Application Report
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Auto-Frequency Mode Setting for Improved Boost Efficiency in White LED Backlight Drivers

Travis Eichhorn

ABSTRACT

As the load current of a boost converter is reduced, the ratio of conduction losses to switching losses begins to lower. Conduction losses are losses that are a function of current. Switching losses are losses that are a function of switching frequency. As this ratio is reduced the boost switching losses begin to dominate the total circuit losses. When this happens, the benefit of lowering the boost switching frequency is more advantageous than the benefit of inductor ripple current reduction (higher boost frequency).

1 What is Auto-Frequency Mode?

To optimize efficiency by taking advantage of the reduced switching losses vs boost switching frequency, some of TI's white-LED backlight drivers have the ability to automatically change their boost switching frequency based on the programmed LED current. This mode, called auto-frequency mode, operates by using 2 programmable registers: Auto Frequency High Threshold Register and Auto Frequency Low Threshold Register. The high threshold determines the switchover from the high frequency (1 MHz) to an intermediate frequency (500 kHz). The low threshold determines the switchover from (500 kHz) to the low frequency (250 kHz). Both the High and Low Threshold Registers accept an 8-bit code, which corresponds to a current between 0 and the maximum LED string current of the device. The programmed values in the Auto-Frequency Registers are compared against the 8 most significant bits (MSB's) of the brightness code. When the brightness code falls below the threshold the boost switching frequency automatically switches to the lower frequency setting. Currently, all devices which incorporate the auto-frequency function operate with an 11-bit brightness code. The 11-bit brightness code is a function of both the I2C programmed code (programmable via an MSB register (8 bits) + an LSB register (3 bits)) and the 11 bit representation of the PWM input duty cycle. The brightness code is I2C (code) × PWM(D) rounded to 11 bits. The auto-frequency thresholds are compared against the MSBs of the brightness code.

1.1 Auto Frequency vs Variable Frequency

The programmable auto-frequency mode was chosen vs having a device with a constant variable frequency for two main reasons:

- Discrete steps in frequency are easier to make stable using current-mode control
- Discrete steps in frequency are more predictable, thus making them easier to design around for EMI purposes.

2 Devices With Auto-Frequency

The following devices contain the Auto-Frequency mode:

Table 1. Auto-Frequency Mode Devices

Device	Description	# of LED Channels	Max VOUT	Inductor	Auto Frequency High	Auto Frequency Low	Frequency Options	
							Nominal	Frequency Shifted
LM36922	White LED Driver	2	28 V	10 µH/22 µH	0x15	0x16	250kHz/500kHz/1MHz	220kHz/440kHz/880kHz
LM36923	White LED Driver	3	28 V	10 µH/22 µH				
LM36922H	White LED Driver	2	38 V	4.7 µH to 15 µH				
LM36923H	White LED Driver	3	38 V	4.7 µH to 15 µH				
LM36272	White LED Driver + Bias Supply	2	28 V	4.7 µH to 15 µH	0x07	0x06		
LM36273	White LED Driver + Bias Supply	3	28 V	4.7 µH to 15 µH				
LM36272	White LED Driver + Bias Supply	4	28 V	4.7 µH to 15 µH				

Note: When both the Auto Frequency Low and Auto Frequency High Registers are set to 0x00, the device operates at a fixed frequency (either 1 MHz or 500 kHz), depending on the user programmed fix frequency setting.

2.1 Frequency Shift

For each device with auto-frequency mode, there is an optional frequency shift. The frequency shift causes the programmed frequency and all auto-frequency forced lower frequencies to be shifted down by approximately 12%. This is beneficial in the situation where the programmed frequency lands in a region that causes interference.

2.2 Auto-Frequency and Mapping Mode

Each auto-frequency-enabled device has a linear and an exponential current mapping mode. Linear-mapped mode forces the LED current to follow a proportional response for each 11-bit LSB change in I2C (BRT) × PWM Duty Cycle. In exponential-mapped mode the LED current follows an exponential response of 0.3% per each 11-bit LSB change in I2C (BRT) × PWM duty cycle. Due to this different mapping, the equivalent brightness code that corresponds to a specific LED current is different whether in linear mode or in exponential mode. This results in a different auto-frequency threshold for the same LED current, depending on the mapping mode (see Table 3 and Table 4) .

