regions of poor performance.

It is possible to meet these criteria with proper design of an ELV transformer and low-voltage LED load. However, like the MLV transformer case, it is nearly impossible to predict if these are met by either a particular LED product or an existing transformer in a retrofit application. The only way to ensure the dimming will be smooth and continuous, especially at low end, is to test all the devices together as a complete system.

## 4 General Application Concerns

There are particular issues to be aware of when pairing LEDs with ELV or MLV transformers. Many of the compatibility issues described can be prevented by designing, pre-testing and approving specific transformers for use with specific LED loads. Many of the design suggestions provided in this paper

are beneficial when done at design stage of the LED fixture by the manufacturer, but are difficult to implement in an existing installation.

As described, systems of dimmers controlling transformers can have varying performance depending on how they are loaded or how many transformers are on a dimmer. In many applications, especially those where strip or tape lights are used, the load can be highly variable. Unless the transformer is tested with different amounts of the LED load in question, it is very possible for unexpected behavior to occur once installed.

Also, mixing transformers with different amounts of load on the same circuit may still result in unacceptable performance, e.g. dimming curves between different loads not all tracking together.

Because there is a large installed base of low-voltage halogen MR16 fixtures, MR16 LED lamps are commonly being used to replace existing halogen MR16s, but it is often difficult to know the characteristics of the transformer already installed. For example, the installed transformer may have been designed for the 35-70 Watt halogen lamp, and its minimum-load rating may not be met by the lower wattage of the new LEDs. It is impossible to predict with certainty how well a retrofit LED lamp will perform on the existing transformer in such situations.

Beyond just dimming performance, installation of retrofit MR16 LED lamps into recessed fixtures provides thermal challenges. Halogen lamps were designed to operate at very hot temperatures without degradation in performance. The lifetime of LED lamps is highly dependent on their operating temperature. Therefore, improper thermal management of LED lamps, such as enclosing them in a recessed fixture with a lens or filter (which are needed for halogen MR16's, but are not needed for LEDs), may cause premature LED failure due to overheating. LED lamps which are specifically designed for enclosed fixtures should be considered for these applications.

Finally, depending on the construction of the LED load and driver circuitry, it is extremely likely that the LED lamps will have a different dimming curve than any halogen lamps. Usually, LED lamps do not dim as low as halogens, which can easily dim below 1% light level. LEDs may flicker or drop out when they are dimmed down low (for example, below 20%). This poor behavior is sometimes blamed on dimmer compatibility; however, it often is a symptom of compatibility problems between the LED and the transformer, or limitations of the electronic driver built in to the LED load. If poor dimming behavior is observed at low end, e.g., the LED load is still producing a large amount of light, the root cause can be diagnosed by simply connecting a halogen lamp to the output of the transformer. If the halogen dims smoothly to a very low light output, then the dimming is being limited by the LED or driver design, and not the dimmer.

## 5 Conclusions

The combination of new low-voltage LED loads with new or existing ELV and MLV transformers is a very challenging application. Nevertheless, the need for these solutions continues to grow. To ensure customer satisfaction in dimming applications, it is important to properly address design considerations

and understand limitations in both the transformer and the lamp, as summarized in this white paper.

A successful application requires the LED fixture manufacturer to design their product to really be dimmable, meaning smooth, continuous, flicker-free dimming down to 1% measured light output to meet energy codes and allow for aesthetic adjustments. It also requires testing and evaluation of the complete system—dimmer, transformer, and load—to ensure it provides smooth, continuous, and flicker-free dimming performance regardless of the number of LED loads.

Ultimately, working with the installed base of existing ELV and MLV transformers, which were designed for higher-wattage resistive loads, will continue to pose challenges when new, lower-wattage retrofit LEDs that have such different and varying electrical characteristics are used. Today's best solution for ensuring dimming compatibility between dimmers, ELV or MLV transformers, and MR16 LEDs is to test the combination as installed. Otherwise variations between the test setup and installed application may deliver performance discrepancies and result in dissatisfaction.

LED strip and tape lights, on the other hand, will benefit most by being driven by a new, dedicated constant-voltage LED driver, not reusing the existing MLV or ELV transformer.

It will continue to be necessary to research, evaluate, publicize, and properly match LED loads with the optimal control, transformer or power supply in order to meet customer's dimming expectations. As one source of information, the Lutron LED Control Center of Excellence provides testing of a variety of low-voltage LED fixtures and MR16 lamps at [www.lutron.com/ledtool](http://www.lutron.com/ledtool).

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