A Single-Inductor Multiple-Output Converter with Peak Current State-Machine Control

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***Abstract*- An integrated Single-Inductor multiple positive/negative output dual-loop DC-DC converter with multiplexed rectifiers for TFT LCD Display supply will be presented. The converter operates with a tiny chip-size Inductor. Based on the physical behavior of the inductor a very robust power stage will be shown, which can service an unlimited number of positive and negative output channels with a single inductor. All the different voltage levels (positive and negative) will be regulated independently on a cycle by cycle base. There are two different types of regulation loops running in the converter. The control of the individual channels is managed by a STATE MACHINE (first loop) which takes care of the power stage switching pattern and allows the hysteretic converter to run in a pseudo continuous current mode to guarantee a high power conversion capability. The second loop works as a variable peak current control to minimize the inductor current. It will be demonstrated why running with a controlled peak current also yields in a small output voltage ripple and how the state-machine can help to further control the amount of energy delivered into one output channel. To achieve even lower ripple voltages below 10mV and high accuracy the main output is post-regulated by a tracking current-mode LDO. Finally the whole TPS6512X architecture with the multi-output converter, LDO's and control circuitry will be shown. The converter with 4.5ksqmil chip-size fits in a 16-pin 3x3 QFN Package. Due to the high maximum switching frequency of the device a single, inexpensive and ultra-thin 10µH inductor can be used, which offers a very compact and small power supply solution to provide all voltage levels required by small form-factor TFT-LCD panels.**

I. Introduction

Small Form Factor Active Matrix LCD Thin Film Transistor (TFT) Displays are used in a large percentage of portable equipments (e. g. Cellular Phones, PDA's, Digital Still Cameras, MP3-Players…). Apart from the energy requirement for the backlight, these displays need several (3+) different positive- and negative supply- and bias voltages which are generally not available in the system [1]. Depending on the display technology one would need up to +/- 20V for the poly silicon thin film transistor bias and up to 5.3V for the main driver supply.
All this different voltages usually need to be generated from a single LI-ION cell. The total power consumption for the display bias is in the range of 75mW to 150mW, mainly depending on the physical size of the display. Traditional LCD power supplies use either multiple Charge Pumps, inductive based switching converters with multiple inductors or combinations of both. The major disadvantages of all these solutions are a large amount of external components (inductors and/or capacitors) and high pin-count (up to 24pins) packages. Especially Charge Pump solutions are very unattractive due to their limited voltage conversion capability per storage capacitor and their efficiency being linked to the V_{IN}/V_{OUT} ratio.

II. Chip Inductors – The "Ideal" Storage Element for Low Power Ratings

The latest inductor developments from companies like Taiyo Yuden or TDK offer a large variety of chip inductors in small packages. E.g. the Taiyo Yuden "CBL2012T100M" [2] inductor with 10uH inductance is rated for 205mA (max) and is available in a 0805 package with 0.9mm height.
The performance if this inductor is illustrated in Fig. 1. In Discontinuous Conduction Mode (DCM) and Continuous Conduction Mode (CCM) the maximum possible power which can be transferred with an inductor is:

DCM: $$P_{MAXDCM} = \frac{I_{PEAK}}{2} * V_{IN} \quad (1)$$

CCM: $$P_{MAXCCM} = \left[I_{PEAK} - \frac{V_{IN}\left(1 - V_{IN}/V_{OUT}\right)}{2\, f_{CLK} * L} \right] * V_{IN} \quad (2)$$

Using an L=10uH inductor with $I_{PEAK} = 0.2A$, V_{IN}=2.5V (min voltage of a LI-ION cell), V_{OUT}=10V and f_{CLK}=2MHz this would result in a theoretically available output power of 250mW in DCM and 380mW in CCM. So even when we would have an over-all efficiency of just 70% and the inductor is operated in DCM, there is about 175mW available on the output of the converter which will be sufficient to fulfill the LCD-panel power requirement.