For example, assume the optimal auto-frequency thresholds is 10 mA/string for the high threshold and 5 mA/string for the low threshold. Using the LM36923H (I_{LED_MAX} = 25 mA) we get the following:

Linear Mode: 5mA per string corresponds to 51d (0x33) for Auto-Frequency Low and 10mA per string corresponds to 102d (0x66) for Auto Frequency High. These can be found by (1)

$$Code(D) = \frac{ILED}{ILED\_MAX} \times 255 \tag{1}$$

Exponential Mode: 5mA/string corresponds to 189d (0xBD) for Auto-Frequency low and 10mA/string corresponds to 218d (0xDA) for Auto-Frequency high. These can be found by (2)

$$Code\ (D) = \frac{LN\left(\frac{ILED \times 500}{ILED\_MAX}\right)}{0.02432} \tag{2}$$

2.3 Auto-Frequency and PWM

One advantage of the devices with Auto-Frequency mode (see Table 1) is their ability to automatically optimize the switching frequency based on both the programmed I2C brightness code and the PWM input duty cycle. If PWM is enabled, the LED current becomes a function of I2C (BRT) × PWM (Duty Cycle). In these devices the PWM input is sampled and converted to an 11-bit code. This 11-bit code is multiplied with the 11-bit I2C brightness code and the result is rounded to 11 bits. This 11-bit result is then considered the effective brightness code. Table 2 shows an example of the effective brightness code with and without PWM enabled. The last column (MSB's of Effective Brightness Code) is used in the comparison against the Auto-Frequency Threshold Registers.

Table 2. Auto Frequency Comparison Example

I2C Brightness Register (MSB)	I2C Brightness Register (LSB)	11 Bit I2C Brightness Code	PWM	PWM Input	Effective Brightness Code	MSBs of Effective Brightness Code
0xCC	0x05	0x665	Disabled	Don't Care	0x665	0xCC
0xCC	0x05	0x665	Enabled	D = 40%	0x665 × 0.4 = 0x28F	0x51

To help illustrate the Auto-Frequency mode, Figure 1 shows the functional block diagram for the current control in the Auto-Frequency enabled back-light drivers.

