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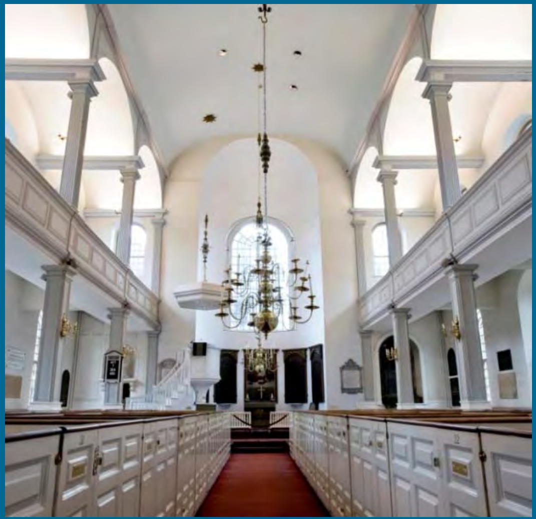
LED Dimming: What you need to know



DOE SSL Program

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Why dim LED sources?

- Additional energy savings
- Increased visual task performance
- Enhanced ambience
- Fewer light sources to specify, maintain, stock
- Enhanced space flexibility, satisfaction
- Demand response load shedding
- Potentially improved light source efficacy, lifetime

What's the big deal?

- Dimming LED sources in the real world can be challenging, particularly with phase-cut dimmers
- Wide variation in LED source and dimmer characteristics
- Little can be assumed
- Not all claims are equal
- Difficult to predict

What you need to know

- LEDs are inherently dimmable
- LEDs typically need a "Driver"
- Dimming an LED source can change the behavior of the Driver
- LED dimming performance is determined by Driver capability and compatibility with the dimming equipment
- Multiple compatibility issues are rooted in circuit level interactions between the LED Driver and dimmer
- What you think you know may no longer be valid

You can dim today, if you want to

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- Good LED dimming solutions are available today
  - with various trade-offs
  - new standards, technologies in development
  - user experiences should improve in future
- Chances for success correlated with willingness, ability to learn new things
  - unfamiliar issues
  - new standards, technologies
- Chances for success also correlated with willingness, ability to evaluate products first hand
  - not new guidance
  - color rendering, glare, etc.

What you need to figure out

- What your options are
- Where information and guidance is available
- What questions to ask
- What potential trade-offs are important, or not important to your application
- What your risk tolerance is
- How much you are willing to learn

Controlling current in simple (resistive) loads

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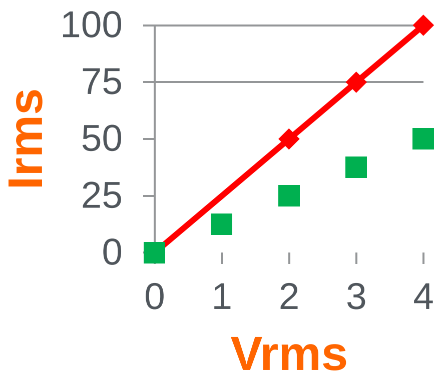
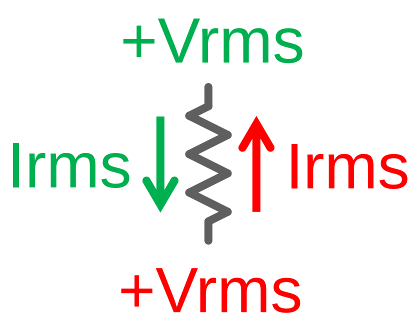
- Resistive loads have linear current-voltage relationships
  - I = (1/R) x V
  - For AC input, only care about Vrms
  - Time independency: Irms = (1/R) x Vrms

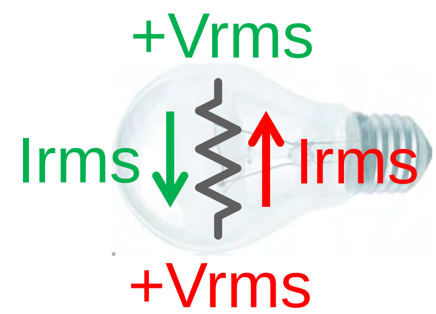


- Resistive loads are bidirectional
  - Applying ±Vrms results in the same Irms
  - Irms = (1/R) x |Vrms|



Incandescent sources are simple (resistive) loads

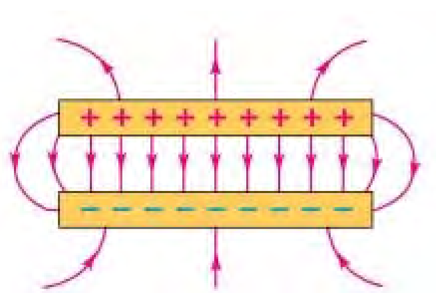
- Incandescent sources electrically behave like resistors (unlike pretty much every other lighting technology)
- Incandescent sources effectively only care about Vrms
  - Constant R at steady state
  - R is a function of filament temperature
- Incandescent sources are bidirectional
  - Applying ±Vrms results in the same Irms
  - Irms = (1/R) x |Vrms|



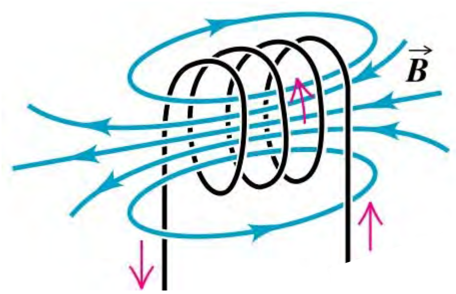
- Important caveat: thermal persistence
  - If I(t>0)→0 in resistor, no power consumption
  - If I(t>0)→0 in incandescent source, light output continues as long as filament is hot (10s to 100s of milliseconds)

Controlling current in complex loads

- Complex loads contain complex electronic devices (e.g. capacitors, inductors)
- Complex loads contain devices which store energy
- Complex loads contain devices with non-linear current-voltage relationships
- Complex loads contain devices with time-dependencies (e.g. dv/dt, di/dt, on/off switching)



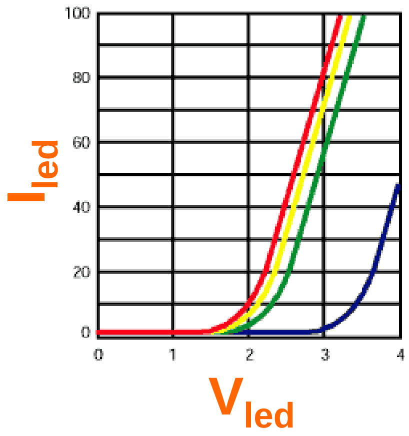
Capacitors store energy in electric fields

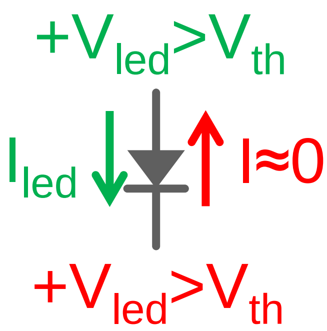


Inductors store energy in magnetic fields

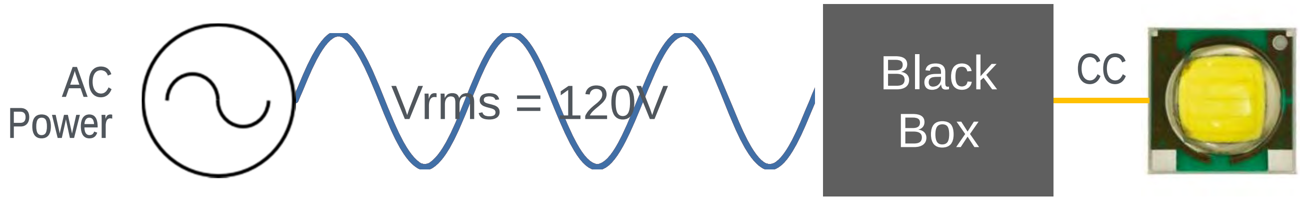
LEDs are complex loads

- LEDs are non-linear devices
  - Different current-voltage relationships in different regions of operation
  - Small change in voltage can equal large change in current
  - (Average) current must (typically) be controlled
- LEDs are unidirectional
  - (Forward) current only flows in one direction
  - Light output only for forward current
- Important caveat: fast response
  - If I(t>0)→0 in diode, no power consumption
  - If I(t>0)→0 in LED, no light output
  - Careful attention to time where I≈0





LEDs (typically) need a "Driver"



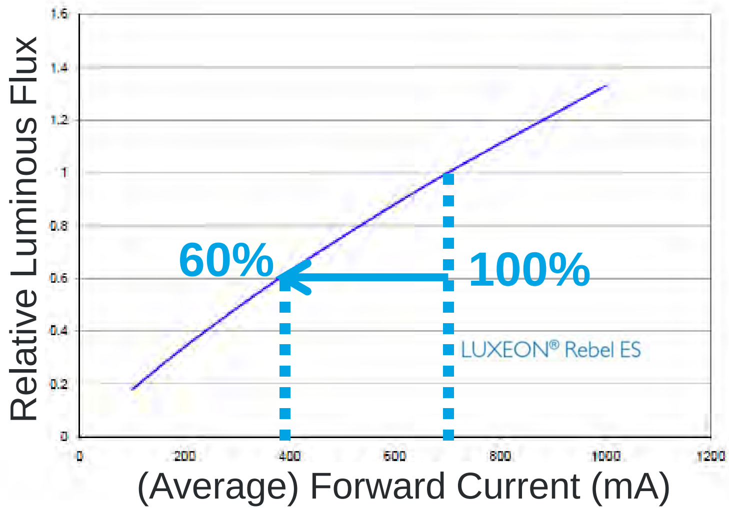
- Non-linear Iled vs. Vled relationship, together with manufacturing variation in Vf, mean LEDs are best regulated by controlling their current
- Typically, LEDs are operated (or "Driven") such that their (average) current is constant (Constant Current)
- Typically, power electronics components are used to create circuits which convert AC voltage into regulated LED constant (average) current

LED's are dimmable

Constant Current Reduction

- Varying LED current, LED always on
- Longer LED lifetime
  - Lower current and temperature
- No noise generation
- Potentially higher efficacy at lower dimming (lower current) levels
- Does not create flicker
- Objectionable color shift?
- More difficult dimming regulation at deep dimming (low current) levels

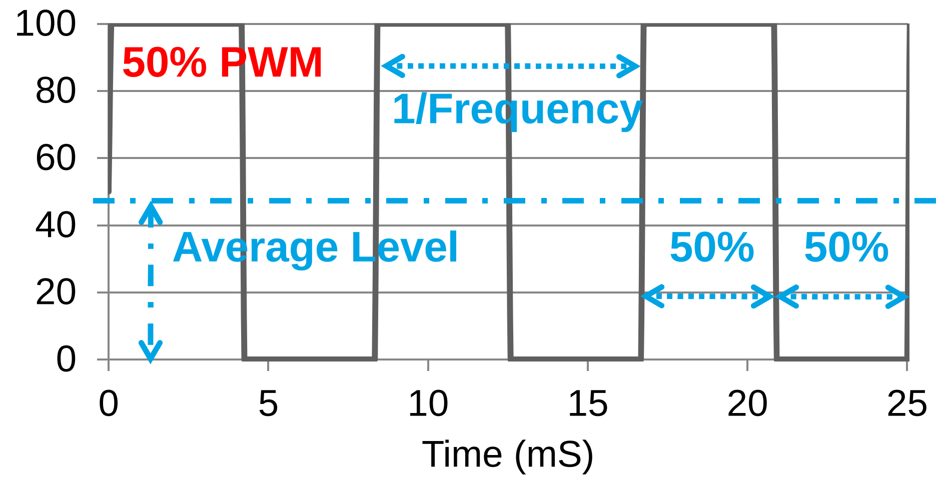
Also known as CCR, Analog

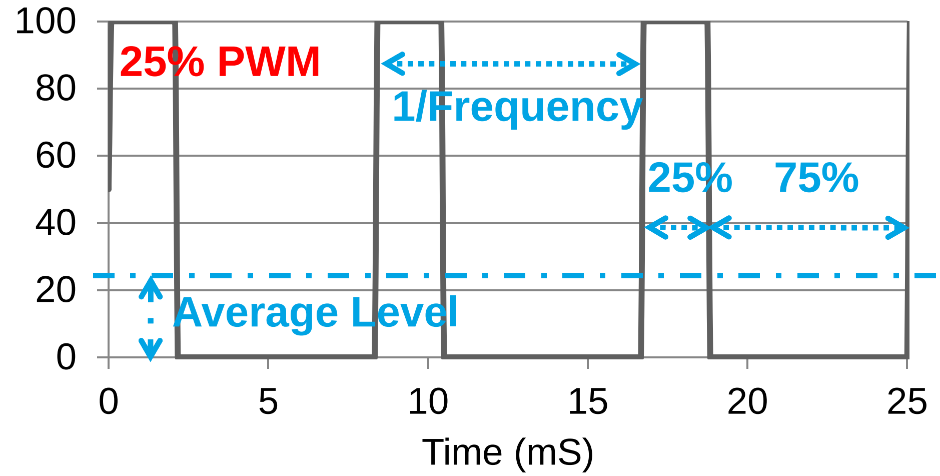


<u>Pulse Width Modulation</u>

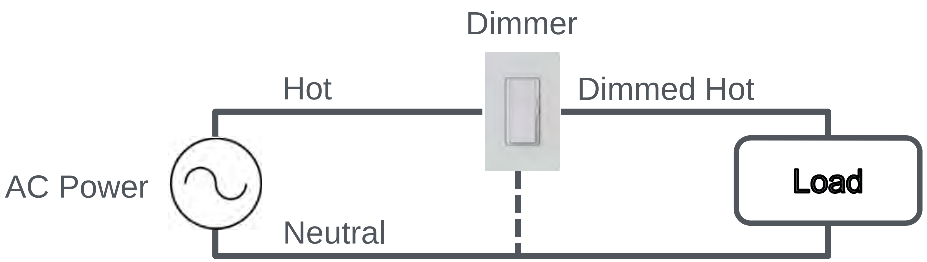
- Same LED current, varying LED on/off (typically) times
- Longer LED lifetime
  - Less LED on time, lower temperature
- Good dimming regulation at deep dimming (same current) levels
- No color shift?
- Potential noise generation
- PWM frequency is important
  - Potentially undesirable flicker
  - Minimum dimming level