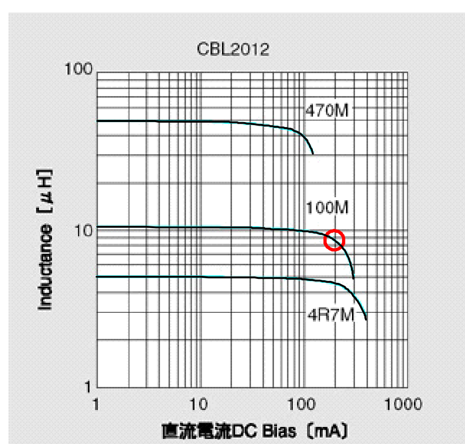

Fig. 1. Taiyo Yuden "CBL2012T100M" Inductance over DC-bias

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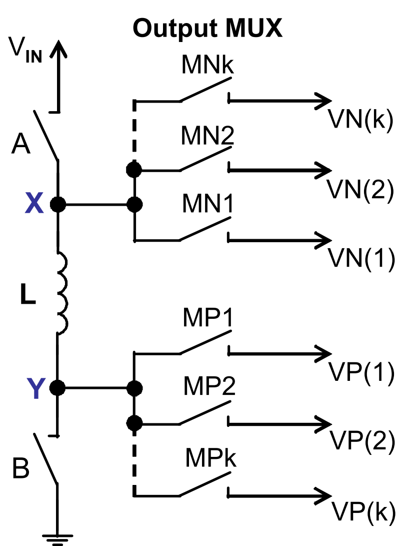
III. SINGLE-INDUCTUR- MULTIPLE OUTPUT CONVERTER

The major advantage of an inductor used as an energy storage element compared to a capacitor comes from the fact that inductive converters can theoretically generate unlimited voltage conversion ratios. It is possible to produce 20V from 2.5V with a single inductor boost converter running at a high duty ratio but it takes four! "flying" capacitors to do the same job with Charge Pumps. Having this advantage of inductive converters, the power requirements of TFT displays and the capabilities of the latest chip-size inductors in mind, a single inductive storage element in 0805 package may be used to produce all the required voltages of the display module.

A. The Operating Principle

Similar to the converters presented in [3]-[6] which run in a multiplexed constant frequency PWM scheme, the Output Power Stage of the Single-Inductor Multiple-Output converter illustrated in Fig. 2. also takes benefit of this physical behavior of an inductor which is loaded with a certain current (switches A and B are closed).



Operating Pattern

Operation	Switch A	Switch B	Output MUX
Load Ind	ON	ON	----
VN(1)		ON	MN1
VN(2)		ON	MN2
VN(k)		ON	MNk
VP(1)	ON		MP1
VP(2)	ON		MP2
VP(k)	ON		MPk

Fig. 2. Multi-Output Single-Inductor Converter (principle)

Since the current in an inductor cannot make a discontinuous step the inductor always generates a voltage with reverse polarity across its nodes when disconnected from the supply. For the positive inductor node "X" getting open (switch A off) this node goes negative (below GND), since the inductor tries to keep the current running the same direction and magnitude than before. Due to the same reason a positive voltage (above V_{IN}) is generated on node "Y" if switch B is switched off and disconnects the negative node of the inductor from the supply. In these two situations the multiplexing switches MN1…MNk and MP1…MPk determine which output VN(1)…VN(k) and VP(1)…VP(k) is getting the energy stored in the inductor. When the inductor is periodically loaded with current (switches A and B closed), each output VN and VP can be supported with energy on a cycle by cycle base.

B. The Power Output Stage

The Converter Output stage which is shown in Fig. 3 needs to generate 2 Positive voltages (V_{GH} and V_{BOOT} and one negative Voltage (V_{GL}). Therefore there is just a need for one 2-Channel MUX (N2+D1/P2 and N3+D2) for the positive voltages. The "V_{BOOT}"- channel requires about 70% of the total output power and needs to produce a relatively low voltage level compared to V_{GH} and V_{GL}, therefore a synchronous rectifier "P2" runs in parallel to the Schottky Diode D1 to enhance efficiency. Compared to standard boost converters back-to back isolated rectifiers in the output multiplexers are required, otherwise to lower positive output voltage would always clamp the higher one. Since there is only one negative output needed there is just a single (off-chip) Schottky Diode D3 necessary for the negative rectification. The transistors N1 and P1 connect the "flying" inductor L to the supply terminals.