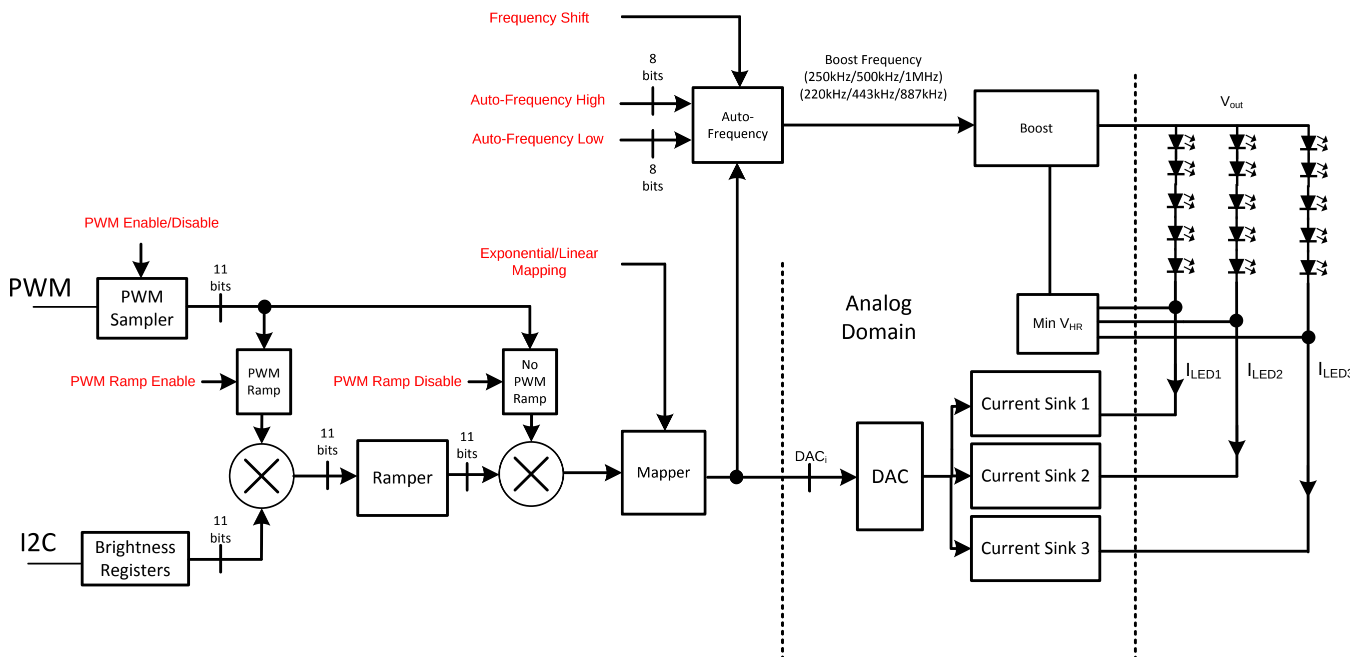

Figure 1. Current Control Block Diagram

3 Auto-Frequency Thresholds vs Operating Conditions

Various operating conditions can affect the optimum threshold for the Auto-Frequency switch point. These are primarily (input voltage, diode capacitance, and inductor DC resistance). Figure 2, Figure 3, and Figure 4 show the variation from nominal when each of these operating conditions are varied. The nominal operating conditions are with (the LM36923H configured with 2P8S (V_F = 3.25V/LED), L = 4.7 µH (R_L = 0.1 Ω), C_D = 20 pF).

3.1 Auto-Frequency Threshold vs Input Voltage

Varying (V_{IN}) effects the optimal auto-frequency thresholds mostly from the variation in the inductor peak-to-peak ripple current and the boost duty cycle. Both of these change the amount of conduction losses in the inductor, power switch, and diode. Figure 2, shows the variation in optimum auto-frequency thresholds of the LM36923H for a typical Li+ voltage range: 3 V (minimum), 3.7 V (typical), and 4.2 V (maximum).

Typically the auto-frequency threshold would be selected at the nominal (or average) operating input voltage. For single cell Li+ input range this is 3.7 V.

