
Digital Architecture for Driving Large LED Arrays with Dynamic Bus Voltage Regulation and Phase Shifted PWM

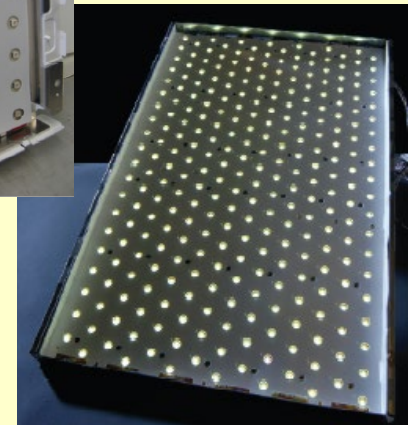
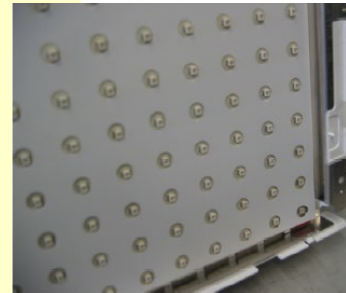
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Drive Requirements for Solid State Lighting

A large number of LEDs may be required for many applications due to low light output per LED

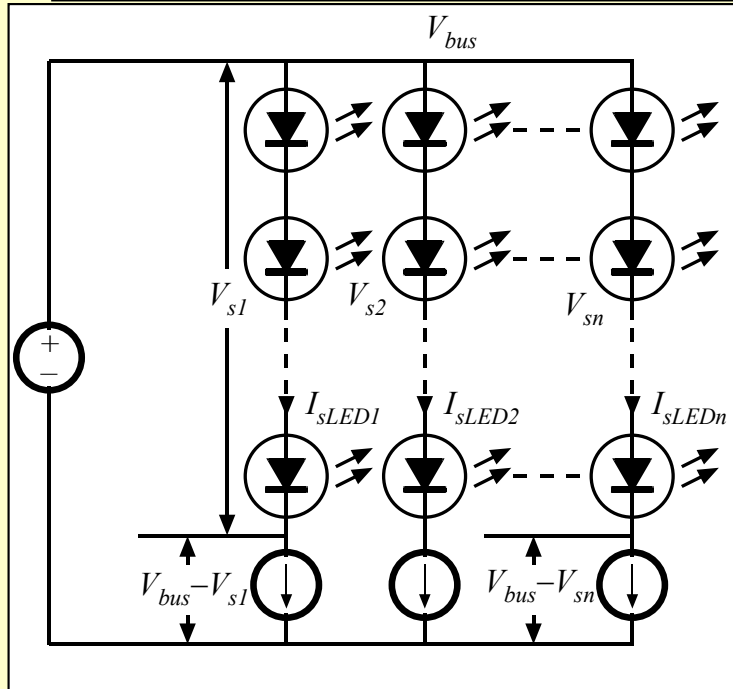
- Topology must be capable of driving multiple series LED strings
- Require high efficiency and long operating life
- Current regulation with amplitude control required to calibrate and maintain a constant light output
- High resolution PWM on/off control of LEDs required for dimming

General lighting



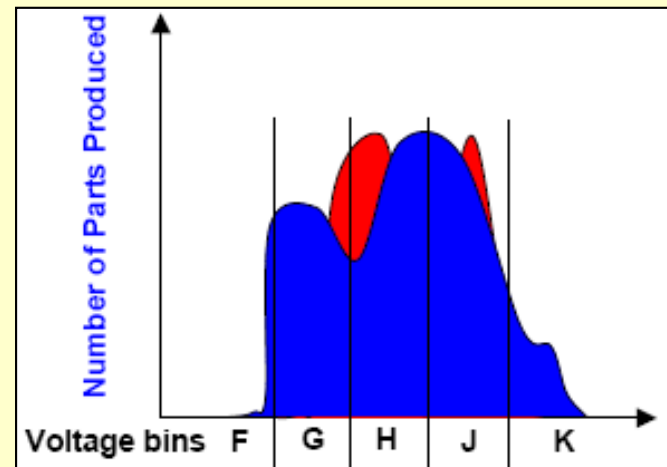
LCD backlighting

Challenge: Forward Voltage Variations



- The number of LEDs in a series string depends on the bus voltage
- The number of LED strings in parallel is set by the total light flux output requirement
- Variations in the string to string voltages result in power loss