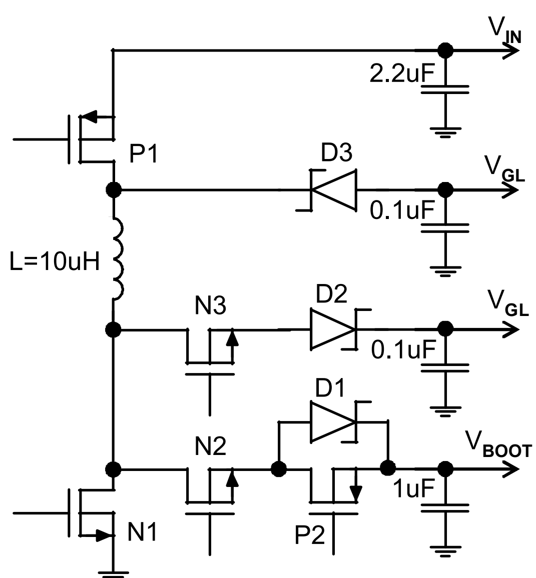


Fig. 3. Power Output Stage of TPS65120

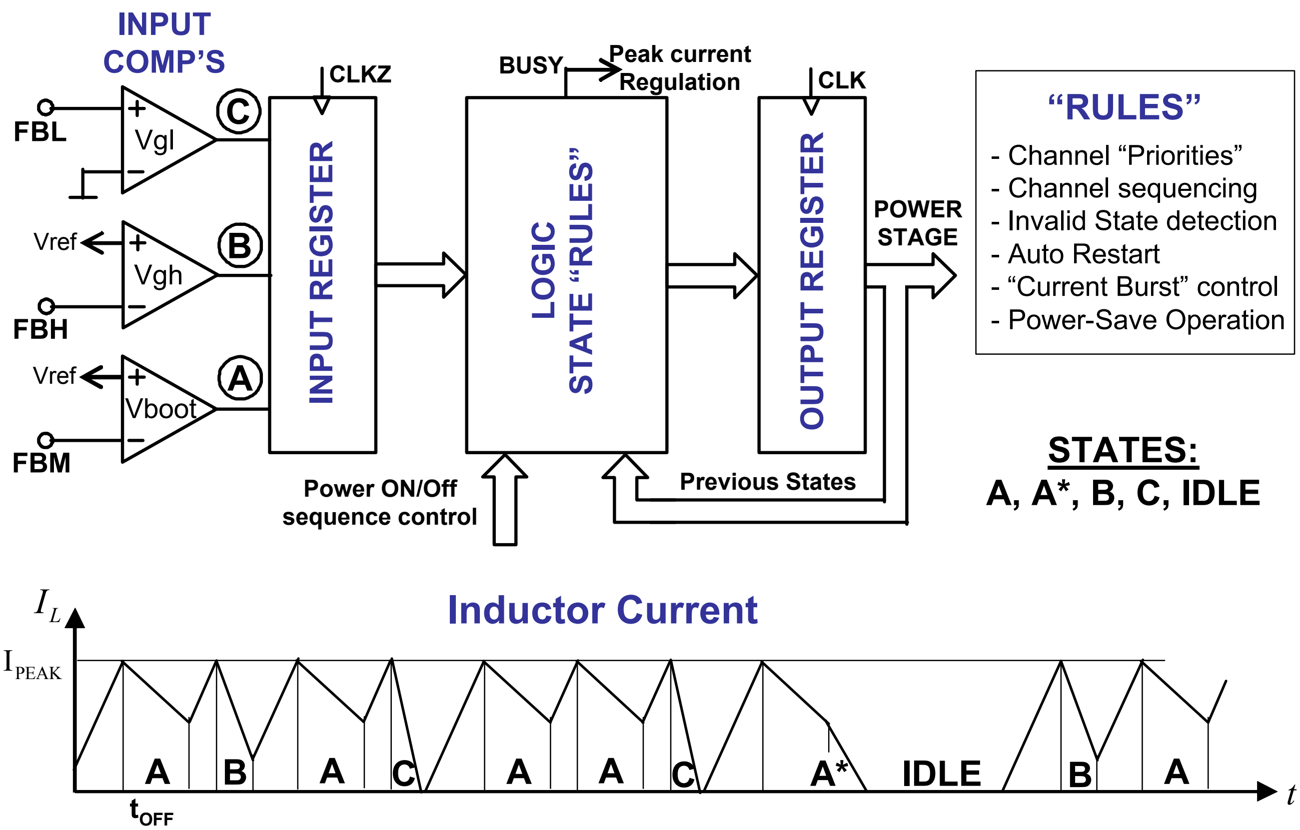


Fig. 4. STATE_MACHINE with Hysteretic CCM control

C. STATE-MACHINE with Hysteretic CCM Control

A State-Machine (see Fig. 4) determines the switching pattern of the Output Power Stage. To regulate the individual output voltages a separate comparator for each channel V_{GL}, V_{GH}, V_{BOOT}, measures the voltage-level on the respective output and checks if it needs to be serviced. The result of this measurement is then stored in the Input Register of the State-Machine. The logic part of the State-Machine takes the input-output (previous states) and sequence control information and "calculates" the next state of the Power Stage. This state is finally stored in the Output Register. As long as at least one of the three channels signals lacking of power the State-Machine periodically toggles between Inductor-Charge- and Transfer Phase and services the individual outputs according to the "Rules" in the Logic. A "BUSY"-signal is generated during this time which controls the Power-Save operation and Peak Current regulation. Since an inductor with a given saturation current can transfer up to two times the power in CCM compared to DCM, CCM should be the preferred mode of operation. Whereas the Multi-Output Converters described in [3] … [6] just can run in DCM-PWM operation with good cross-regulation performance, the Multiple-Output Single-Inductor Converters in [7] (buck) and [8] (boost) run in CCM operation still with PWM control and acceptable cross-regulation but with extremely complex control circuits and additional switches.

Due the nature of the control scheme in Fig. 4. being pure "hysteretic", the State-Machine can simply run with a fixed Off-Time t_{OFF} and Peak Current Control without taking care of the actual current value when initiating a new On-State. Since at the begin of the Off-State the inductor always is loaded with a defined peak current, independent on the previous state , a hysteretic CCM operation with Peak Current Control of the Multiple-output Converter still yields in a negligible output cross-regulation.

D. Adaptive Peak-Current Control

The frequency of a hysteretic converter with constant Peak Current Control is directly coupled to the load on the converter outputs, so at light loads with the "IDLE" State being dominant the effective operation frequency will move down into the audio range. To avoid this, the inductor peak current is adjusted accordingly to the duty ratio on the State-Machine- "BUSY" signal. This means that for low duty ratios on "BUSY" (light load) the peak inductor current is being reduced which also means a smaller amount of energy being delivered to the individual outputs during each inductive transfer phase. Now again the input comparators of the three channels more often ask for being serviced, which will reduce the converter "IDLE" rate (duty cycle of "BUSY" signal increases).