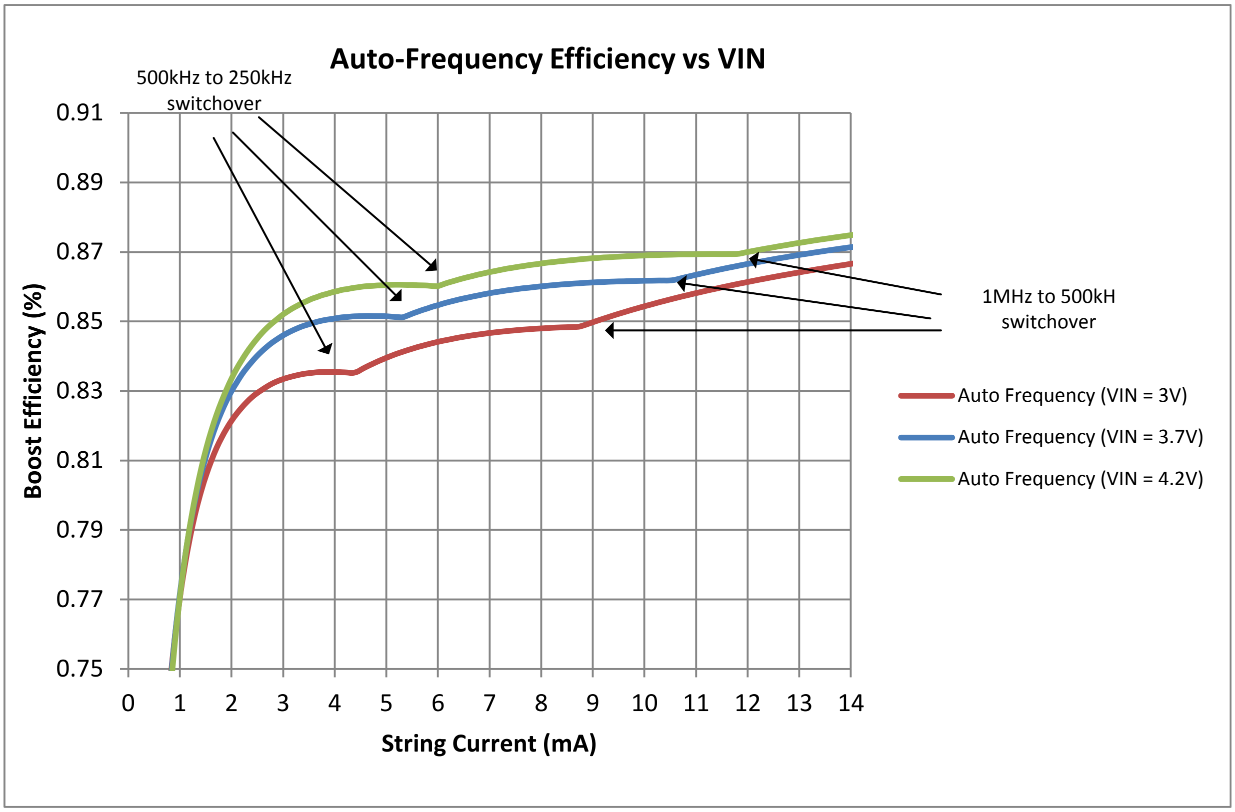

Figure 2. Auto-Frequency Threshold With Different Input Voltages

3.2 Auto-Frequency Thresholds vs Diode Selection

The Schottky diode selection can have the largest impact on the optimal transition point for the Auto-Frequency threshold. This is primarily due to the amount of capacitance from the diode that gets added to the boost switching node. This can add anywhere from 20 pF to 200 pF, which can drastically alter the amount of boost switching losses. Figure 3 shows the optimal auto-frequency efficiency response when the diode capacitance changes from the nominal conditions (20pF) to a larger diode with 160 pF.