Also known as PWM

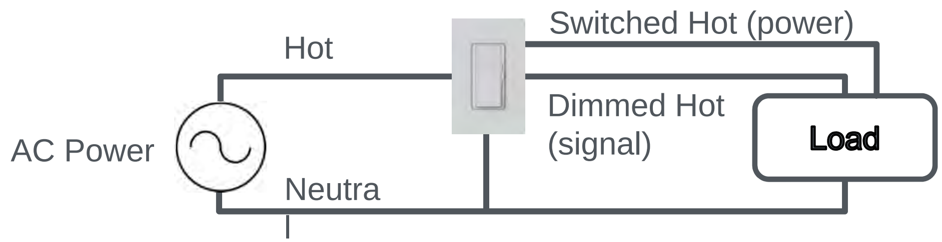




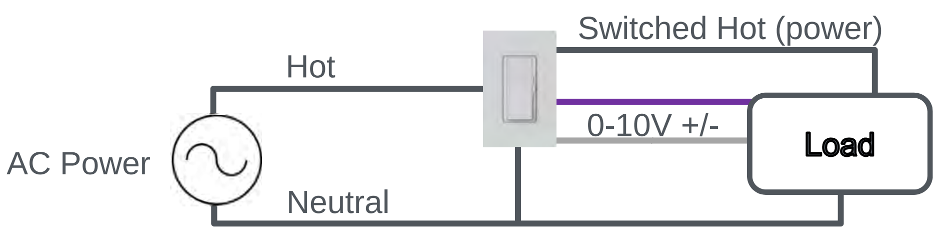
Dimming technologies



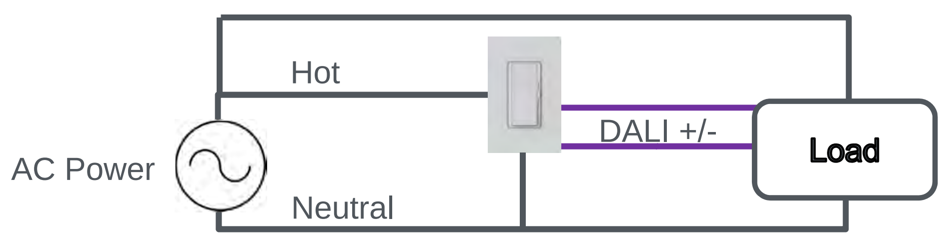
Phase-Cut



Fluorescent 3-Wire



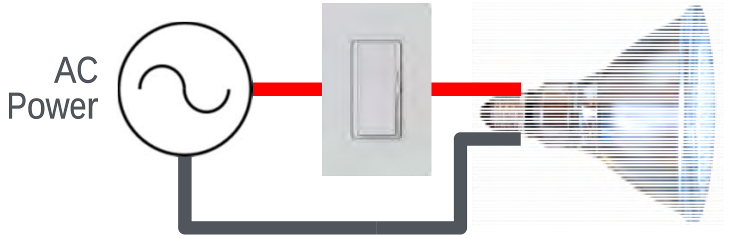
0-10V

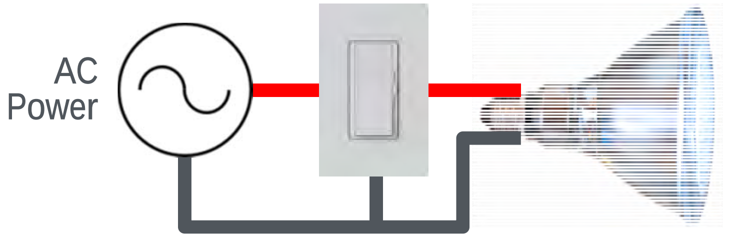


DALI

Coincident AC power and control signal

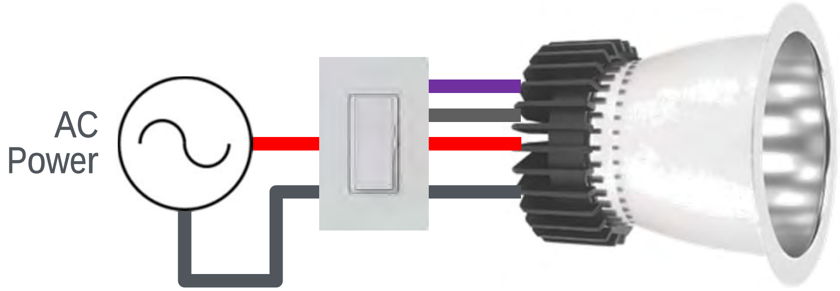
- Phase-cut AC sine wave
  - Forward or reverse phase
  - 2-Wire (hot, dimmed hot)
  - 3-Wire (hot, dimmed hot, neutral)
- Reduced amplitude AC sine-wave





Separate AC power and control signal

- Fluorescent 3-Wire
- 0-10V
- DALI
- DMX512
- PWM



Example: LED Luminaires with 0-10V dimmer

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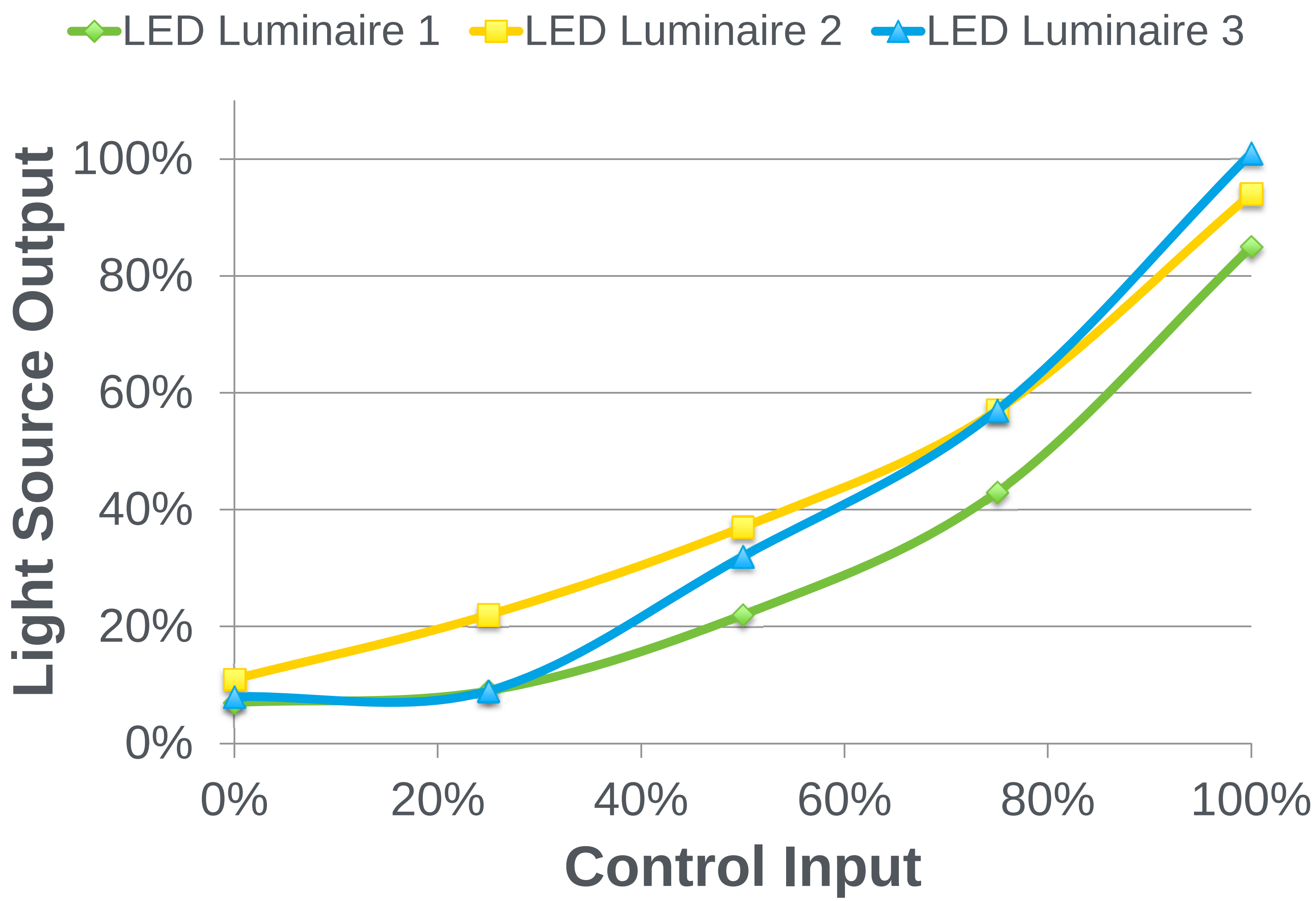

LED luminaire 1 + 0-10V dimmer A

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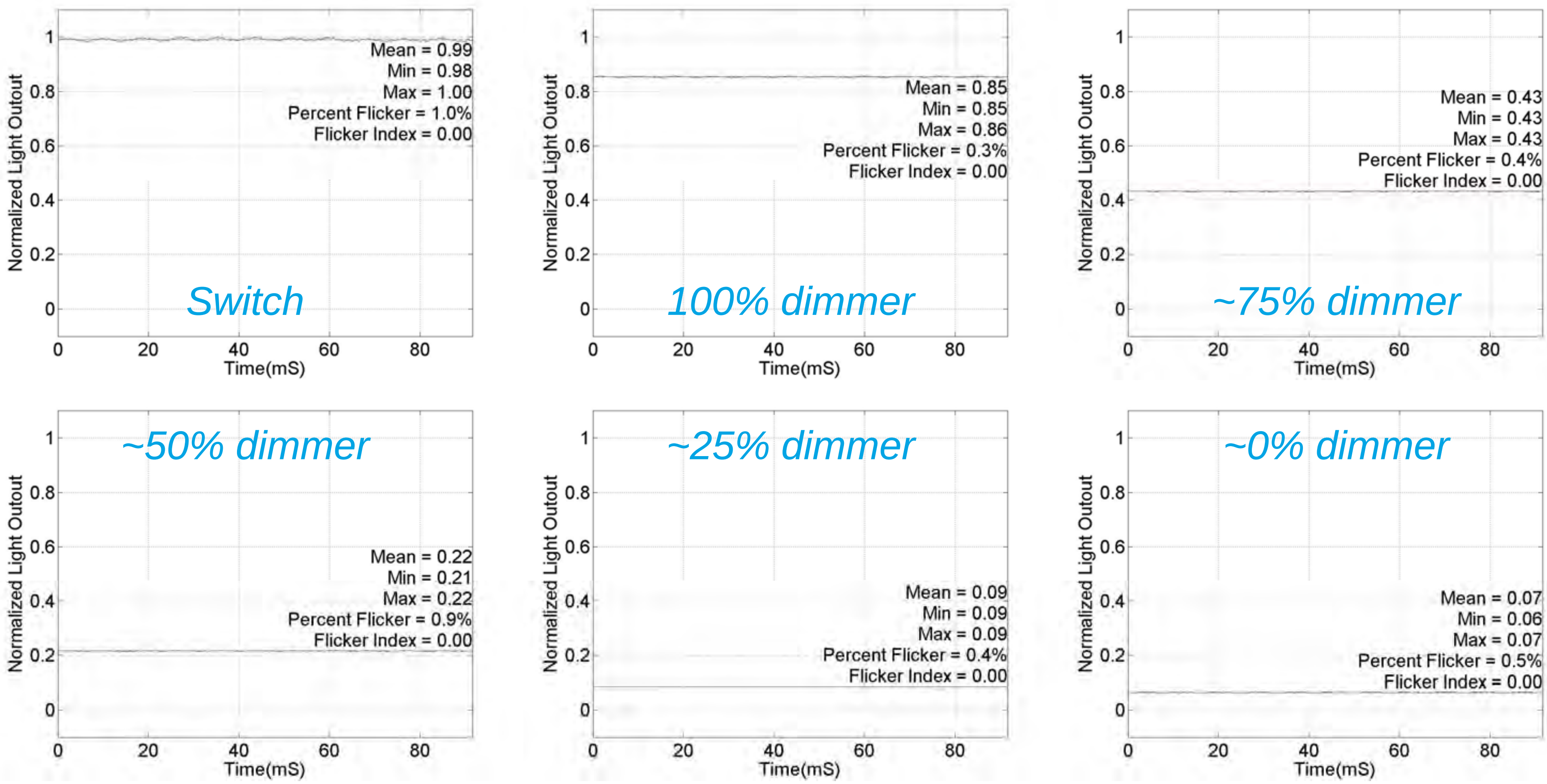

LED luminaire 2 + 0-10V dimmer A

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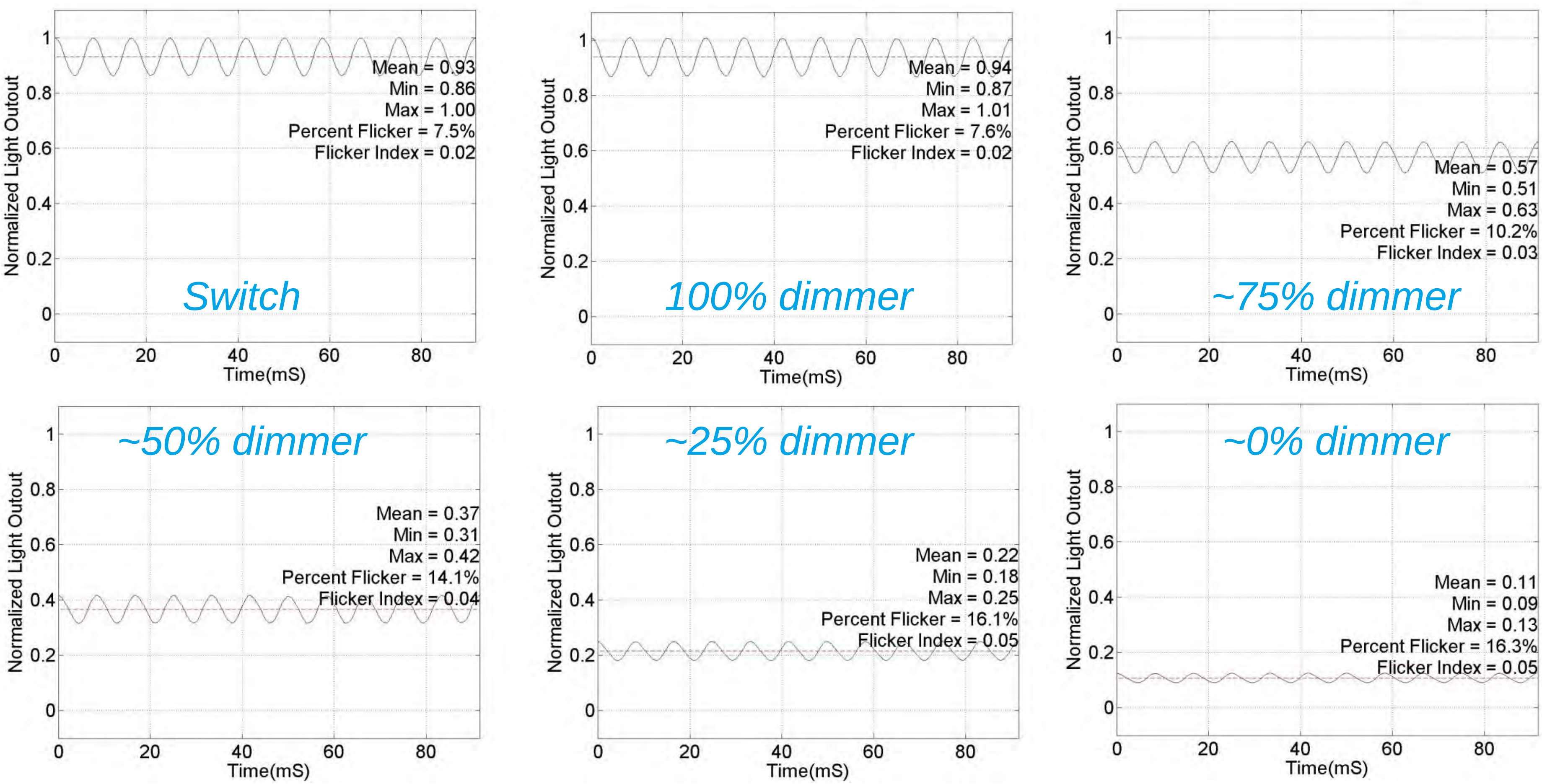
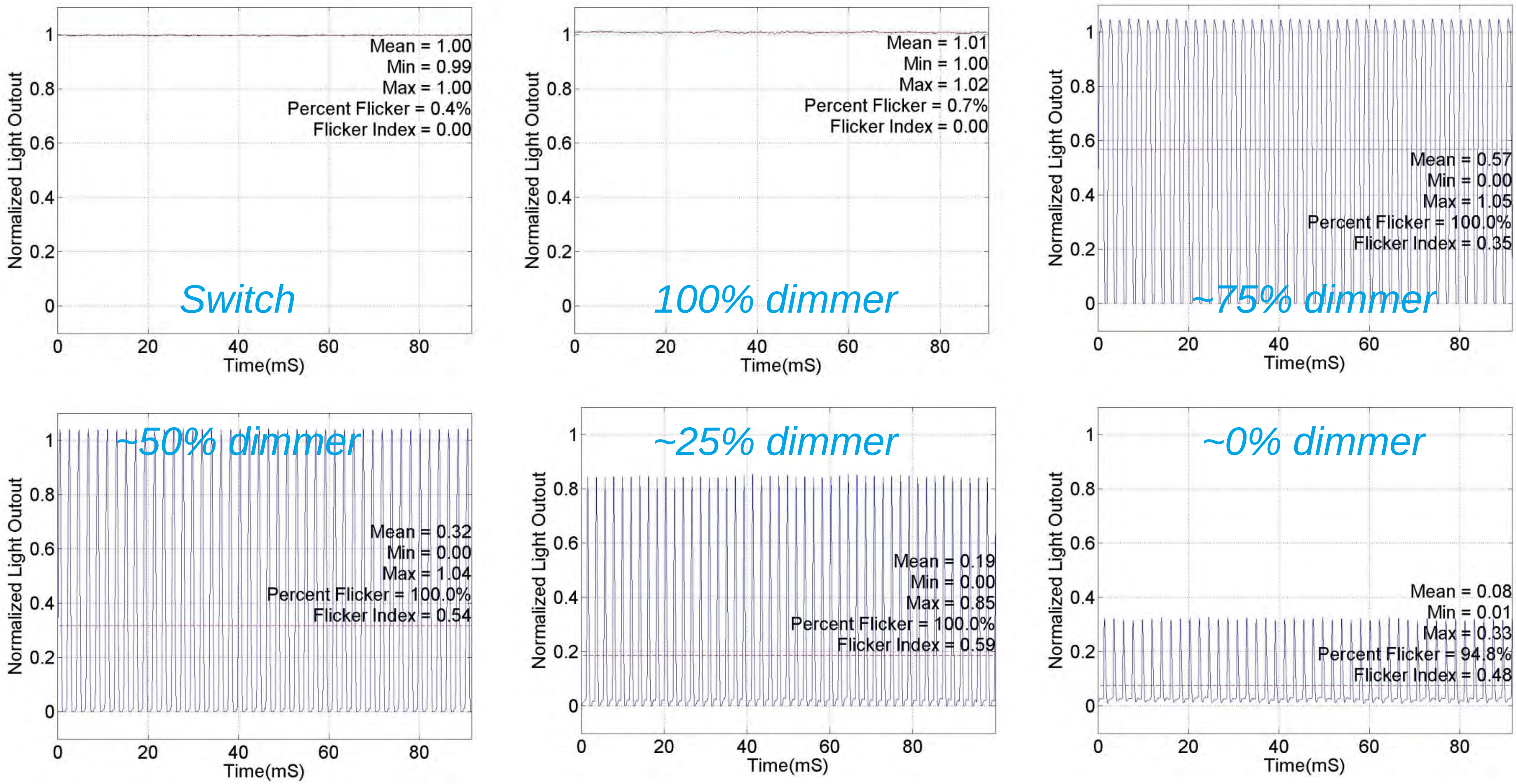