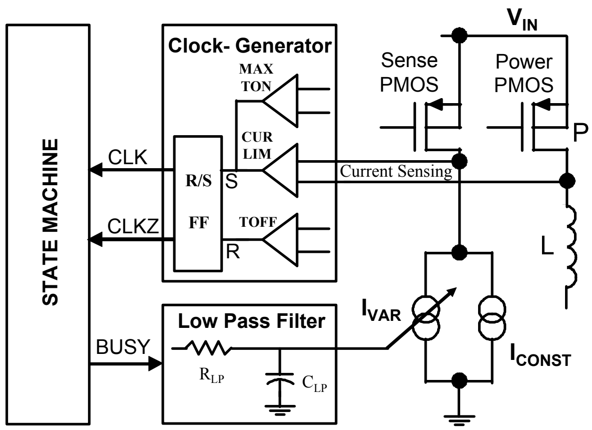


Fig. 5. Adaptive Peak Current Control

As a result the effective operating frequency will stabilize to a fixed value. To keep the efficiency up and to guarantee a reliable operation at light loads it must be avoided that the converter runs at high switching frequency with extremely small inductor currents since in this situation the switching losses may be higher than the required output power. Therefore a constant sense current I_{CONST} is put in parallel to the controlled sense current I_{VAR}. The effect will be that the converter stops to reduce the inductor peak current at light load at a limit which is determined by the value of I_{CONST}. The implementation of the Adaptive Peak Current regulation is illustrated in Fig. 5.

So there are two different types of regulation loops running in the converter. A hysteretic loop is taking care of the individual output voltages and the low-frequency Peak Current Regulation loop adjusts the inductor current to the output power. This mode of operation works in a similar way like "Active-Cycle Control" [9]. A positive effect of the converter running with a controlled peak current is that the output voltage ripple and noise gets reduced. Additionally the user can choose an inductor with lower current rating when he wants to drive displays which do not require the full output power so the converter can be used more universal for different LCD panels.

E. Low Ripple Operation

Small output voltage ripple is a key requirement to the converter. The output voltage ripple in CCM comes with:

$$V_{RIPPLE(CCM)} = \left(I_{PEAK} - \frac{V_L t_{OFF}}{2\,L} \right) * \frac{t_{OFF}}{C_{OUT}} \qquad (3) \quad \text{with}$$

$$V_L = V_{OUT} - V_{IN} \ (\textit{positive Output}) \qquad (4)$$

$$V_L = V_{OUT} \ (\textit{negative Output}) \qquad (5)$$

Whereas the ripple in CCM-Mode is well under control, the mayor limitation comes from the "Final" state of a current burst.

Before the device can enter the "IDLE" State (see Fig. 4.) the inductor current must decay to zero. For a positive output, the "Final" Off-Time of this last pulse is proportional to the ratio: $1/(V_{OUT}-V_{IN})$ which can be much longer than the Off-Time during a CCM burst. The voltage glitch generated by the "Final" DCM pulse is:

$$V_{RIPPLE(DCM)} = \frac{L}{C_{OUT}} * \frac{I_{PEAK}^2}{2V_L} \qquad (6)$$

Since we want to keep the efficiency at a high level, "burning" the remaining energy of the inductor in a resistor is not an option, so one output has to take the remaining power. Here the V_{BOOT}-output is the "ideal" candidate for this job due to the fact that there will be an LDO post regulator with high PSRR [10] connected to this output for additional ripple rejection anyway. So simply after each V_{GH}- or V_{GL}-State a V_{BOOT}-State is automatically initiated from the State-Machine such that a V_{BOOT}-State is always the "Final" state of a current burst.

So we cannot avoid the "Final" state with higher energy in a current burst, but the State-Machine can lead this energy to one special output where additional measures (LDO) can be taken to further reduce the ripple.

IV. Practical Realization of the Converter

The TPS65120 [11] device was fabricated in Texas Instrument LBC4X BI-CMOS process which offers both high voltage (up to 60V) LDMOS, Extended Drain HV-PMOS transistors (up to 50V), high voltage Schottky Diodes (up to 60V) and Bipolar Transistors in combination with low pitch 1u CMOS logic on a monolithic chip.