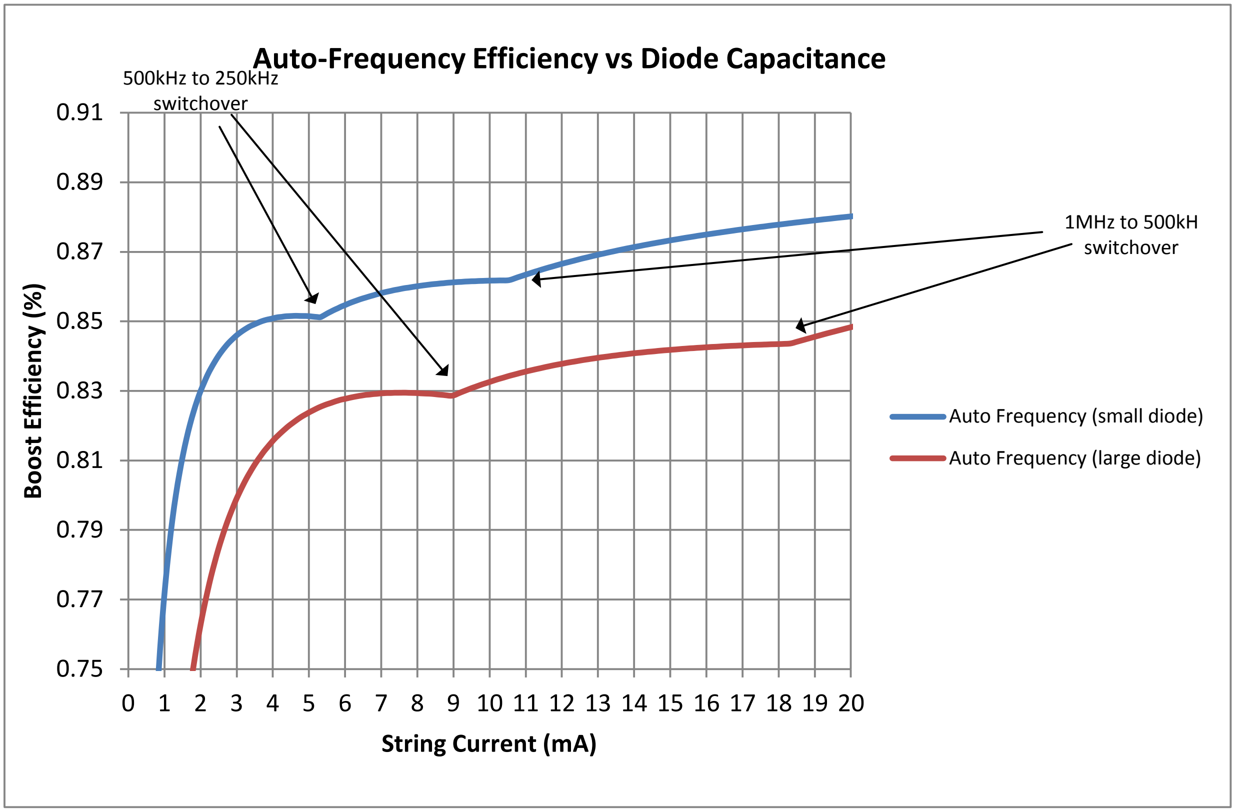

Figure 3. Auto-Frequency Threshold With Different Schottky Diodes

3.3 Auto-Frequency Thresholds vs Inductor Resistance

Inductor DC resistance can vary widely for a specific value inductor for a given application. This causes the conduction losses to have a slight variation around the auto-frequency thresholds. Figure 4 shows the optimized high and low auto-frequency threshold for two different values of the inductor DC resistance (L = 4.7-µH). The low threshold has less variation than the high threshold due to the lower inductor currents at the frequency shift point.