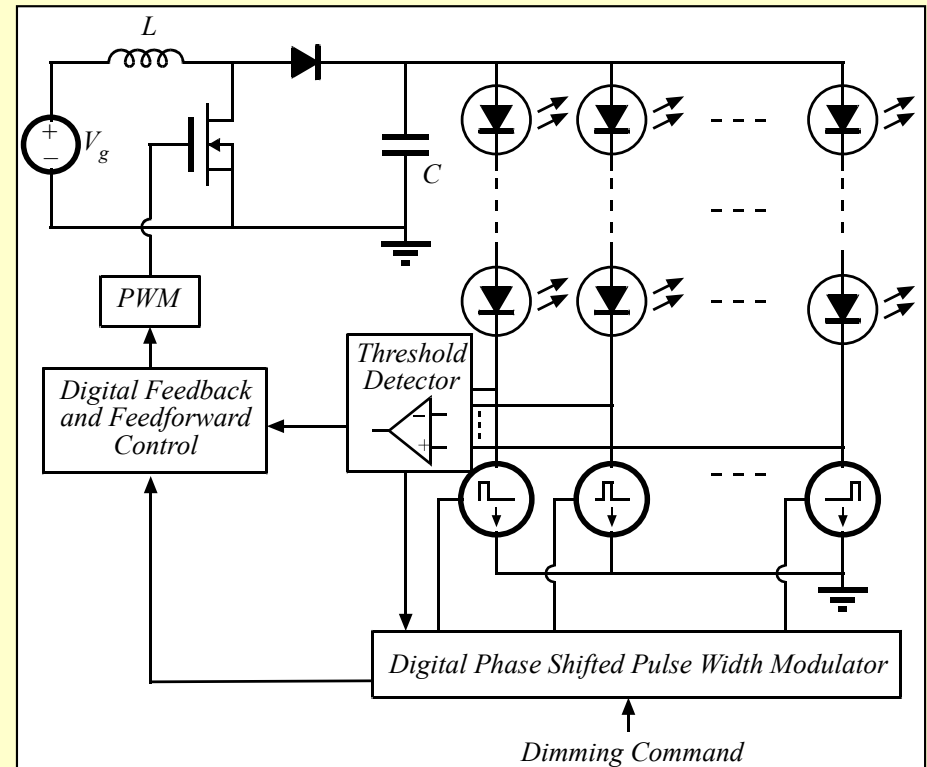
- Binning is performed to reduce mismatch and improve efficiency
- Results in increased system cost



APEC '07 - Digital Architecture for Driving Large LED Arrays ...