LED luminaire 3 + 0-10V dimmer A



Sidebar: What is flicker?

- Variation in time (modulation) of light output (luminous flux)
- Present in all traditional commercial electric light sources running on AC power
  - Including incandescent, halogen, fluorescent, metal-halide
  - Typically (but not always) periodic, and property of light source
  - Whether you are aware of it or not
- Not to be confused with electrical flicker
  - Noise on AC distribution line directly creates additional (light) modulation on resistive (incandescent) loads
  - Not a property of the light source
- Measurement and reporting is not a standard practice for commercially available light sources

Sidebar: Who cares about flicker?

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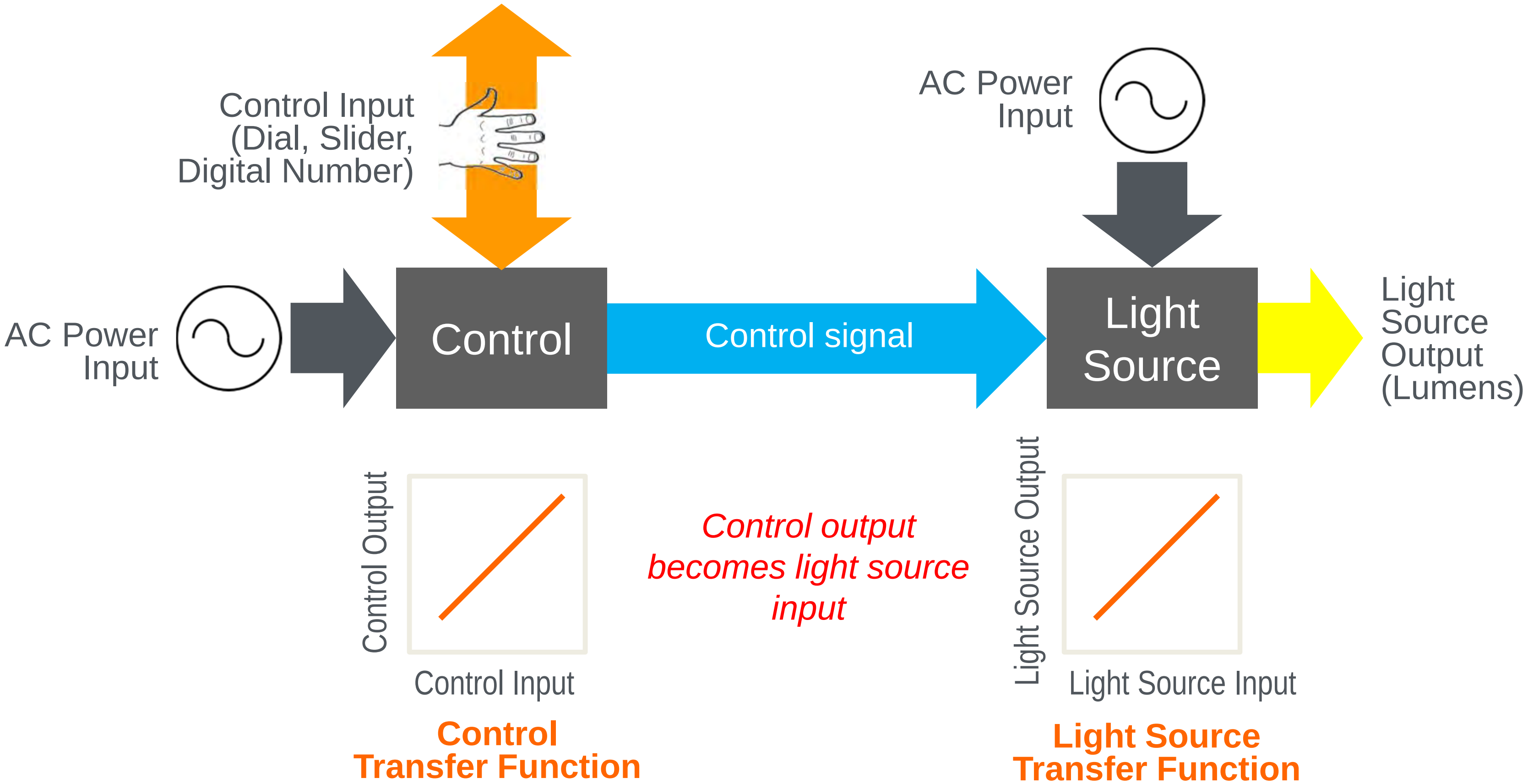
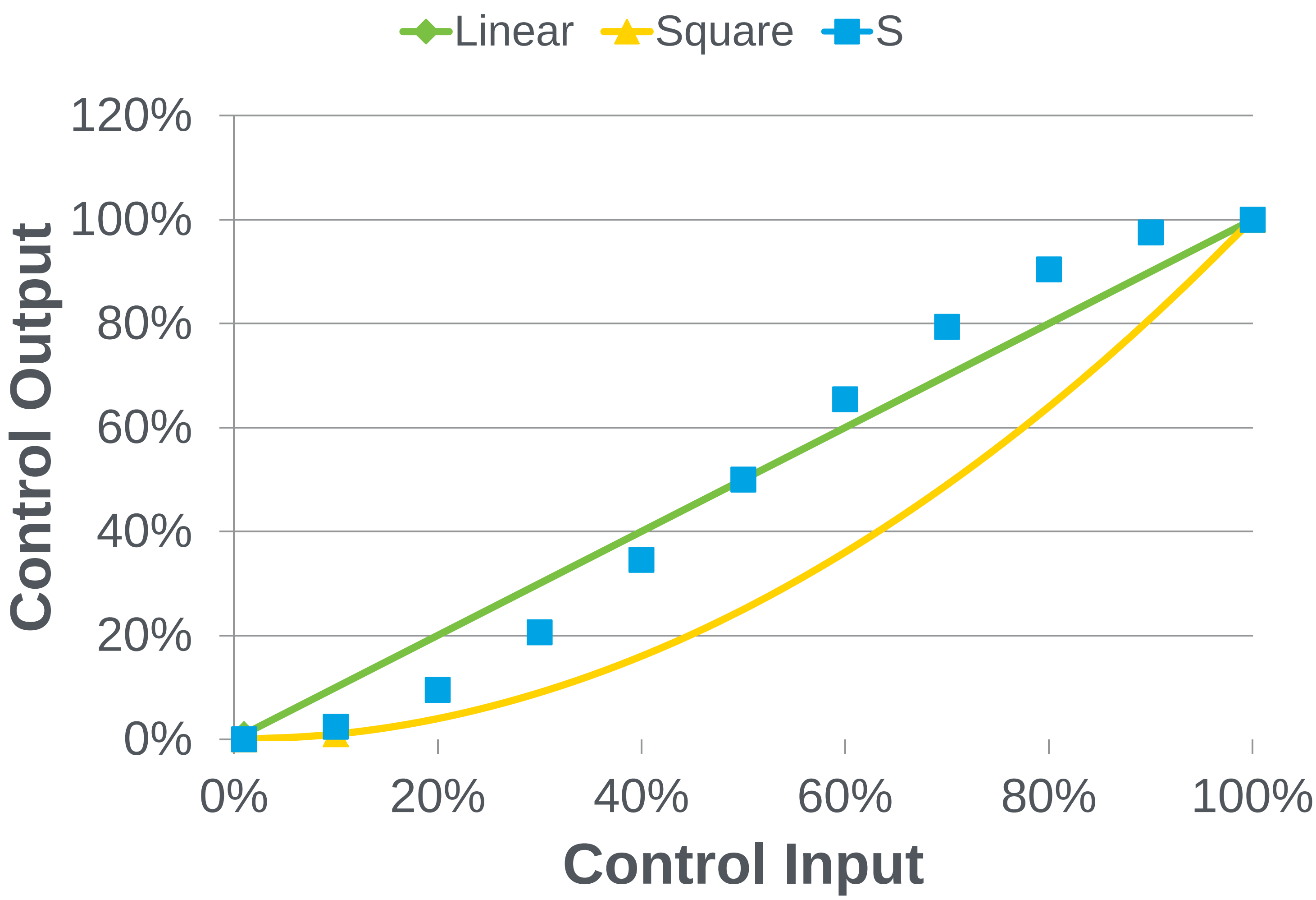
- Anyone who is sensitive
- Anyone responsible for human health, well-being and/or performance in spaces with electric lighting
- At-risk populations for specific impairments
  - Photosensitive epileptics: 1 in 4000
  - Migraine sufferers
  - Not all at-risk populations identified
- Young people
- Autistic people

Basic lighting control block diagram

Separate AC power and control signal



Common control transfer functions



Different dimmer manufacturers target different transfer functions

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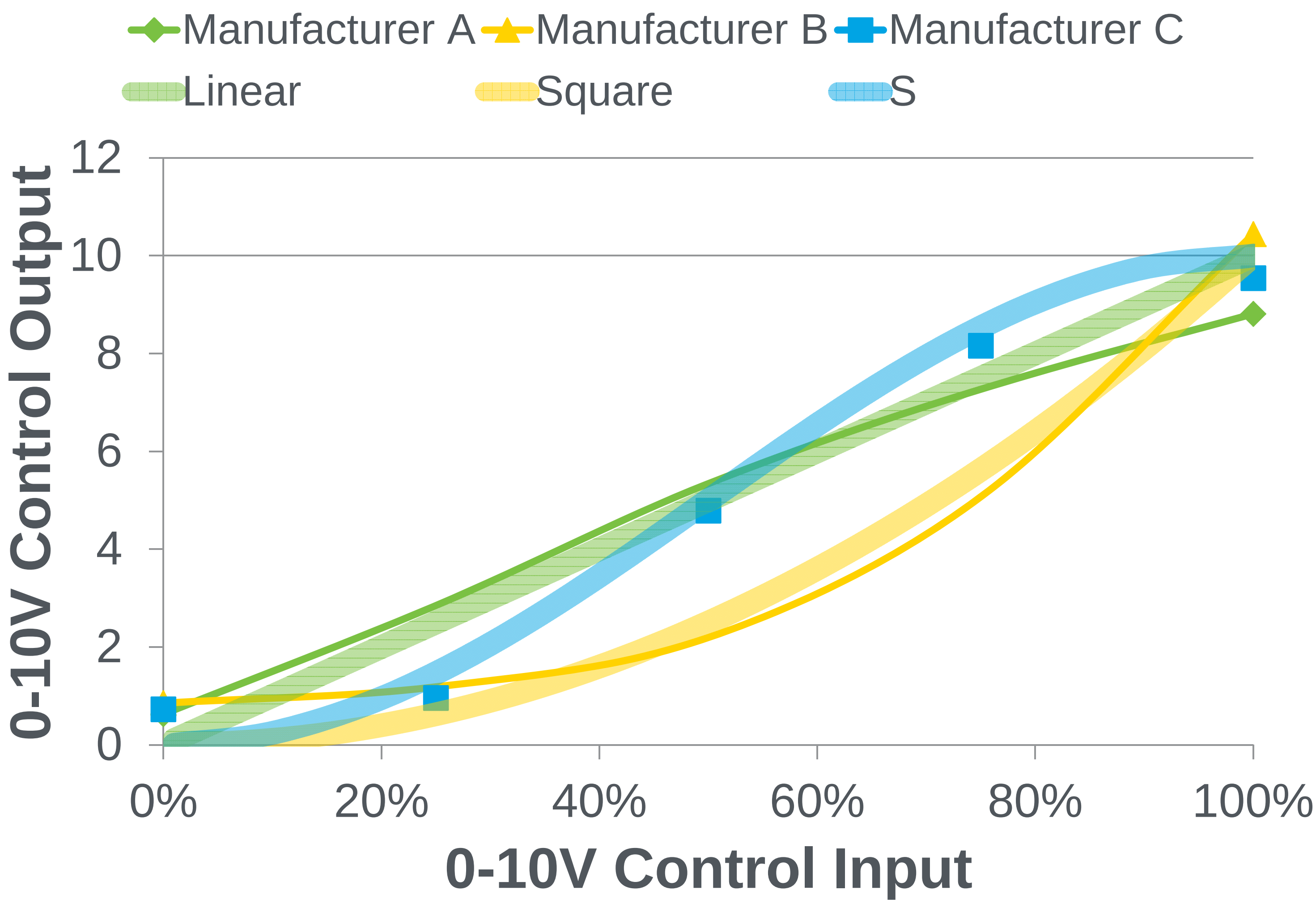