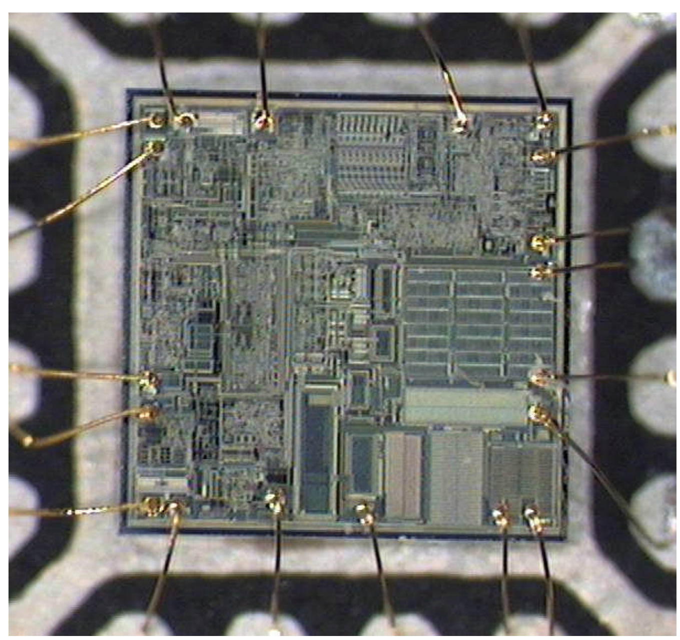


Fig. 6. Chip Photo of TPS65120 Single-Inductor Multiple-Output Converter

Additional to the core regulator blocks (State-Machine, Power-Stage, Clock-Generator and Current- Regulation) some further support functions are implemented. Two Current-Mode LDO's [10] generate low-ripple output voltages on V_{MAIN} and V_{AUX}. The programmable Power ON/OFF sequence controller in combination with the Pre-Charge circuit determines the Output Voltage sequence at Power up and -down of the LCD Panel. A Band-gap reference (VREF/IREF) delivers all internal reference voltages and bias currents. Finally all the trimming information is stored in an on-chip EEPROM device. All the display output voltages can be user-adjusted via external resistive dividers. There are four different versions of the TPS65120 available: The TPS65120 … TPS65123 offer a fixed V_{MAIN}, V_{GH} and V_{GL} Power ON and OFF sequence. The various output voltages of TPS65124 can be independently enabled and disabled.

A summary of all basic features of the device can be found in Table. 1. The architecture of the TPS6512X device can be seen in Fig. 7.

Table 1. Features of TPS 65120

- Process: LBC4X
- CHIP-Size: 1700um x 1700um (4.5kmil²)
- Main Output, VMAIN
  Adjustable from +3.0V to +5.6V / 20mA
  Low Ripple (10mVpp) ±1% Accuracy
- Converter Core Efficiency: up to 83%
- Positive Output, VGH
  Adj. up to +20V / 2mA; ±3% Accuracy
- Negative Output, VGL
  Adj. down to -18V / 2mA; ±3% Accuracy
- Auxiliary Output 1.8V to 3.3V / 20mA
- Peak Current Regulation: 50mA…200mA
- Maximum Operating Frequency: 4MHz
- Automatic or Programmable Sequencing
- +2.5V to +5.5V Input Voltage Range
- Outputs Short Circuit Protected
- 16-Pin QFN Package (3x3x0.9mm)