Digital Architecture for Driving LED Array

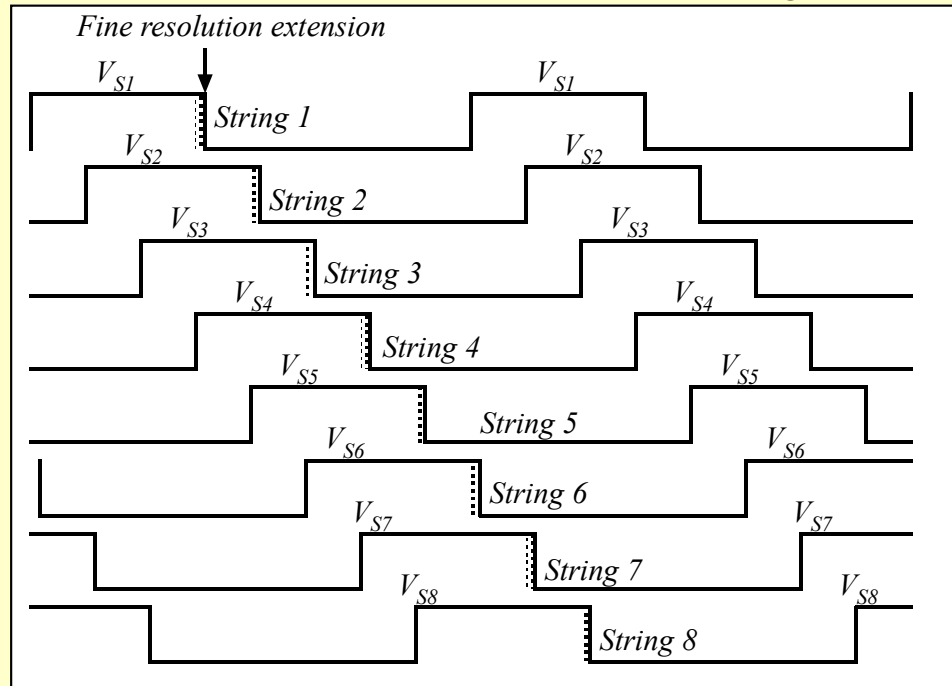
- Current regulation via series programmable sources
- Optimize power stage by eliminating large pulsating load currents using phase shifted pulse width modulation (PS-PWM)
- Improve efficiency by performing dynamic voltage scaling
 - Feedforward calibration performed by threshold detector



Single controller coordinates system behavior

Digital Phase Shifted Pulse Width Modulation

PWM commands for LED strings



8-bit PS-PWM at 40% dimming

Upper 3 bits: $011_{bin} = 3_{dec}$ (37.5%)

Lower 5 bits: $= 00110_{bin}$ (2.5%)

- Upper bits of the dimming command designate the number of strings that are on at the same time
- Lower bits extend pulse width for fine resolution
- PWM pulses are evenly phase shifted
- Results in near constant power supply current
- Leverage hardware efficient architecture¹²

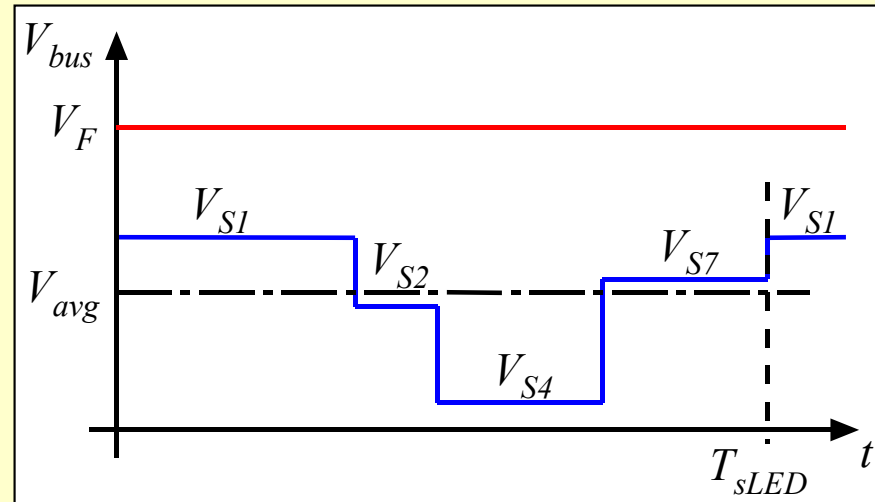
Dynamic Voltage Scaling

- The minimum required bus voltage is set by which strings are on at any time
- With PS-PWM, each string is pulsed on and off in sequence during a PWM period
- Dynamic scaling tracks the minimum required voltage via feedforward control
- For fixed bus voltage V_F