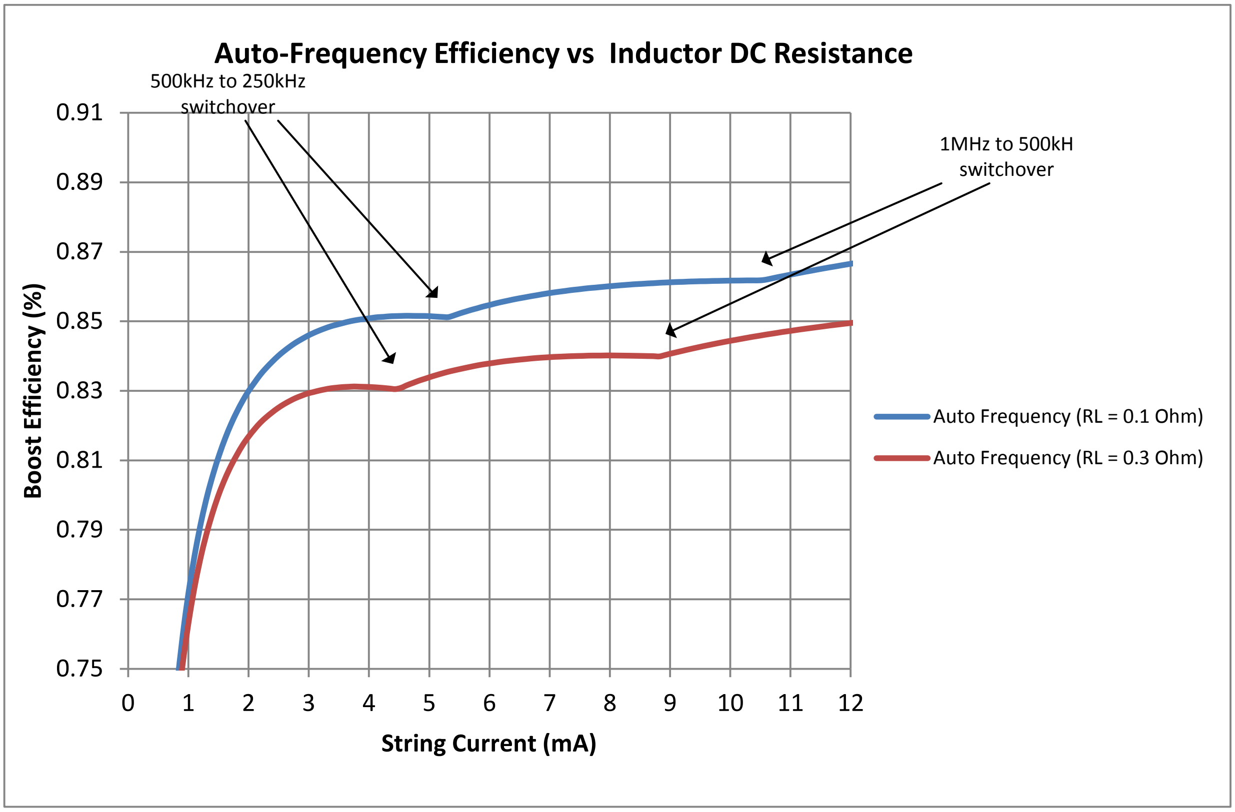

Figure 4. Auto-Frequency Threshold With Different Inductor Resistance

3.4 Typical Target Thresholds

Table 3 and Table 4 list typical thresholds for the LM3692x and LM3627x devices. These typical thresholds can be used with good results for a wide range of components and operating conditions. However, for optimum results where the components and/or operating conditions vary widely from the those listed, the optimum auto-frequency thresholds would need to be further evaluated.

Table 3. LM36272/3/4 Typical Setting for Auto Frequency High and Low Threshold (V_{IN} = 3.7 V, Schottky = NSR0530P2, L = VLF403212MT-4R7/100/150, V_F = 3.3 V at I_{LED} = 30 mA)

Device	Configuration	Inductor Value	Low TH (mA)/String	High TH (mA)/String	Mode	Auto-Frequency Low Code	Auto-Frequency High Code
LM36272/3/4	2P4S	4.7 µH	5.7825	10.5795	Linear	0x31	0x5A
					Exponential	0xBC	0xD5
		10 µH	6.6015	11.983	Linear	0x38	0x66
					Exponential	0xC2	0xDA
		15 µH	6.7185	12.568	Linear	0x39	0x6B
					Exponential	0xC2	0xDC
	2P5S	4.7 µH	5.5485	10.3455	Linear	0x2F	0x58
					Exponential	0xBA	0xD4
		10 µH	6.2505	11.866	Linear	0x35	0x65
					Exponential	0xBF	0xDA
		15 µH	6.3675	29.9	Linear	0x36	0xFF
					Exponential	0xC0	0xFF
	2P6S	4.7 µH	5.4315	10.4625	Linear	0x2E	0x59
					Exponential	0xBA	0xD5
		10 µH	6.0165	11.515	Linear	0x33	0x62
					Exponential	0xBE	0xD8
		15 µH	6.2505	29.9	Linear	0x35	0xFF
					Exponential	0xBF	0xFF
	2P7S	4.7 µH	5.1975	10.2285	Linear	0x2C	0x57
					Exponential	0xB8	0xD4
		10 µH	6.1335	11.866	Linear	0x34	0x65
					Exponential	0xBF	0xDA
		15 µH	6.4845	29.9	Linear	0x37	0xFF
					Exponential	0xC1	0xFF
	2P8S	4.7 µH	5.3145	10.3455	Linear	0x2D	0x58
					Exponential	0xB9	0xD4
		10 µH	6.1335	15.259	Linear	0x34	0x82
					Exponential	0xBF	0xE4
		15 µH	6.2505	29.9	Linear	0x35	0xFF
					Exponential	0xBF	0xFF

Table 3. LM36272/3/4 Typical Setting for Auto Frequency High and Low Threshold (V_{IN} = 3.7 V, Schottky = NSR0530P2, L = VLF403212MT-4R7/100/150, V_F = 3.3 V at I_{LED} = 30 mA) (continued)