Different LED source manufacturers target different transfer functions

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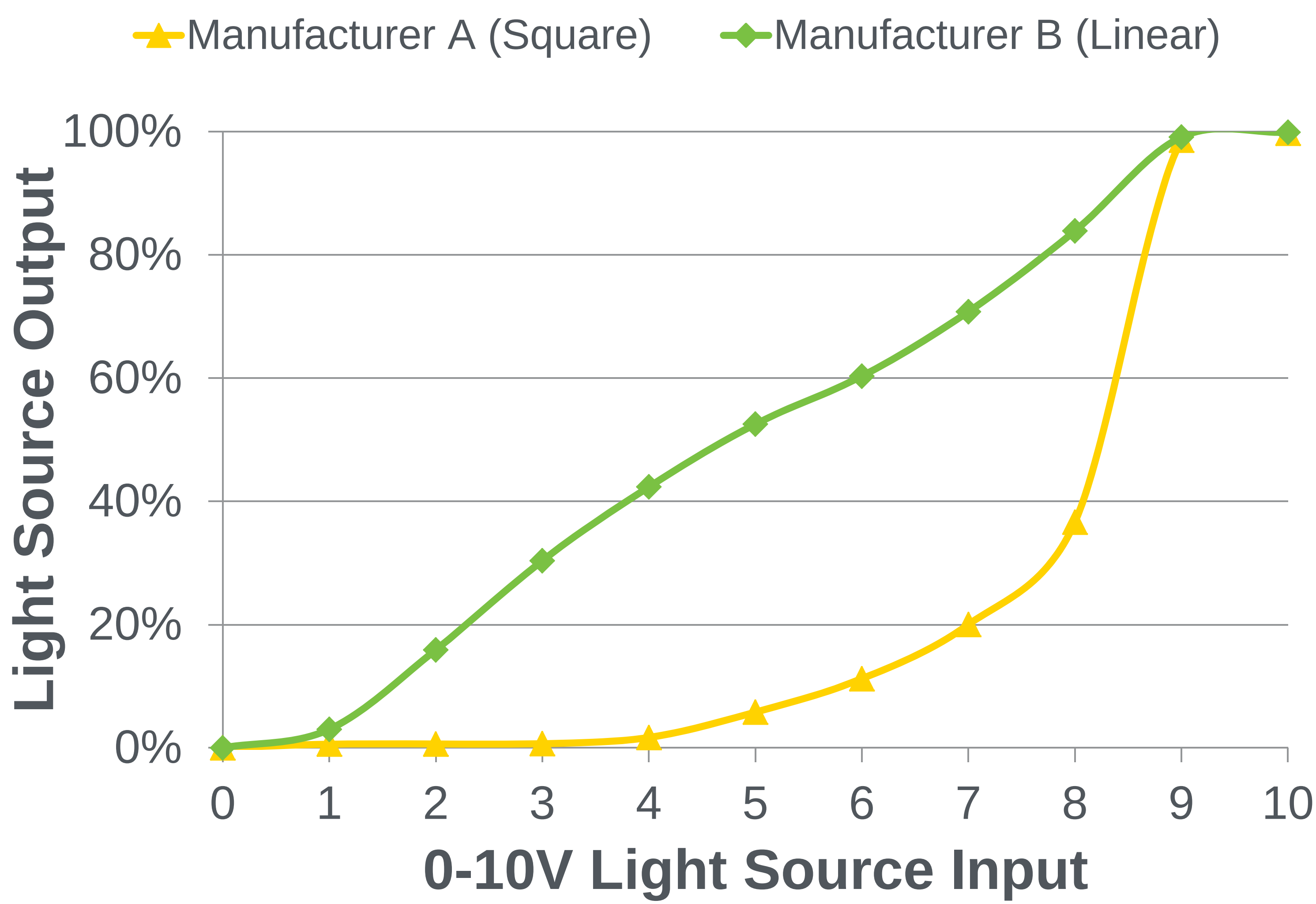

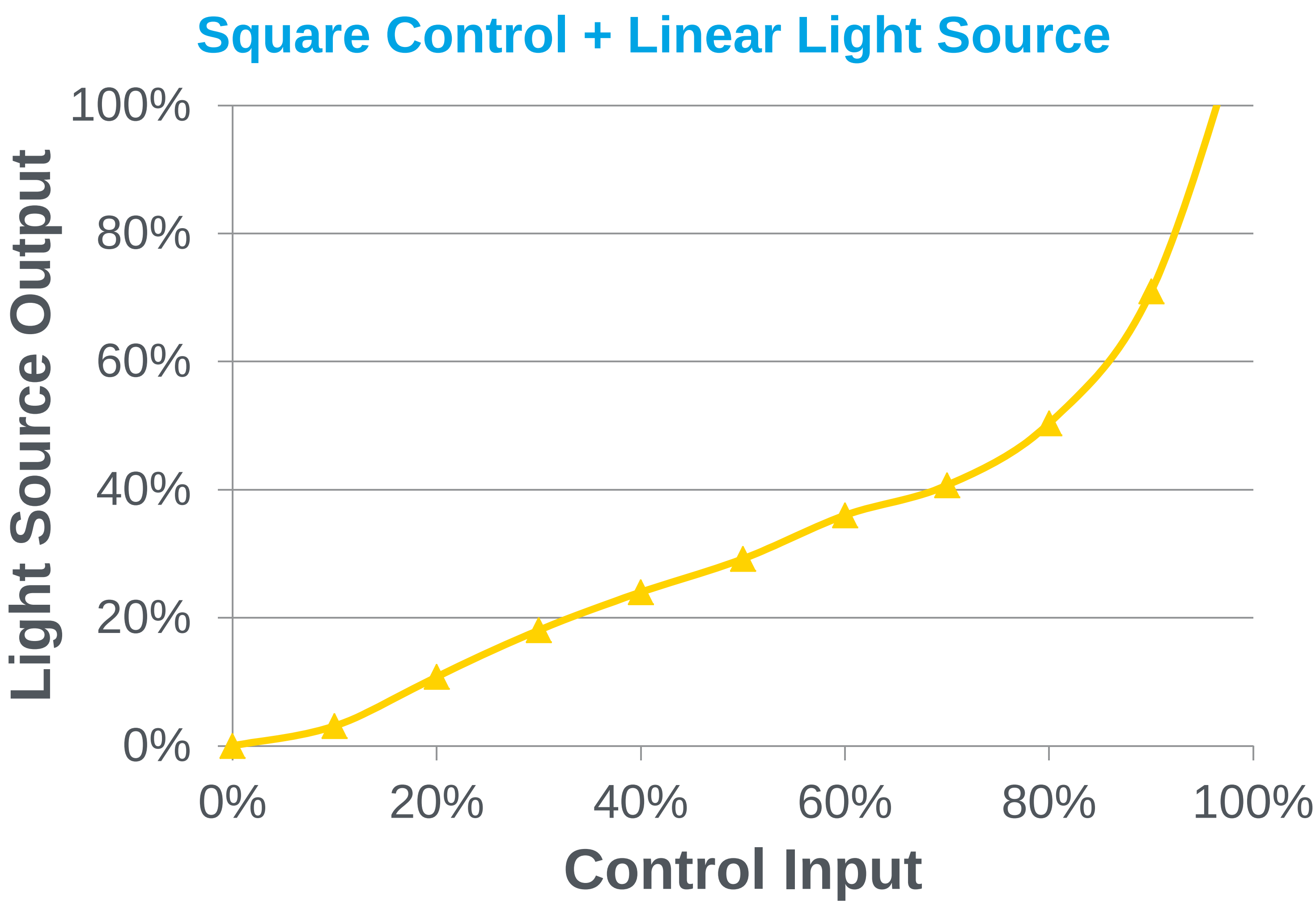
Square Control + Linear Light Source
Light Source Output
100%
80%
60%
40%
20%
0%
0%
20%
40%
60%
80%
100%
Control Input

Sometimes this doesn’t work

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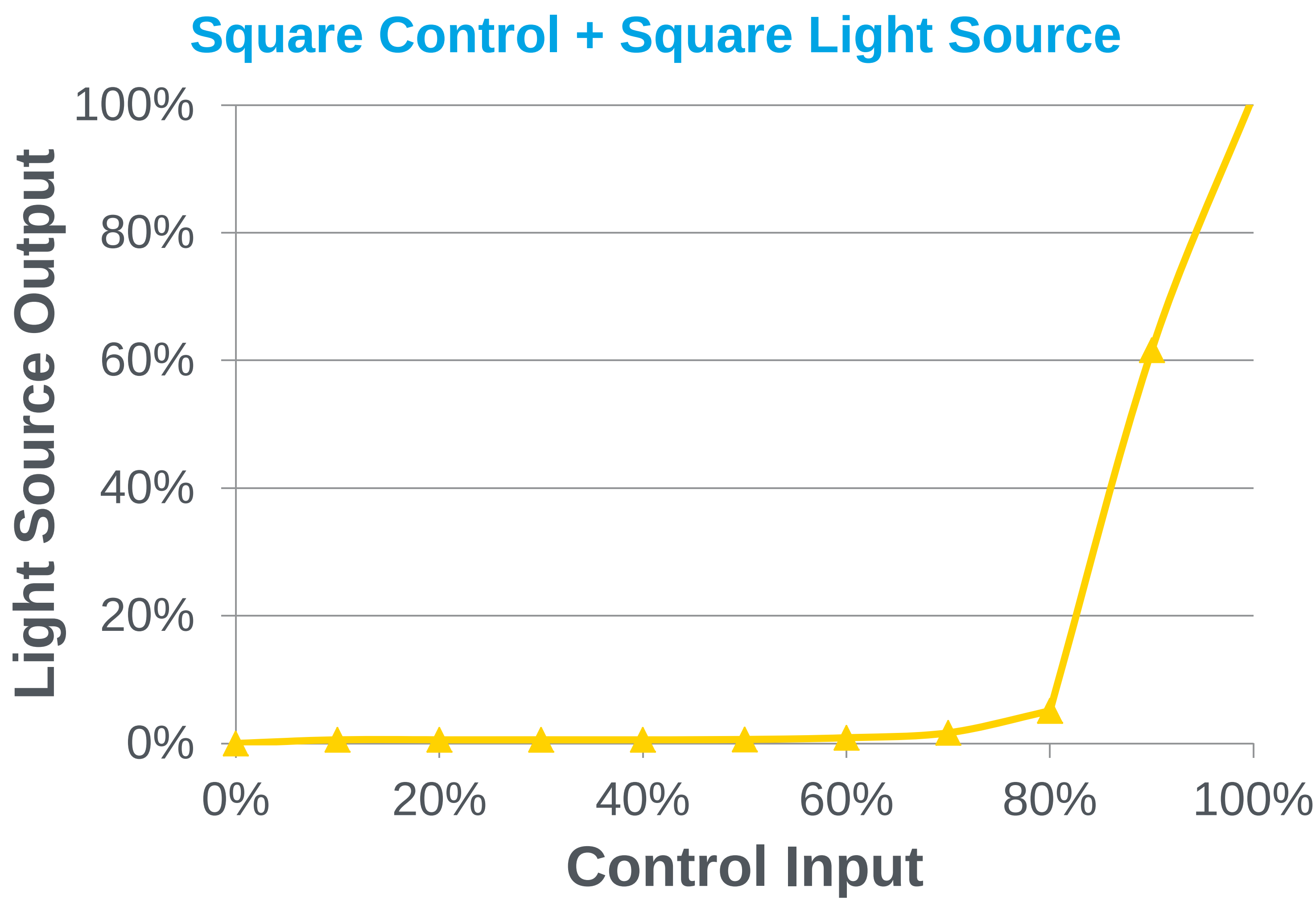

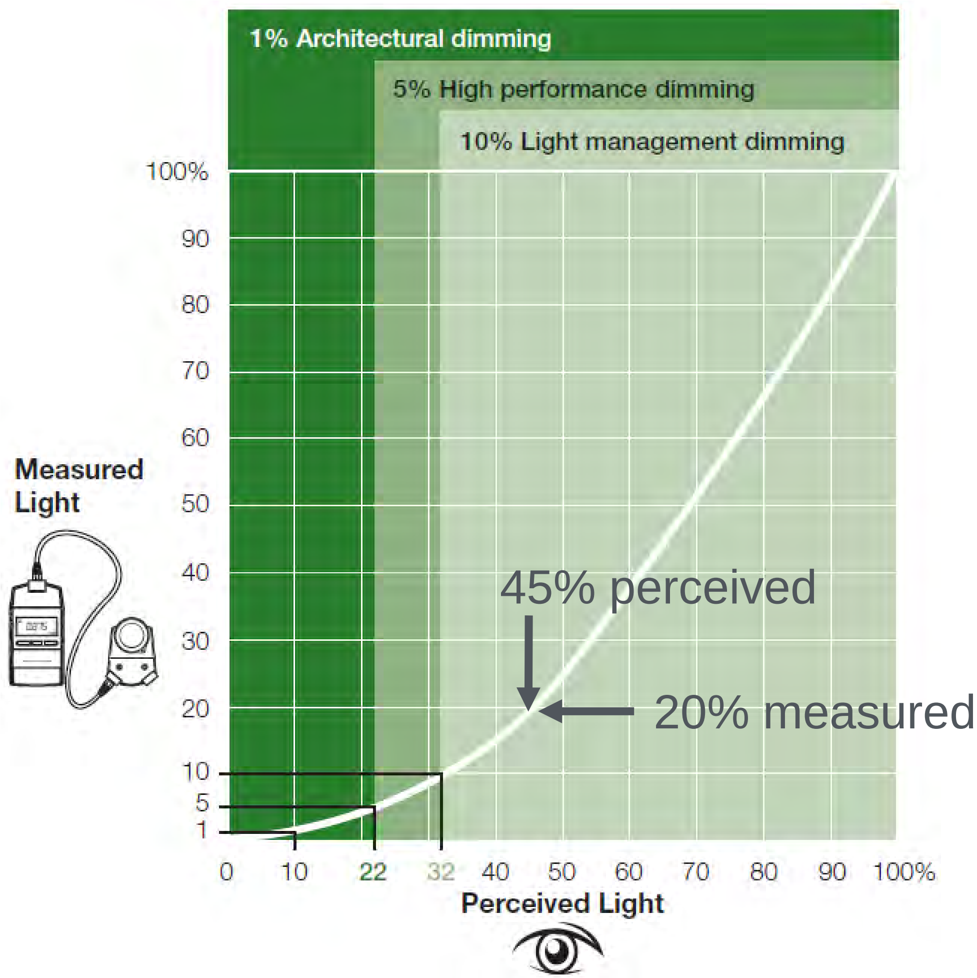

- Measured light
  - light meter reading
  - illuminance
- Perceived light
  - visual interpretation
  - affected by adaptation, eye dilation
- What does 50% dimmed mean?
  - dimmer position
  - energy consumption
  - measured light
  - perceived light

Source: IESNA Lighting Handbook, 9th Edition

A word about power quality

- Dimming an LED source can change the behavior of the Driver
  - Efficiency can degrade, but may be offset by improving LED efficacy
  - Flicker can be induced or increased
  - Power quality, as quantitatively evaluated by the Power Factor and Total Harmonic Distortion metrics, can be degraded
- LED Drivers typically can not maintain consistent performance over a wide range of conditions
  - Temperature
  - Connected load
  - Input voltage
- LED Driver performance varies with technology, cost

Sidebar: What is power quality?