$$\eta = (\sum V_{si}) / (N \cdot V_F)$$
- For dynamic scaling

$$\eta = (\sum V_{si}) / (N \cdot V_{avg})$$

Bus voltage over one PWM period

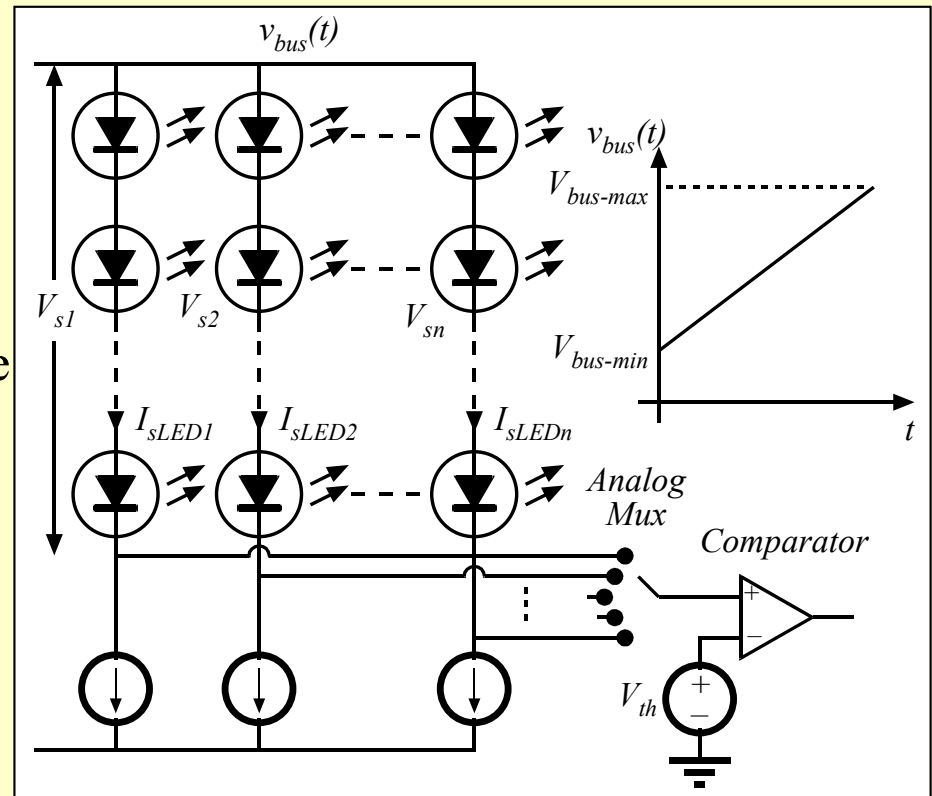