LM36273/4	3P4S	4.7 µH	3.9105	7.0695	Linear	0x21	0x3C
					Exponential	0xAC	0xC4
		10 µH	4.4955	8.0055	Linear	0x26	0x44
					Exponential	0xB2	0xC9
		15 µH	4.4955	8.4735	Linear	0x26	0x48
					Exponential	0xB2	0xCC
	3P5S	4.7 µH	3.677	6.9525	Linear	0x1F	0x3B
					Exponential	0xA9	0xC4
		10 µH	4.1445	7.8885	Linear	0x23	0x43
					Exponential	0xAE	0xC9
		15 µH	4.4955	12.1	Linear	0x26	0x67
					Exponential	0xB2	0xDA
	3P6S	4.7 µH	3.56	6.8355	Linear	0x1E	0x3A
					Exponential	0xA8	0xC3
		10 µH	4.1445	7.8885	Linear	0x23	0x43
					Exponential	0xAE	0xC9
		15 µH	4.3785	29.9	Linear	0x25	0xFF
					Exponential	0xB1	0xFF
	3P7S	4.7 µH	3.56	6.8355	Linear	0x1E	0x3A
					Exponential	0xA8	0xC3
		10 µH	4.0275	7.7715	Linear	0x22	0x42
					Exponential	0xAD	0xC8
		15 µH	4.2615	29.9	Linear	0x24	0xFF
					Exponential	0xB0	0xFF
	3P8S	4.7 µH	3.56	7.0695	Linear	0x1E	0x3C
					Exponential	0xA8	0xC4
		10 µH	4.1445	9.7605	Linear	0x23	0x53
					Exponential	0xAE	0xD2
		15 µH	4.2615	29.9	Linear	0x24	0xFF
					Exponential	0xB0	0xFF
LM36274	4P4S	4.7 µH	2.975	5.4315	Linear	0x19	0x2E
					Exponential	0xA1	0xBA
		10 µH	3.326	6.0165	Linear	0x1C	0x33
					Exponential	0xA5	0xBE
		15 µH	3.443	6.3675	Linear	0x1D	0x36
					Exponential	0xA7	0xC0
	4P5S	4.7 µH	2.741	5.1975	Linear	0x17	0x2C
					Exponential	0x9D	0xB8
		10 µH	3.092	5.8995	Linear	0x1A	0x32
					Exponential	0xA2	0xBD
		15 µH	3.326	8.3565	Linear	0x1C	0x47
					Exponential	0xA5	0xCB
	4P6S	4.7 µH	2.741	5.1975	Linear	0x17	0x2C
					Exponential	0x9D	0xB8
		10 µH	3.092	5.8995	Linear	0x1A	0x32
					Exponential	0xA2	0xBD
		15 µH	3.209	29.9	Linear	0x1B	0xFF
					Exponential	0xA4	0xFF

Table 4. LM36922/22H/23/23H Typical Settings For Auto Frequency High and Low Thresholds (V_{IN} = 3.7 V, Schottky = NSR0530P2, L = VLF403212MT-4R7/100/220, V_F = 3.25 V at I_{LED} = 25 mA)