- Displacements and distortions to voltage and current waveforms
- Metrics
  - Power Factor
  - Total Harmonic Distortion
- Power Factor relates Active Power (P) and Apparent Power (S) by PF = P/S
- Low(er) power factor loads DO NOT consume more energy, BUT they DO draw more RMS current
- Total Harmonic Distortion (THD)
  - THD-V
  - THD-I
- Voltage waveform distortions typically created by generators
- Current waveform distortions typically created by loads
- Common standard for generators is to limit THD-V < 5%
- Common specification for loads it to limit THD-I < 20%

Sidebar: Who cares about power quality?

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Electricity producers and consumers

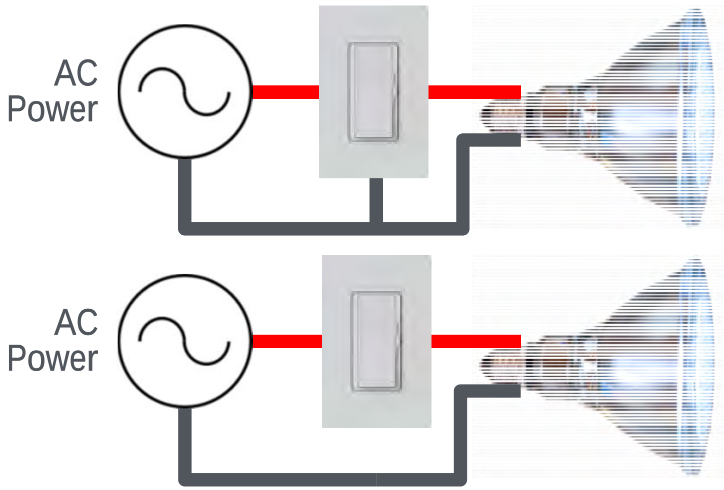
- Increased current requirements
  - Electricity transport (I^2R) losses (<10%)
  - Wire, circuit breaker, transformer, etc. sizing
  - System issue; hard to quantify
- Can in some cases lead to electronic equipment damage, degraded performance

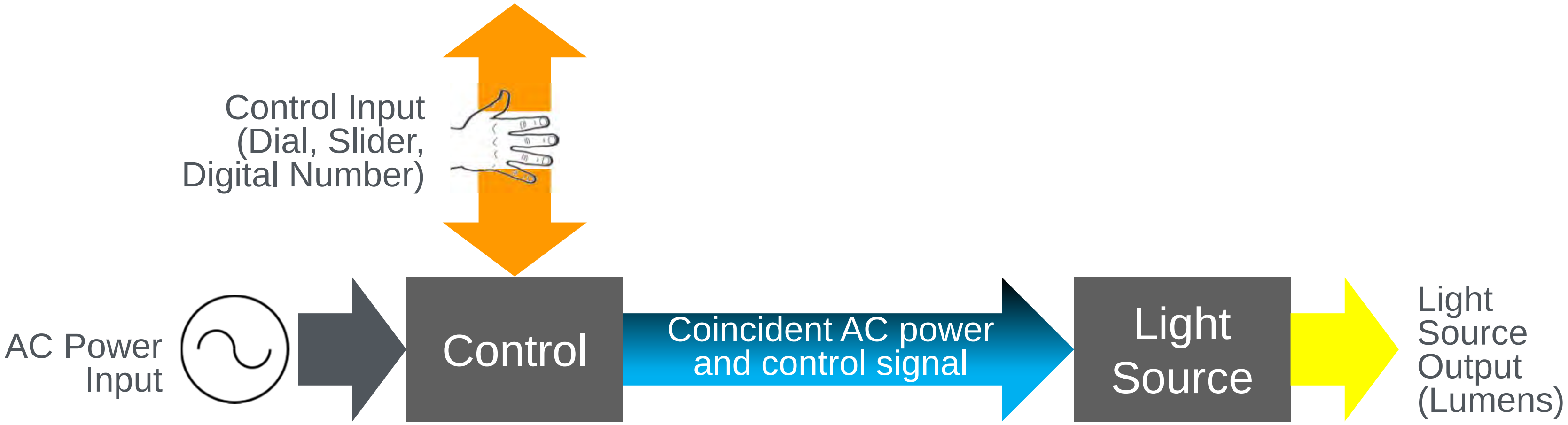
Lighting equipment manufacturers

- Voluntary requirements for lighting equipment in ANSI C82.77-2002
  - Most recent published version
  - Revision under development
- System design tradeoffs for some LED sources
- Cost and size constraints for some LED sources

Coincident AC power and control signal

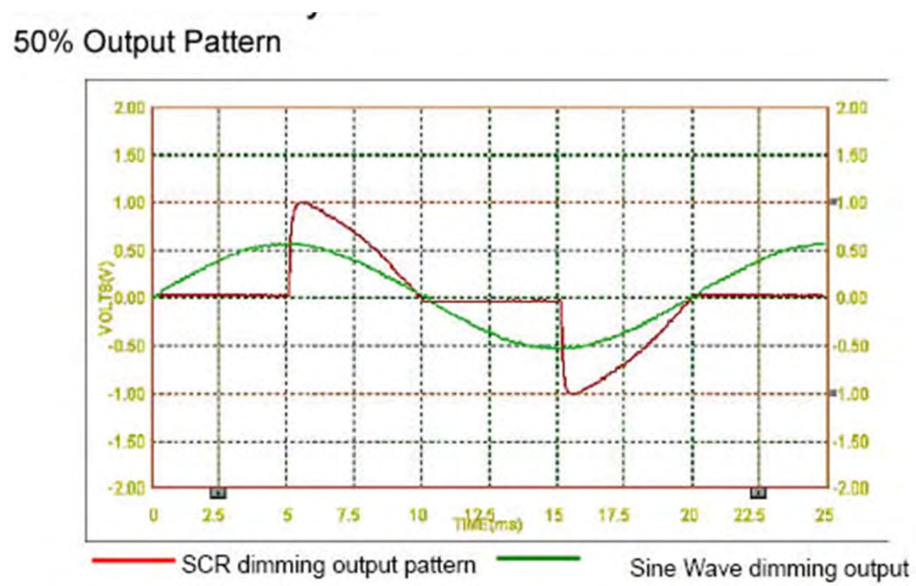
- Phase-cut AC sine wave
  - Forward or reverse phase
  - 2-Wire (hot, dimmed hot)
  - 3-Wire (hot, dimmed hot, neutral)
- Reduced amplitude AC sine-wave





Phase-cut vs. Sine-wave dimming

- Phase-cut control is the most commonly deployed dimming technology
- Large U.S. installed base
  - NEMA estimates >150M
  - Mostly “analog” (no neutral)



Phase-Cut Dimmer

Sine-Wave Dimmer

Phase-cut dimming was designed for incandescent sources

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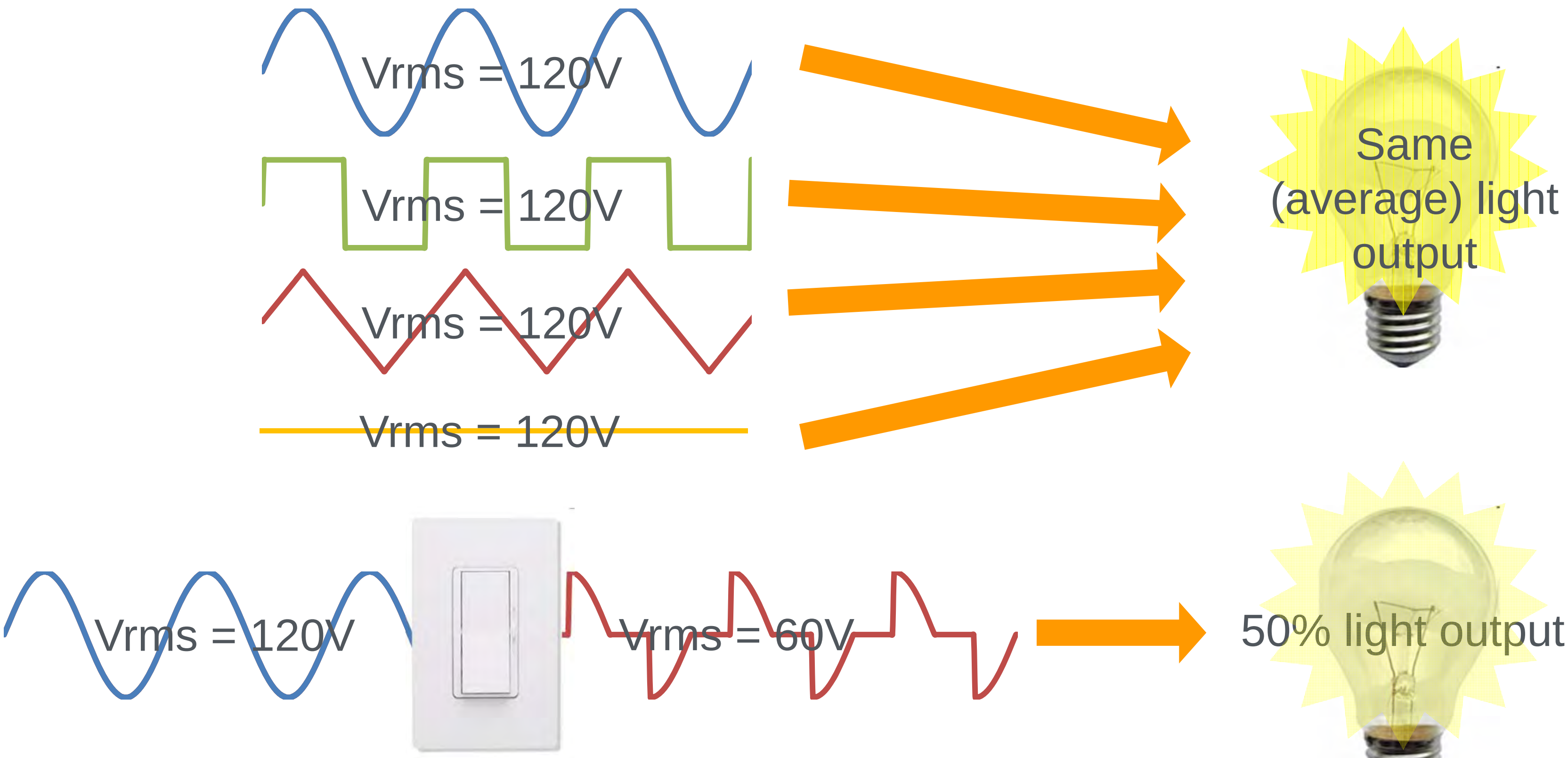

High performance
Inexpensive
Vrms adjuster
Determines dimming performance

Example: Incandescent source + phase-cut dimmers

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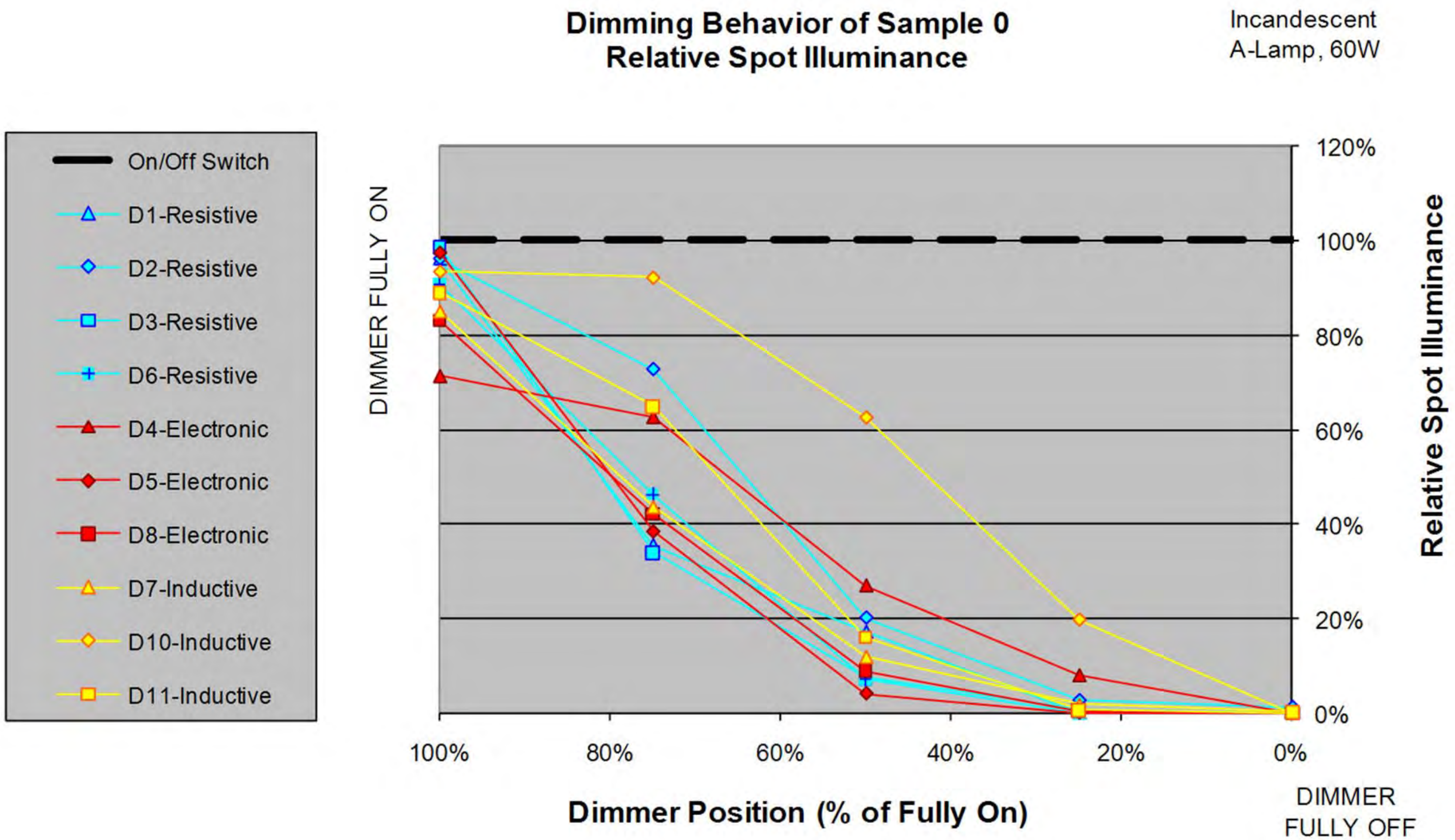
→Similar dimming range, different dimming curves