Overall efficiency improvement compared to a fixed bus voltage

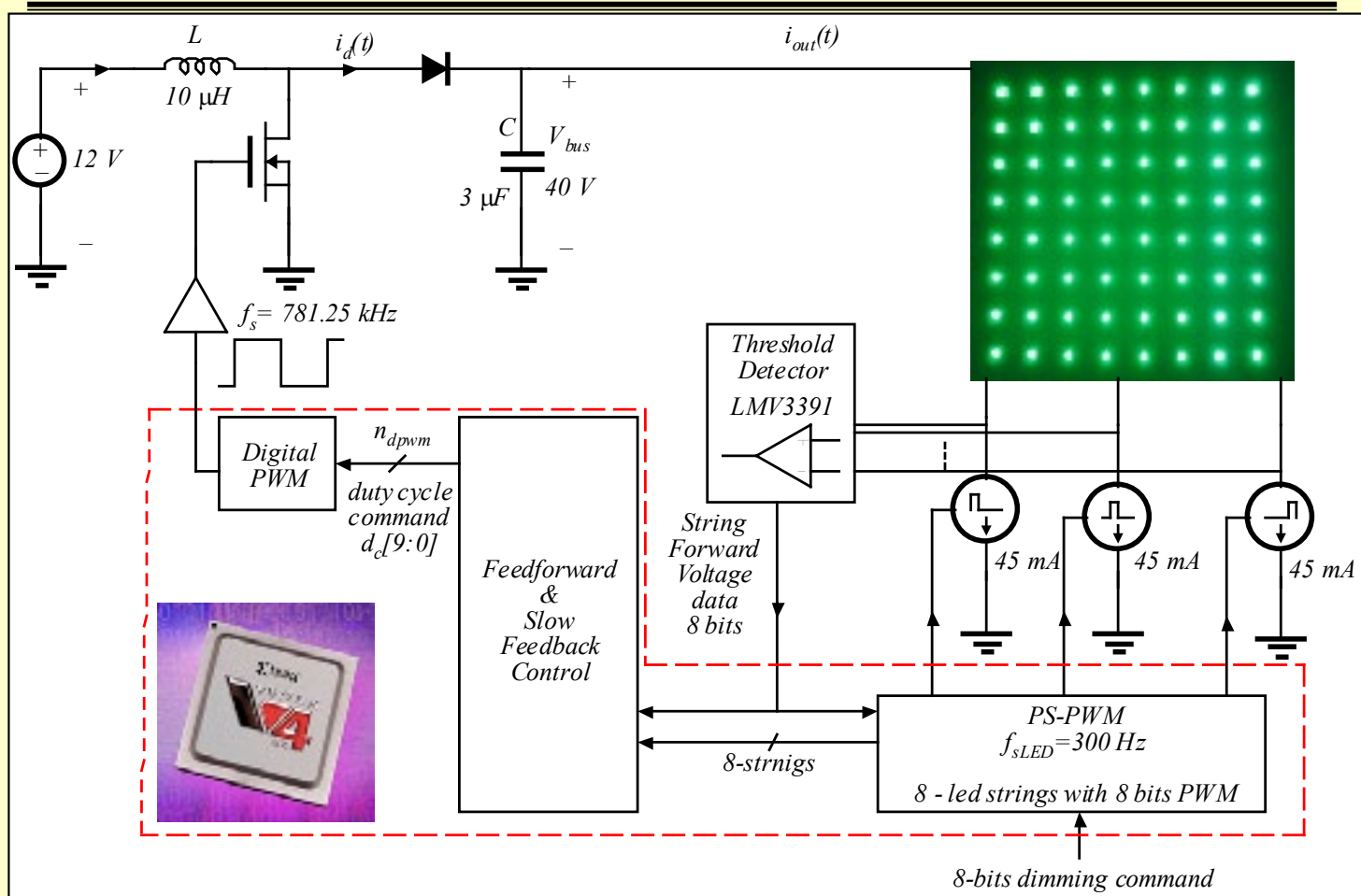
$$\Delta\eta = \left(\frac{V_F - V_{avg}}{N \cdot V_F \cdot V_{avg}} \right) \cdot \sum_{i=1}^N V_{Si}$$