Device	Configuration	Inductor	Low TH (mA)/String	High TH (mA)/String	Mode	Auto-Frequency Low Code	Auto-Frequency High Code
LM3692xH	2P4S	4.7 µH	5.6055	10.673	Linear	0x39	0x6D
					Exponential	0xC2	0xDD
LM3692x/2xH		10 µH	6.58	11.94	Linear	0x43	0x7A
					Exponential	0xC9	0xE1
LM3692x		22 µH	7.1645	24.9	Linear	0x49	0xFF
					Exponential	0xCC	0xFF
LM3692xH	2P5S	4.7 µH	5.508	10.381	Linear	0x38	0x6A
					Exponential	0xC2	0xDC
LM3692x/2xH		10 µH	6.19	11.94	Linear	0x3F	0x7A
					Exponential	0xC6	0xE1
LM36923		22 µH	6.8725	24.9	Linear	0x46	0xFF
					Exponential	0xCB	0xFF
LM3692xH	2P6S	4.7 µH	5.4105	10.2835	Linear	0x37	0x69
					Exponential	0xC1	0xDB
LM3692x/2xH		10 µH	6.0925	11.648	Linear	0x3E	0x77
					Exponential	0xC6	0xE0
LM3692x		22 µH	6.6775	24.9	Linear	0x44	0xFF
					Exponential	0xCA	0xFF
LM3692xH	2P7S	4.7 µH	5.313	10.381	Linear	0x36	0x6A
					Exponential	0xC0	0xDC
LM3692x/2xH		10 µH	6.0925	11.7455	Linear	0x3E	0x78
					Exponential	0xC6	0xE1
LM3692x		22 µH	6.6775	24.9	Linear	0x44	0xFF
					Exponential	0xCA	0xFF
LM3692xH	2P8S	4.7 µH	5.2155	10.4785	Linear	0x35	0x6B
					Exponential	0xBF	0xDC
LM3692x/2xH		10 µH	6.19	24.9	Linear	0x3F	0xFF
					Exponential	0xC6	0xFF
LM3692x		22 µH	6.58	24.9	Linear	0x43	0xFF
					Exponential	0xC9	0xFF
LM3692xH	2P9S	4.7 µH	5.313	10.673	Linear	0x36	0x6D
					Exponential	0xC0	0xDD
		10 µH	6.19	24.9	Linear	0x3F	0xFF
					Exponential	0xC6	0xFF
LM3692xH	2P10S	4.7 µH	5.313	10.673	Linear	0x36	0x6D
					Exponential	0xC0	0xDD
		10 µH	6.0925	24.9	Linear	0x3E	0xFF
					Exponential	0xC6	0xFF
LM36923H	3P4S	4.7 µH	3.851	7.067	Linear	0x27	0x48
					Exponential	0xB3	0xCC
LM36923/23H		10 µH	4.4355	7.9445	Linear	0x2D	0x51
					Exponential	0xB9	0xD1
LM36923		22 µH	4.8255	24.9	Linear	0x31	0xFF
					Exponential	0xBC	0xFF
LM36923H	3P5S	4.7 µH	3.656	6.775	Linear	0x25	0x45
					Exponential	0xB1	0xCA
LM36923/23H		10 µH	4.1435	7.847	Linear	0x2A	0x50
					Exponential	0xB6	0xD0
LM36923		22 µH	4.6305	24.9	Linear	0x2F	0xFF
					Exponential	0xBA	0xFF

Table 4. LM36922/22H/23/23H Typical Settings For Auto Frequency High and Low Thresholds (V_{IN} = 3.7 V, Schottky = NSR0530P2, L = VLF403212MT-4R7/100/220, V_F = 3.25 V at I_{LED} = 25 mA) (continued)

LM36923H	3P6S	4.7 µH	3.5585	6.8725	Linear	0x24	0x46
					Exponential	0xB0	0xCB
LM36923/23H		10 µH	4.046	7.847	Linear	0x29	0x50
					Exponential	0xB5	0xD0
LM36923		22 µH	4.4355	24.9	Linear	0x2D	0xFF
					Exponential	0xB9	0xFF
LM36923H	3P7S	4.7 µH	3.5585	6.8725	Linear	0x24	0x46
					Exponential	0xB0	0xCB
LM36923/23H		10 µH	4.046	7.847	Linear	0x29	0x50
					Exponential	0xB5	0xD0
LM36923		22 µH	4.4355	24.9	Linear	0x2D	0xFF
					Exponential	0xB9	0xFF
LM36923H	3P8S	4.7 µH	3.5585	6.9695	Linear	0x24	0x47
					Exponential	0xB0	0xCB
LM36923/23H		10 µH	4.046	10.186	Linear	0x29	0x68
					Exponential	0xB5	0xDB
LM36923		22 µH	4.533	24.9	Linear	0x2E	0xFF
					Exponential	0xBA	0xFF
LM36923H	3P9S	4.7 µH	3.5585	6.9695	Linear	0x24	0x47
					Exponential	0xB0	0xCB
		10 µH	4.046	24.9	Linear	0x29	0xFF
					Exponential	0xB5	0xFF
			4.533	24.9	Linear	0x2E	0xFF
					Exponential	0xBA	0xFF
LM36923H	3P10S	4.7 µH	3.5585	7.067	Linear	0x24	0x48
					Exponential	0xB0	0xCC
		10 µH	4.046	24.9	Linear	0x29	0xFF
					Exponential	0xB5	0xFF
			4.533	24.9	Linear	0x2E	0xFF
					Exponential	0xBA	0xFF

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