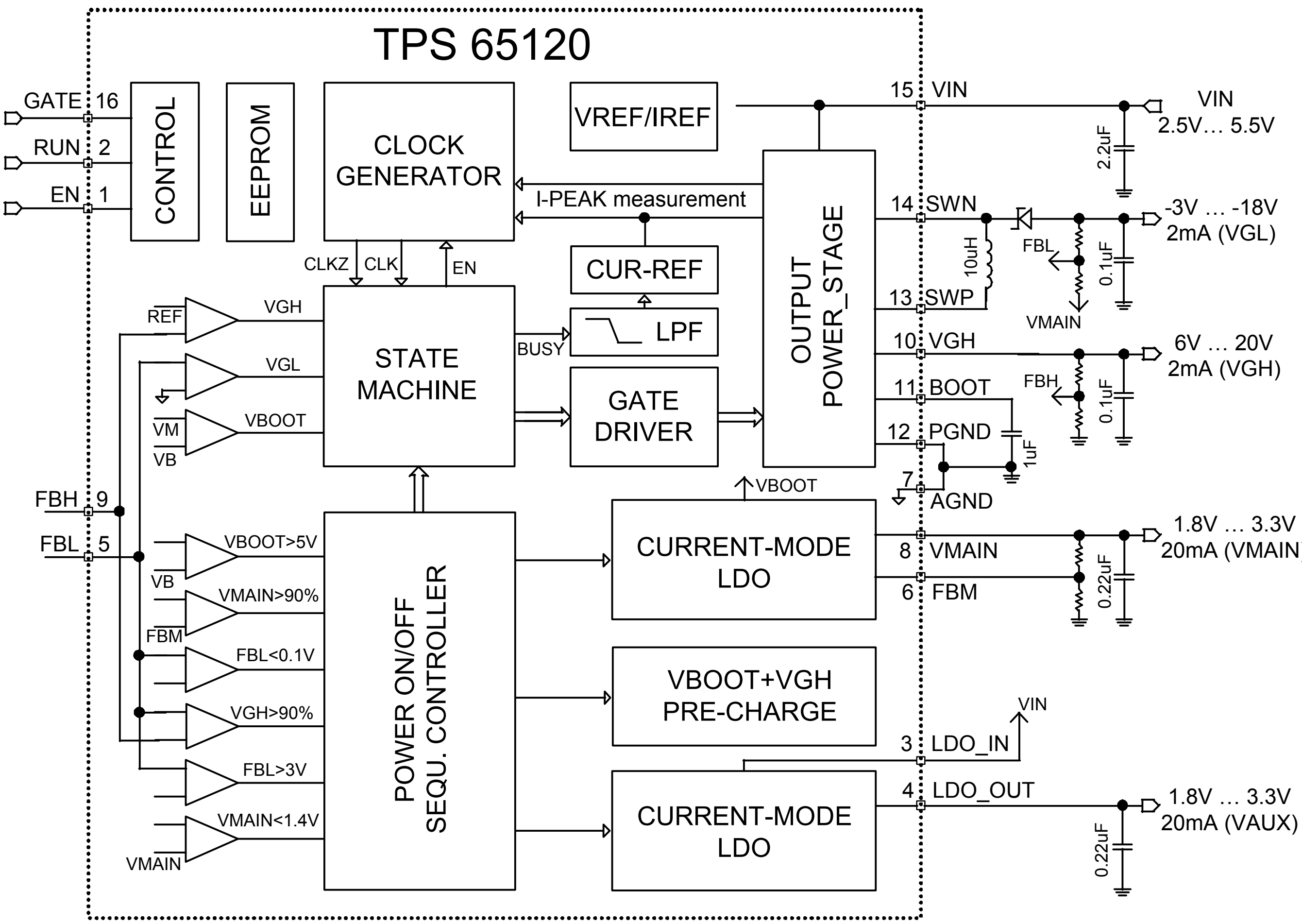


Fig. 7. TPS65120 Block Diagram

The core converter efficiency of TPS65124 is illustrated in Fig. 8. The device is operated with different inductor types with a variable load current (I_{BOOT}) at the BOOT terminal. The measurements were performed with an input voltage (V_{IN}) of 3.6V an output voltage (V_{MAIN}) of 5.0V. V_{GH} and V_{GL} run at +/- 12V with a constant load of 100uA. It can be seen that the influence of the inductor to the efficiency is in the range of 5% at full load which mainly comes from the series resistance and the core quality of the inductor.

Fig 9. shows the output voltage variation at the V_{GH} output with variable supply voltage and load current (line- and load regulation). The measurements were done under a constant load at V_{MAIN} (5.3V/100uA) and V_{GL} (-18V/100uA) when V_{IN} is varied from 2.30V to 5.50V and I_{OUT} is swept from 0.1mA to 4mA V_{GH} varies approximately by 0.9%.Similar to the contents in Fig. 9., Fig. 10. shows the line- and load regulation of V_{GL} with V_{MAIN} held at 5.3V with 100uA load and V_{GH} adjusted to 19V at 100uA .

The cross-regulation of V_{GL} with a variable load at V_{GH} (0.1mA to 4mA) and variable V_{IN} is illustrated in Fig. 11.

Fig. 12. shows the cross-regulation of V_{GH} with the same test procedure (load now swept at V_{GL}) like in Fig.11.

Finally, Fig. 13. shows the influence of a variable load at V_{GH} to the output V_{MAIN} at different V_{IN} steps.