Threshold Detection

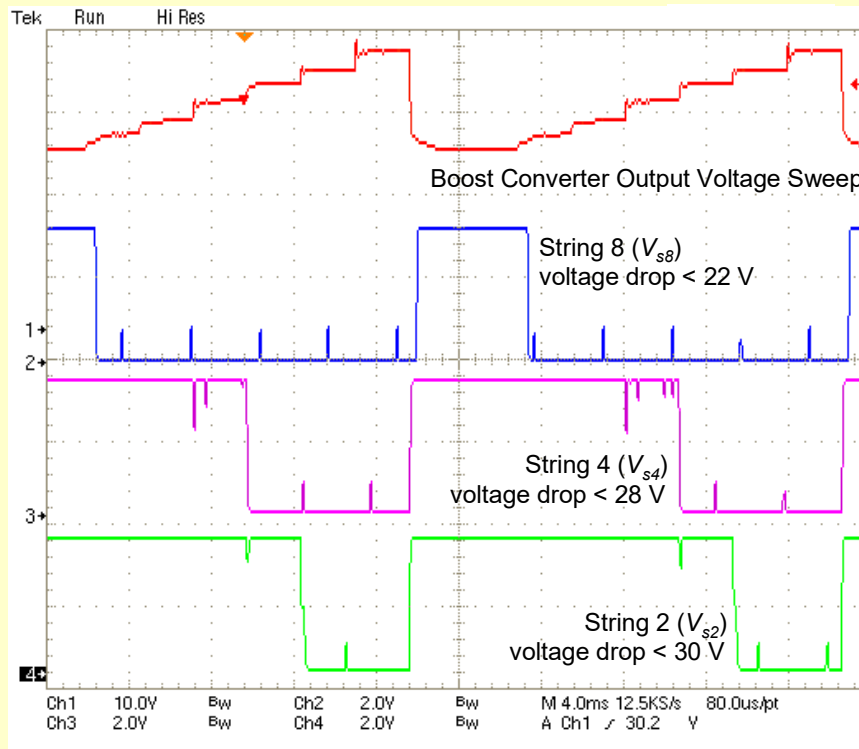
- Used to calibrate feedforward control for dynamic voltage scaling
- Voltage drop on each LED string is sensed by sweeping the bus voltage and recording threshold points
- LED strings are binned and sorted for PS-PWM and feedforward voltage scaling
- Detection circuit can be used during manufacturing and operation for failure detection and monitoring changes in string voltages



Experimental System



Experimental Results - Threshold Detection

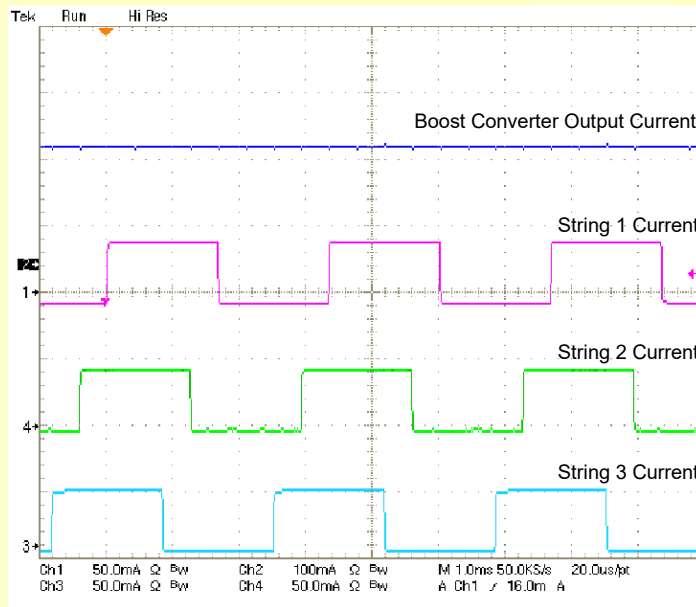


- Threshold detection implemented at $Dim = 100\%$
- Boost output voltage (V_{bus}) stepped from 22 V to 35 V
- Comparator output goes low at minimum required voltage for each string
- The threshold point is latched and used to bin and sort LED strings for PS-PWM and dynamic voltage scaling