Example: Incandescent source + phase-cut dimmers

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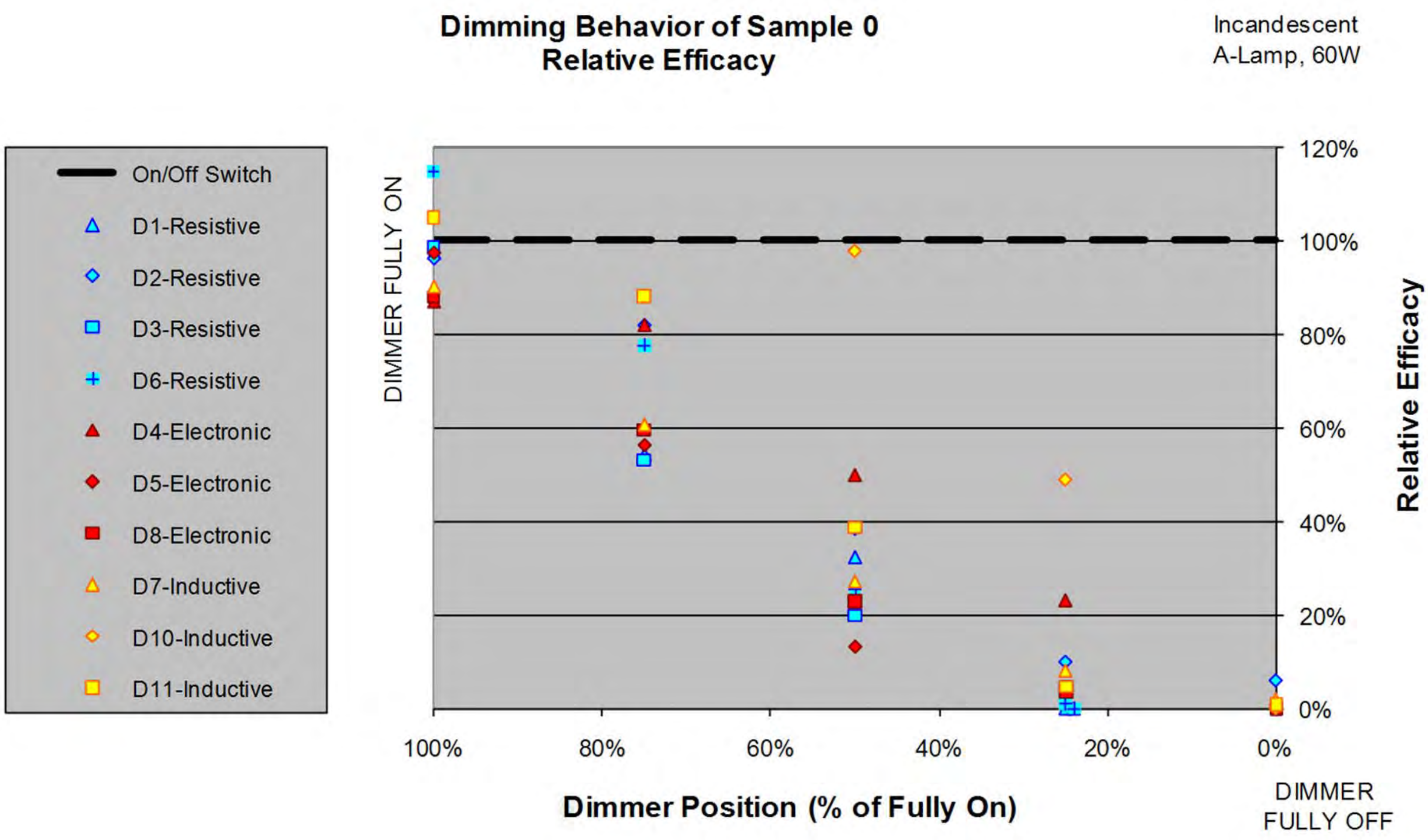
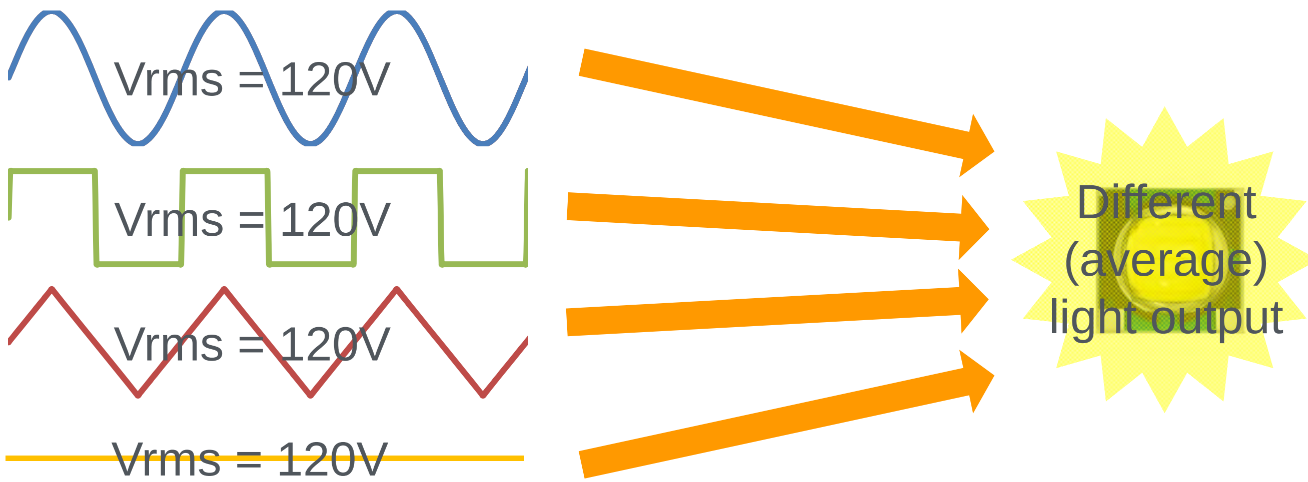
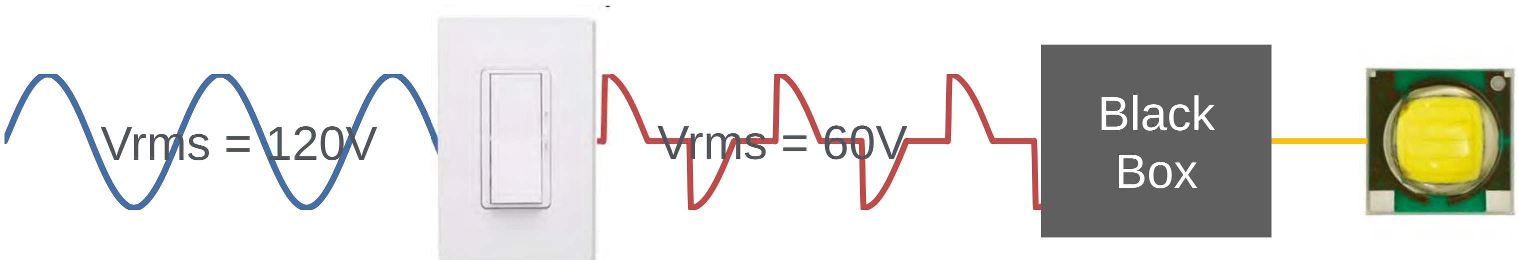
→Reduced efficacy when dimmed



Phase-cut dimming of LED light sources





High performance
Inexpensive
Vrms adjuster

Controls current to LED
Capability, compatibility determines dimming performance

Example: LED source + phase-cut dimmers

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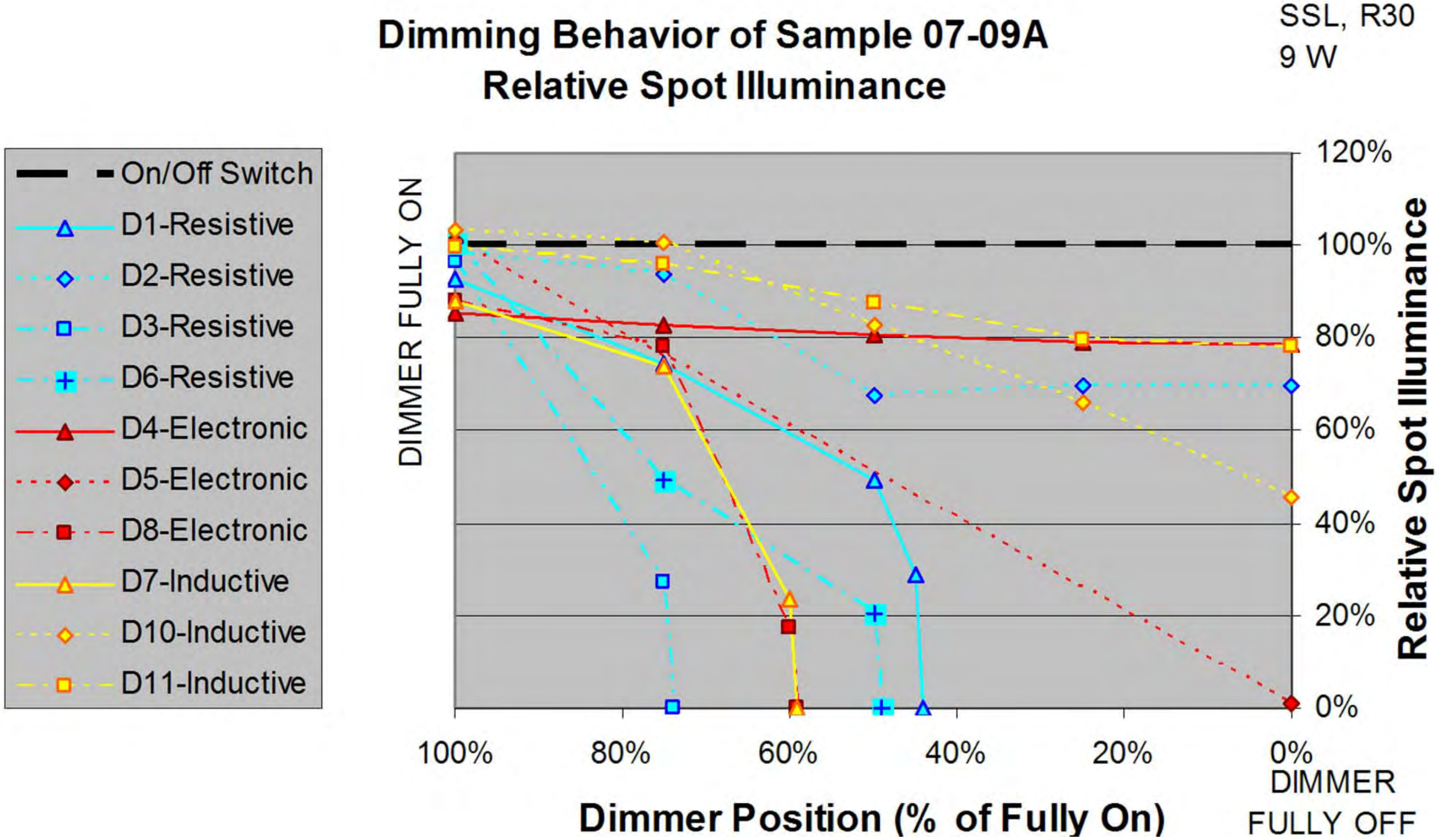
→ Varying dimming ranges and curves

SSL, R30
9 W



Example: LED source + phase-cut dimmers

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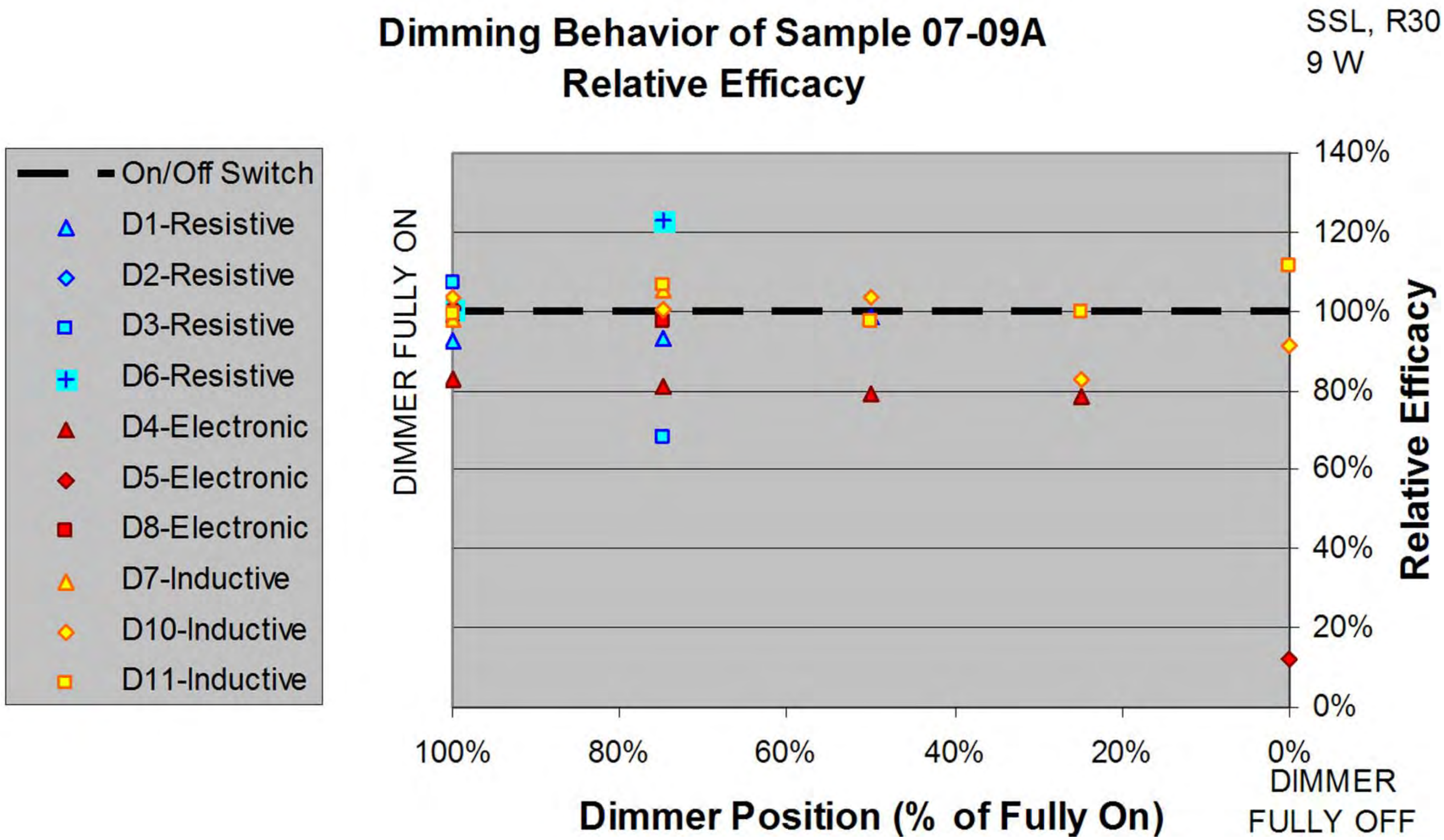
→ Maintains efficacy when dimmed