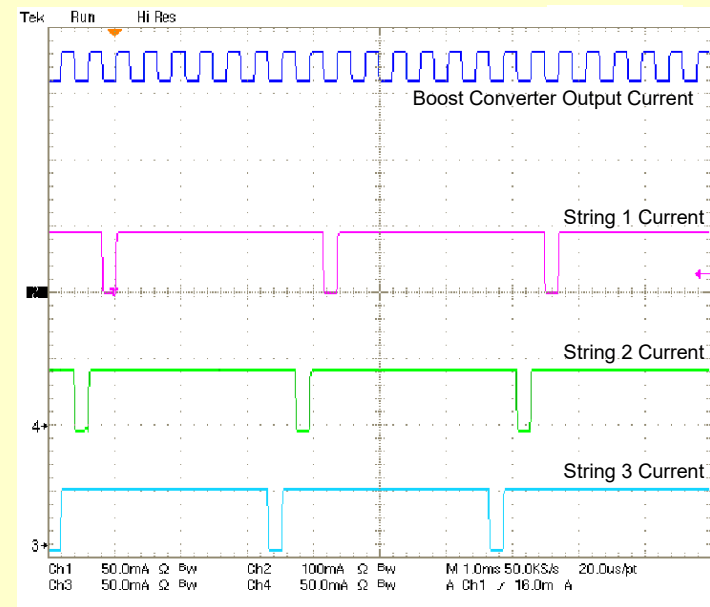
V_{S1}	V_{S2}	V_{S3}	V_{S4}	V_{S5}	V_{S6}	V_{S7}	V_{S8}
31.7	29.4	29.3	27.7	26.6	25.9	25	21.9

Experimental Results - PSPWM

PS-PWM for $Dim = 50\%$



PS-PWM for $Dim = 93.7\%$

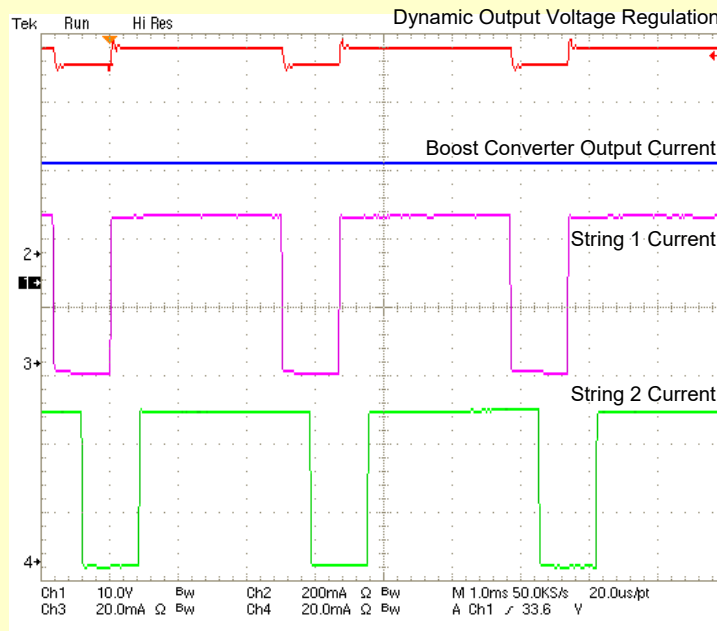


- Load current pulses on converter are no greater than one LED string current peak to peak for complete range of dimming command
 - Results in reduced EMI and required output capacitance
- Uniform phase shifting may improve light uniformity

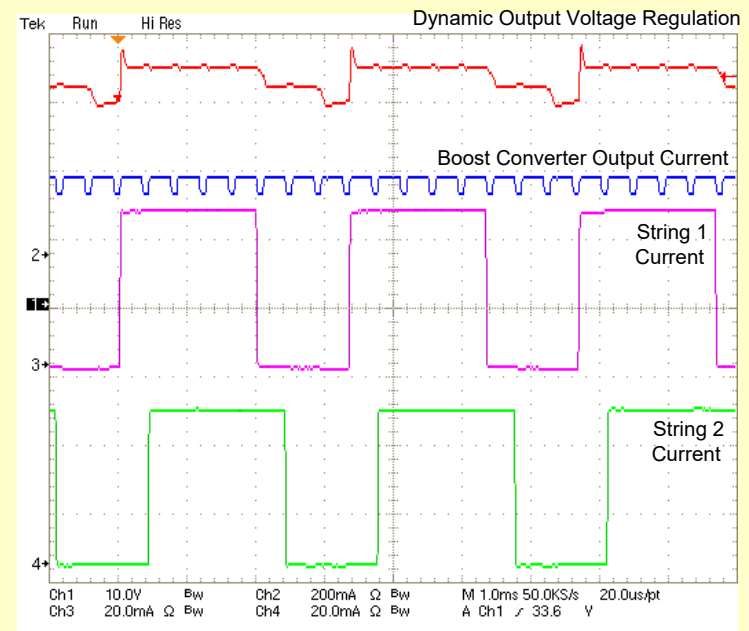
Experimental Results

Dynamic voltage scaling

Voltage scaling for $Dim = 80\%$



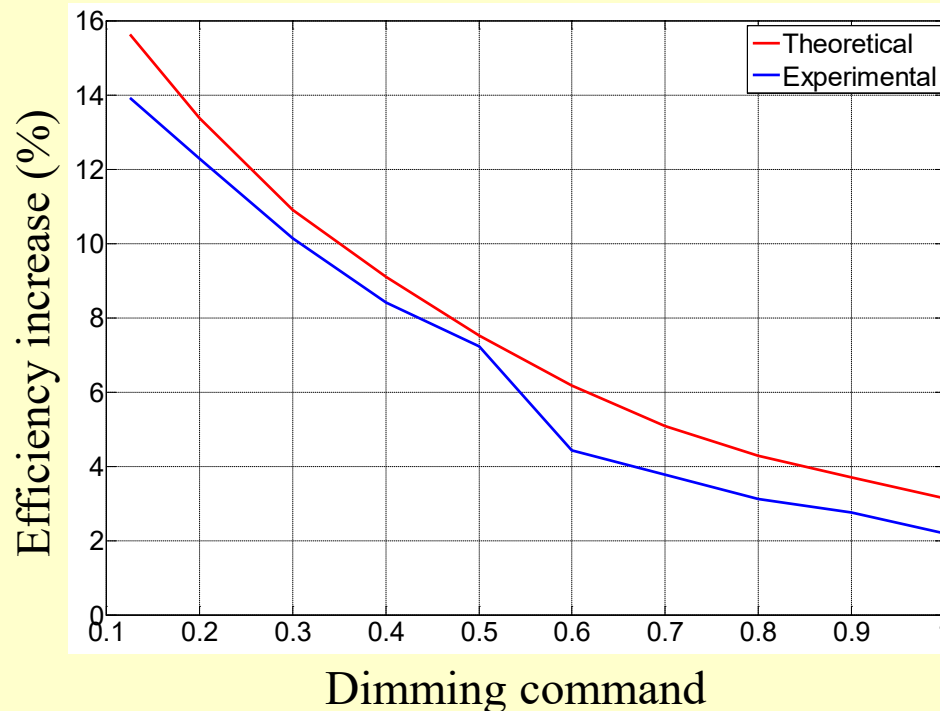
Voltage scaling for $Dim = 60\%$



- Feedforward techniques are employed to achieve fast dynamic response to voltage step transients (re-calibration can be performed periodically)
- Accurate current regulation and PWM control is maintained

Efficiency Improvement

Comparison between theoretical and experimental efficiency improvement



- Up to 8% *increase* in efficiency at Dim = 60% compared to a fixed worst-case bus voltage
- Measured 14% increase in efficiency at *Dim* = 12.5%
- Experimental results below theoretical limit due to course binning of LED strings

Conclusions

- Developed a digital drive architecture for high efficiency and performance drive of large LED arrays
 - Single power converter combined with series current source control for each string (or phase), *with amplitude and fast on/off PWM control*
 - Hardware efficient phase shifted PWM of LED string *for reduced bus current ripple, EMI and required bus capacitance; also achieves good color uniformity*
 - Feedforward of load transients combined with optimal control *to achieve fast dynamic response with further reduction in required bus capacitance*
 - Dynamic bus voltage scaling to track minimum required bus voltage *for improved system efficiency*
- Performance verified using a 64 (8x8) LED board driven from a 15 W Boost converter with PSPWM and feedforward control algorithm