Example: LED lamp 1 + phase-cut dimmer A

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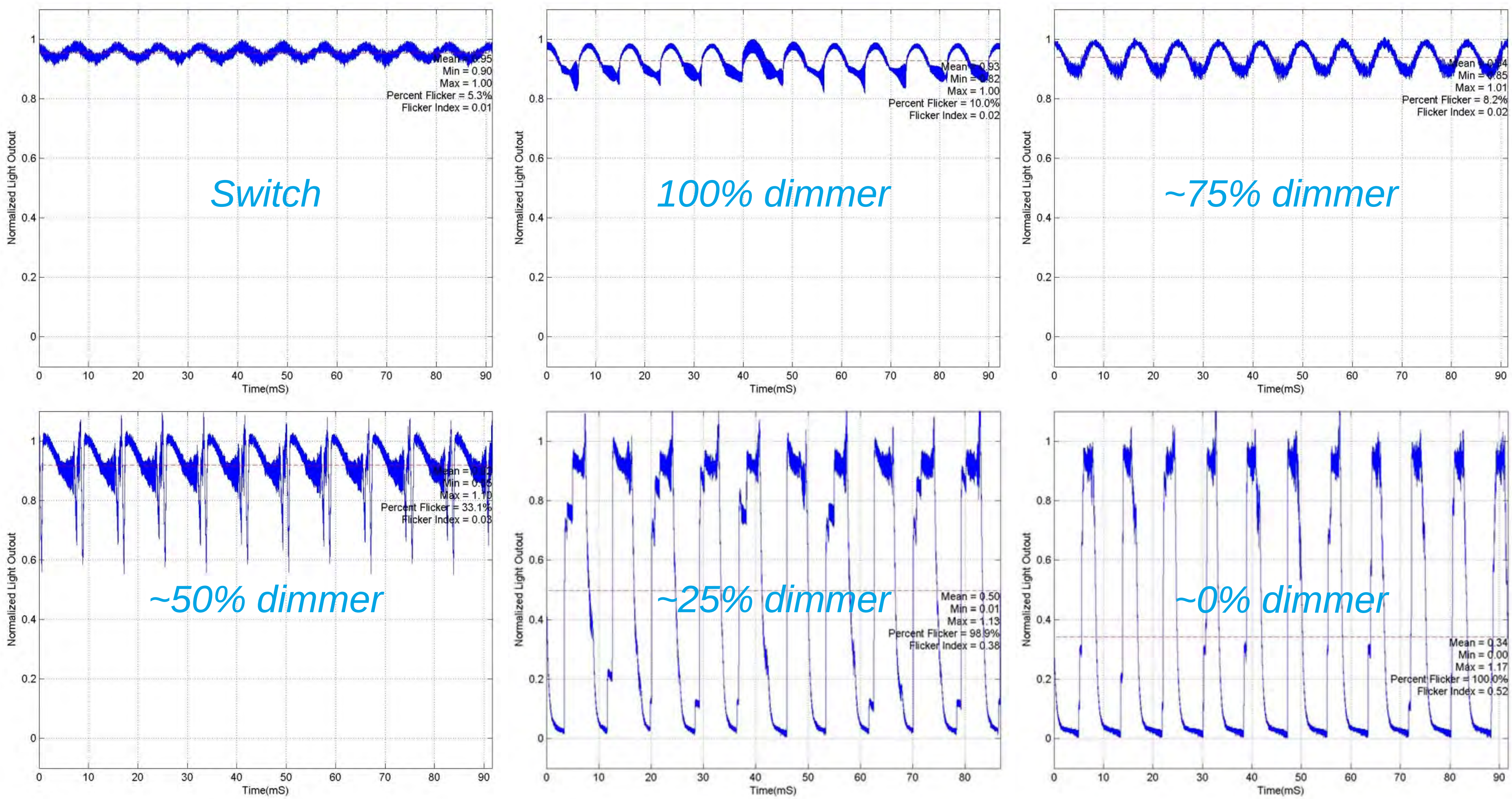

Example: LED lamp 1 + phase-cut dimmer B

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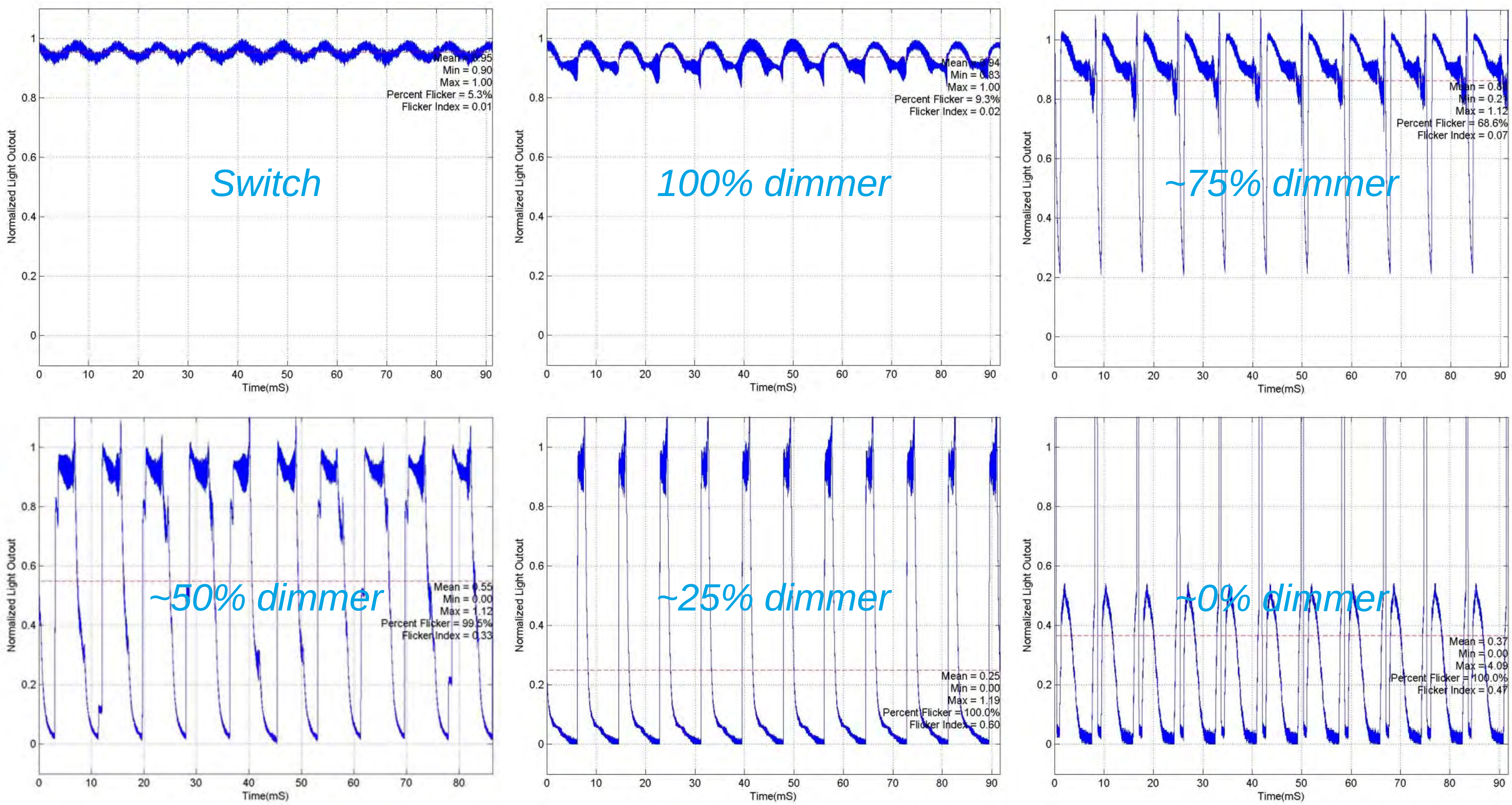

What's the big deal, again?

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- Dimming LED sources in the real world can be challenging, particularly with phase-cut dimmers
- Wide variation in LED source and dimmer characteristics
- Little can be assumed
- Not all claims are equal
- Difficult to predict

- Performance
  - Dimming range, curve
  - Efficacy
  - Flicker
  - Power quality
- Compatibility
  - Dead travel
  - Popcorn
  - Flashing, Ghosting
  - Pop-on, Drop-out
  - Audible noise
  - Inoperability
  - Premature failure

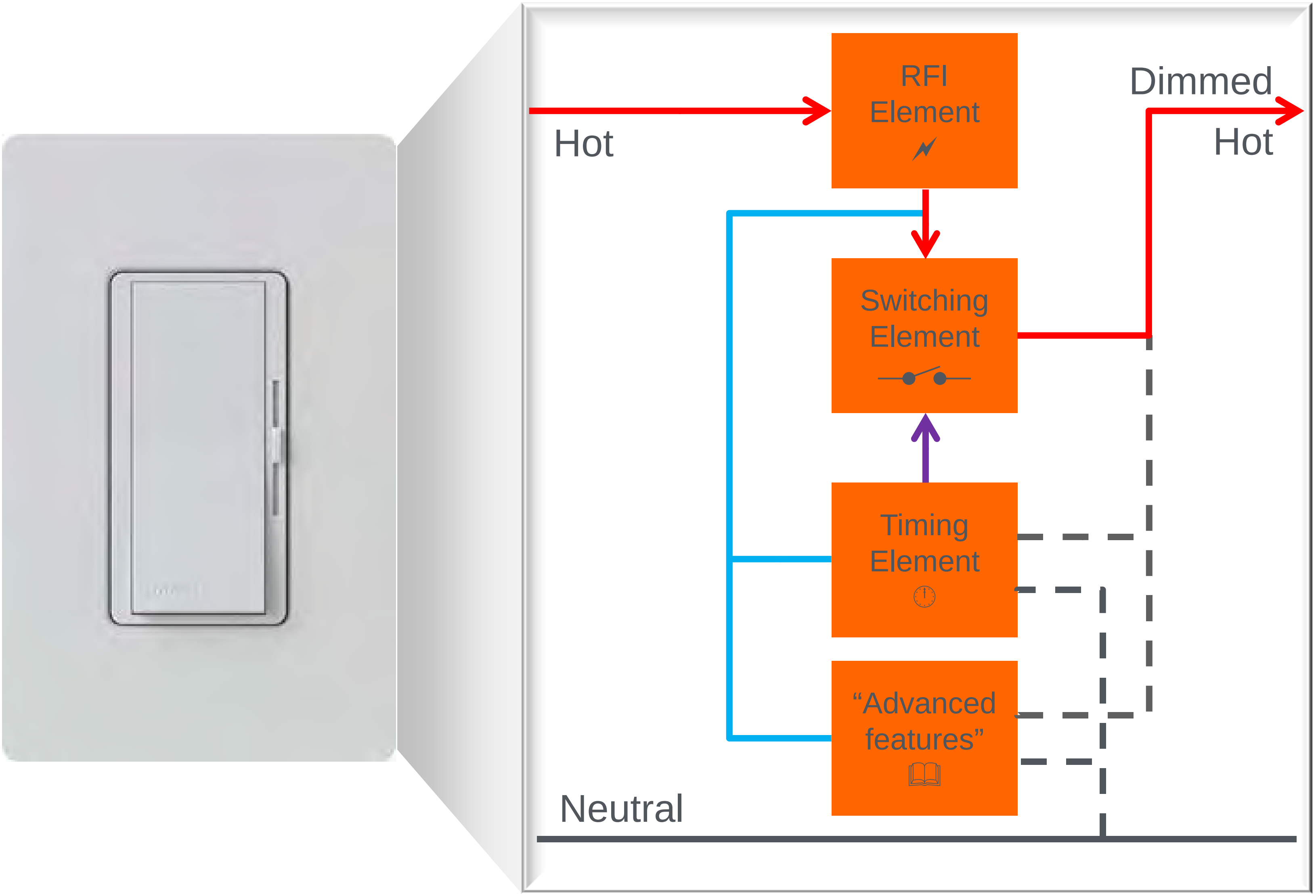
Phase-cut dimming challenges

- The behavior of an LED source on a circuit controlled by a phase-cut dimmer is a function of:
  1. the characteristics of the LED source (driver)
  2. the number and type of light sources on the circuit
  3. the characteristics of the dimmer
- Many types of behavior variation
- Many sources of behavior variation
- Behavior variation spans compatibility, performance, interoperability
- Behavior variation is significant in magnitude
- Behavior is only predictable via circuit level testing
- Currently no standard definitions or test procedures for evaluating dimming behavior

Compatibility issues

- Dead travel: Adjusting the dimmer setting without a corresponding change in light level
- Pop-on: Dimmer setting needs to be raised above its existing setting in order to get light output at turn-on
- Drop-out: No light output at the bottom of the dimming range
- Popcorn: Different turn-on times for different light sources on a dimmed circuit
- Flashing: Light source is intermittently on when it should be off
- Ghosting: Light source is at a low-level on state when it should be off
- Audible noise
- Inoperability
- Premature failure

Anatomy of a phase-cut dimmer



Sources of phase-cut dimming compatibility issues

- LED load can not measure V_{RMS} and/or conduction angle presented by the dimmer
- LED load does not draw enough current to keep dimmer switching element(s) closed, leading to erratic behavior
- LED load creates a series impedance which disrupt dimmer timing element(s), leading to erratic behavior
- LED load in off state does not pass dimmer current in a manner which keeps dimmer advanced features functioning while remaining in off state
- LED load draws currents which create stresses on dimmer above and beyond what its rated (incandescent) wattage indicates, leading to reduced dimmer lifetime

Dimmer loading rules have changed

- Minimum load varies by dimmer and LED source
- Maximum load varies by dimmer and LED source

Dimmer	Source	Possible loading
600W incandescent	60W incandescent 	1-10
600W incandescent	12W LED 	~~1-50?~~ 3-10
600W ELV	50W halogen 	1-12
600W ELV	10W LED 	~~1-60?~~ 2-30

Review: What's the big deal?

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- Dimming LED sources in the real world can be challenging, particularly with phase-cut dimmers
- Wide variation in LED source and dimmer characteristics leads to wide variation in dimming performance and compatibility
- Little can be assumed, as historical practices are unreliable
  - "600W maximum load", technology and model independent
  - "works with ELV dimmers"
- Not all claims are equal, given lack of standard criteria
- Difficult to predict, given lack of standard test procedures

Review: What you need to know

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- LEDs are inherently dimmable
- LEDs typically need a "Driver"
- Dimming an LED source can change the behavior of the driver
  - Source efficacy typically maintained during dimming
  - Dimming can induce or increase flicker
  - Dimming can degrade power quality
- LED dimming performance is determined by Driver <u>capability</u> and <u>compatibility</u> with the dimming equipment
- Multiple compatibility issues are rooted in circuit level interactions between the LED Driver and dimmer
- What you think you know may not longer be valid

Recommendations: Know your options

Is the LED product a lamp or luminaire?

- Lamp
  - Typically retrofit, standard base
  - Integral, non-replaceable driver
  - Constrained to phase control
- Luminaire
  - Often has driver options
  - Driver options yield control options: (e.g. phase control, 0-10V, DALI, proprietary)
- Consider control technologies which separate AC power and the control signal, if possible
- Use a phase-cut dimmer with a neutral, if possible
- Consider using dimming controls designed for LED sources and/or new dimming technologies

Recommendations: take advantage of available information and guidance

- What is the designed, claimed, (i.e. best-case) dimming performance of the LED source?
  - Dimming range (max – min)
  - Assumptions, requirements
- Is there a recommended dimming control selection guidance?
  - If so, definitely use it
  - Specific makes/models; control type (i.e. forward or reverse phase) is likely not sufficient
  - Dimmer loading requirements (i.e. max/min number of LED sources per control)
  - Beware expectations of exactly the same performance from any/all guidance

Dimmer manufacturer guidance

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LED Product Report Card

Manufacturer: Cree
Applicable Model Numbers: LR24 – 325KA35

Manufacturer's Description
Type of Fixture: Recessed Downlight
Operating Voltage: 120 / 277 Vac
Input Power: 48W
Current: 0.4 – 1.7 A
Frequency: 50 / 60 Hz
Control Types: 0-10 VDC Control Protocol
Dimming Range: 5% - 100%
Output Power: N/A
Lumens: 3200 lumens

Lutron Test Results
Date Tested: Feb 25, 2009
Model Number Tested: LR24 – 325KA35
Smooth and Continuous: Yes
Test Notes:

Lutron Recommended Compatible Products

Product	Part Number	Fixtures per Dimmer	Measured Light Output Range [1]	Comments
Nova	NFTV	1 – 40 [4]	5% - 100%	Requires PP-120H or PP-277H
Nova T*	NTFTV	1 – 40 [4]	5% - 100%	Requires PP-120H or PP-277H
Diva	0-10V Control			Available soon
Interfaces	GRX-TVI [2]	1 – 40 [4]	5% - 100%	Range depends on dimmer selected
	GRX-TVM2 [3]	1 - 40	5% - 100%	Range depends on dimmer selected

[1] Values are based on light output using the specified dimming control, and may not be an indication of the fixture's full capability
[2] Controlled with 3-Wire Fluorescent dimmers, Homeworks, RadioRA, or Commercial Systems
[3] Controlled with Homeworks or Commercial Systems
[4] 60 fixtures for 277V applications.

Comments: The ability to set the low-end trim is available on select 3-Wire Fluorescent dimmers, Homeworks, and Commercial Systems products. Refer to product documentation or www.lutron.com for details.

Dimmer LED Bulb Compatibility

Company	Part Number	Compatible
Juno	TL201LED TRAC 12 LED Module 12W	IPI06, ATE06, 6633-P, TGI06
	120V LED Strip	None
LLF/CREE	LED LR6 2700K 12W 100mA	IPI06
Lightolier	C410LEDDL30KCCLP & C420LEDDL30KCCLP	VPE04, VPE06, IPE04, 6615, ATE06
WAC Lighting	LD-700MA-18-DIM-NIS Dimmable Constant Current LED Driver	VPE04, VPE06, VPI06, IPI06, ATE06, VRE06
	IC20LED & IC22LED	VPE04, VPE06
Cooper Lighting	LED Lamp assembly (LED 71684)	VPE04, VPE06, ATE06, IPE04
Light Emitting Designs, LLC	LED CFLA-120-10-195-SW LED PAR38-120-5-80-DL LED-PAR30-120-7-7-DL LED-A15-120-3-36DL-CL GU10 3X1W AC 85-260V Cree, LED-MR20-12-6-3-SW-60 LED-MR16-12-3-3-SW LED-MR16-12-3-48-DL	None
LEDTRONICS	PAR38-180-XPW-120AND - 120VAC	IPE04, IPI06*, 6615
	R30-123-SIW-120AMD - 120VAC	IPE04, IPI06*
	PAR20-66-XCW-120AND - 120VAC	IPE04, IPI06
	PAR30-15W-XXW-120AMD - 120VAC	6615
	PAR38-7X3W-XIW-120AMD - 120VAC	None
	LEDPAR38WW	VPE06*, VPE04*, VRE06*, ATE06*, VRM10*
Environmental Lights	12VDC LED Strip	VRM10, 6613
Philips LED driver/light engine combination	0-10V LED Driver	IP710
Lightech	LED-36-700-120-D-BF	VPE04, ATE06, VRE06

*Raise low end setting to prevent flickering or turn off at the lowest setting

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Lamp manufacturer guidance

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Brand	Series	Model	Load	Type	Dimming level Max.>Min. (flux%)) 1 lamp	Flickering 1 lamp	Flickering 3 lamp	Flickering 5 lamp	Flickering 8 lamp
Leviton	Decora	6161	500W	LE	99%~0	No	No	No	No
Leviton	Trimatron	6684	600W	LE	100%~0	No	No	at~40%	at~40%
Leviton	SureSlide	6613	600W	LE	100%~2%	No	No	No	No
Leviton	Illumatech	IP106-IL	600W	LE	100%~9%	No	at~60%	~40%-50%	~0%-40%
Lutron	Ariadni	AY-600P	600W	LE	100%~5%	No	No	No	No
Lutron	Diva	DV-600P	600W	LE	99%~2%	No	No	No	at~70%
Lutron	Diva	DVPDC-203P	200W	LE	99%~29%	No	0~50%	no dimmability	no dimmability
Lutron	Glyder	GL-600	600W	LE	100%~2%	No	No	No	No
Lutron	NOVA	NLV-1000	1000W	LE	100%~3%	No	No	No	No
Lutron	Qoto	Q-600P	600W	LE	100%~4%	No	No	No	at~70%
Lutron	Skylark	S-600P	600W	LE	90%~3%	No	No	No	at~80%
Lutron	Toggler	TG-600P	600W	LE	100%~5%	No	No	No	at~70%
Lutron	Credenza	TT-300	300W	LE	100%~0	No	No	No	at~40%

Brand	Model	Man./Country	Type	Load	Dimmability			
					1 lamp	3 lamps	5 lamps	8 lamps
Lutron	TG-600R-WH	USA	–	600W	OK	OK	OK	OK
Leviton	OL1805	–	–	600W	OK	OK	OK	OK
Lutron	GL-600-WH	St. Kitts/USA	–	600W	OK	Flicker	Flicker	Flicker
Lutron	S-600PR-WH	USA	R	600W	OK	Flicker	Flicker	Flicker
Leviton	6613-PL	China	–	600W	OK	OK	OK	OK
Leviton	IP106	–	–	–	OK	OK	OK	Flicker
Leviton	6161	China	–	500W	OK	OK	OK	OK
Lutron	NLV-1000	USA	–	1000W	OK	OK	OK	OK
Lutron	TT-300NLH-WH	St. Kitts/USA	–	300W	OK	OK	OK	OK
Lutron	DVPDC-203P	USA	–	200W	OK	OK	OK	OK
Lutron	Q-600P	–	–	–	OK	Flicker	Flicker	Flicker
Lutron	AY-600P	USA	–	500W	OK	Flicker	Flicker	Flicker
Lutron	DV-600P	USA	–	250W	OK	OK	OK	OK

LED lighting facts
A Program of the U.S. DOE

Dimming information reporting format

Dimmer Make	Dimmer Series - Model	Dimmer Trim Requirements	Transformer Make (low voltage lamps)	Transformer Model (low voltage lamps)	LED Lamp or Luminaire Series - Model	Dimming Range, max-min (% lumens)	Minimum Lamps or Luminaires (per circuit)	Maximum Lamps or Luminaires (per circuit)	Additional Comments
"Dimmer Make 1"	*"Dimmer Series A" - "Dimmer Model #"*	Low End	N/A	N/A	*"PAR38 Series" - "PAR38ABC123"* *"PAR38 Series" - "PAR38XYZ456"* *"PAR38 Series" - "PAR38EFG789"*	99% - 0%	1	6	
"Dimmer Make 2"	*"Dimmer Series A" - "Dimmer Model #"*	N/A	*"Transformer Make 1"*	*"Transformer Model #"*	*"Brand Y MR16s" - "MR16ABC123"*	100% - 5%	1	40	
"Dimmer Make 2"	*"Dimmer Series B" - "Dimmer Model #"*	N/A	*"Transformer Make 1"*	*"Transformer Model #"*	*"Brand Y MR16s" - "MR16ABC123"* *"Brand Y MR16s" - "MR16XYZ456"*	100% - 5%	1 *"MR16ABC123"* + 1 *"MR16XYZ456"*	3 *"MR16ABC123"* + 10 *"MR16XYZ456"*	

Recommendations: ask the right questions

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- What are the dimming transfer functions?
- Does the LED driver implement CCR or PWM to dim?
- What is the PWM dimming frequency?
- Low-voltage source?
  - Need step-down transformer selection guidance
- Universal/multiple input-voltage source?
  - Does the dimming performance vary at different input voltages?
- Was the LED source evaluated for flicker over the dimming range? At all input voltages?
- Was the LED source evaluated for power quality over the dimming range? At all input voltages?
- Does the dimmer require a neutral? Trim-adjustment?

Recommendations: weight the trade-offs

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- Application needs vs. wants
  - How much does flicker matter?
  - How much does power quality matter?
- Option 1: Only use LED sources and phase-cut dimming controls with defined compatibility and performance
  - Manufacturer guidance
  - Standards
- Option 2: Mock up installations
  - All LED sources, all dimmers
  - All source combinations
  - Yes, this means full circuits
  - Beware SSL source or dimmer substitutions, model updates

Recommendations: analyze risk

- Common “fixes”
  - Change the LED source, LED driver, or dimming control
  - Add incandescent or dummy loads
  - Add neutral wires
- Often there are no good solutions once products are installed
- Who is responsible? Who pays?
- Have a plan BEFORE products are ordered and installed

Will this get any easier?

New technology

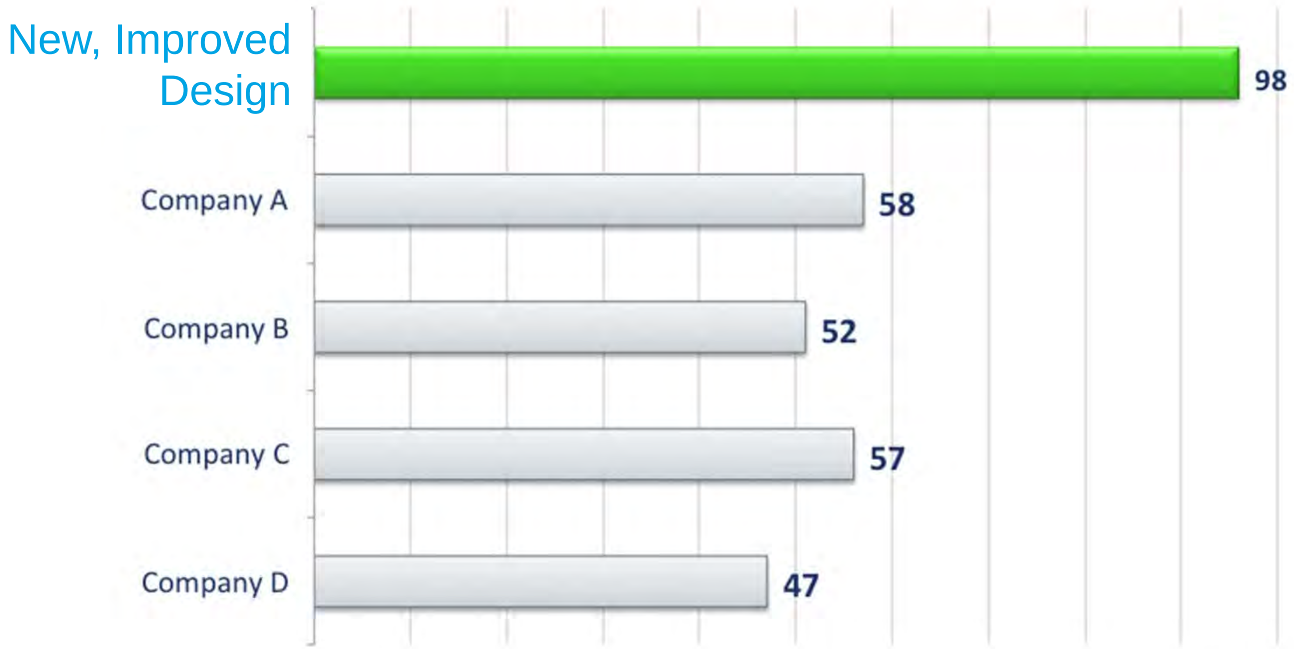
- LED drivers
- Dimming controls
- Control technologies

New standards

- ENERGYSTAR criteria
- NEMA SSL-7
- Insta DLT / IEC 62756-1
- ZigBee Light Link

New LED drivers

- Embedded intelligence “detects” dimmer characteristics
- Could lead to (near) universal compatibility?



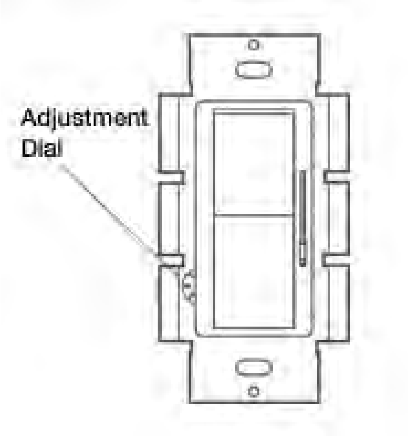
*= Based on 230 V, tested with over 40+ different dimmers: dimming functionality & smoothness, dimming range, flicker free on transient and steady state (120V and 230V)

New dimming controls

- Designed for LED sources and mixed loads

Total CFL/LED Wattage Installed (Watts per bulb x # of bulbs)		Maximum Allowable Incandescent/Halogen Wattage*	
		No sides removed	1 side removed
0 W	+	600 W	500 W
1 W – 25 W	+	500 W	400 W
26 W – 50 W	+	400 W	300 W
51 W – 75 W	+	300 W	200 W
76 W – 100 W	+	200 W	100 W
101 W – 125 W	+	100 W	50 W
126 W – 150 W	+	0 W	0 W

- Dimming range low-end trim
  - Raises minimum dimming level
  - Reduced chance of drop-out, pop-on



New control technologies

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- Powerline carrier
  - Digital modulation of AC power
  - Coincident AC power and control signal
- Wireless
  - Digital open spectrum communication
  - Separate AC power and control signal
- Centralized power supply or LED driver
  - Low-voltage (CV or CC) wiring to LED source
  - Coincident or separate AC power and control signal

NEMA SSL-7

- SSL-7A (compatibility): in development; ETA early 2013
- SSL-7B (performance): initiated upon completion of 7A
- Defined compatibility and performance for SSL-7 compliant phase-cut controls and lamps/luminaires
  - Current scope covers forward phase-cut controls only
  - Current scope covers light sources which connect to electrical branch circuit, and have electronic power supply
- Defines design specifications for lamps/luminaires and phase-cut controls
- Defines compliance test procedures for lamps/luminaires and phase-cut controls

ZigBee Light Link

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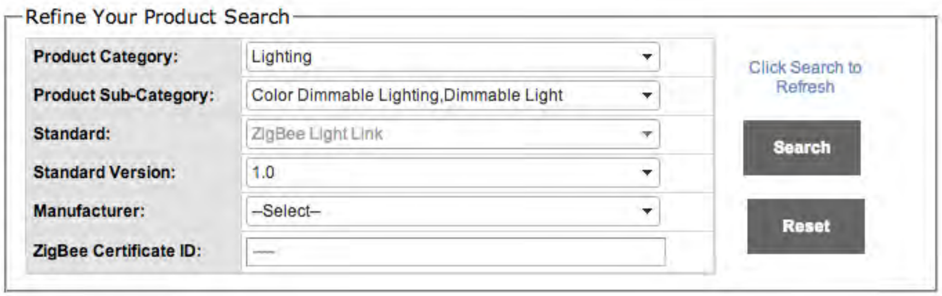
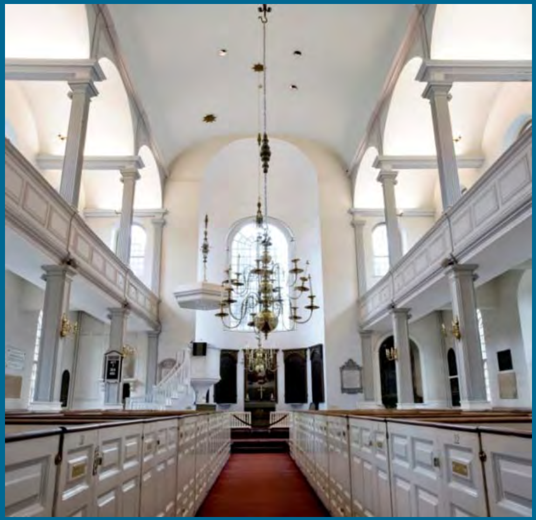
- Requires new control and LED driver
- Low-cost (leverages other Zigbee applications)
- Wire-free installation, retrofit
- Device authentication, AES 128 encryption
- Easy to assign single/individual control devices to one or many light sources (without added wiring)
- Certification ensures compliance, and thereby compatibility



Questions? TINSSL@pnnl.gov



DOE SSL Program

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