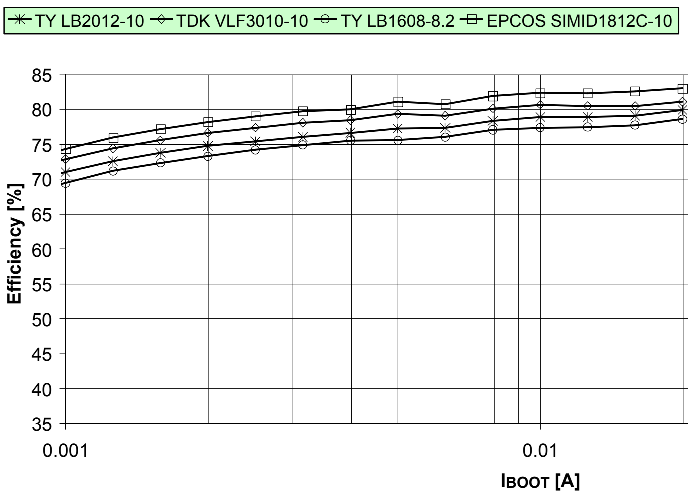


Fig. 8. TPS65120 Efficiency vs. I_{BOOT} for different Inductors (V_{IN}=3.6V)

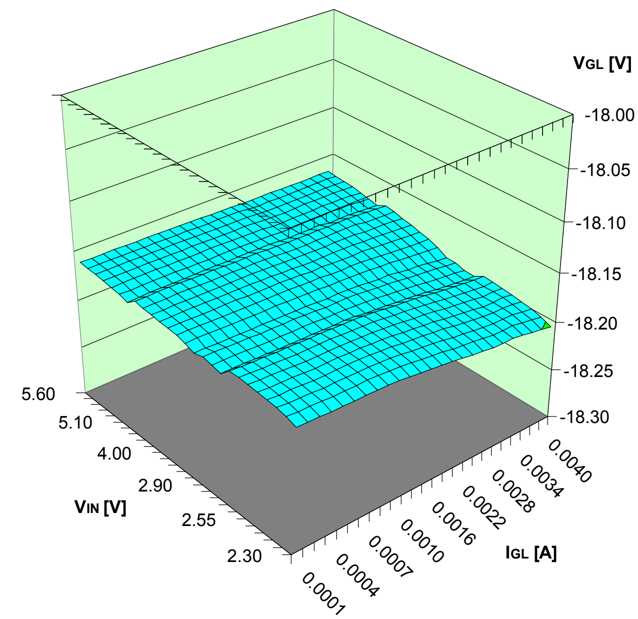


Fig. 10. Line- and Load Regulation at the output V_{GL}

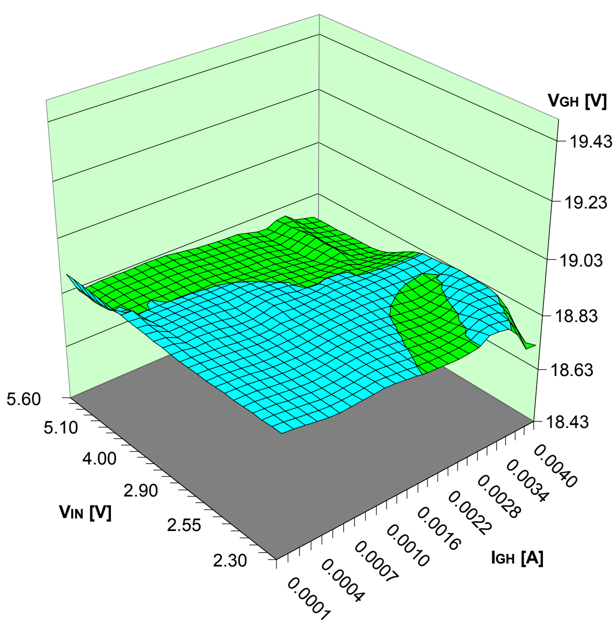


Fig. 9. Line- and Load Regulation at the output V_{GH}

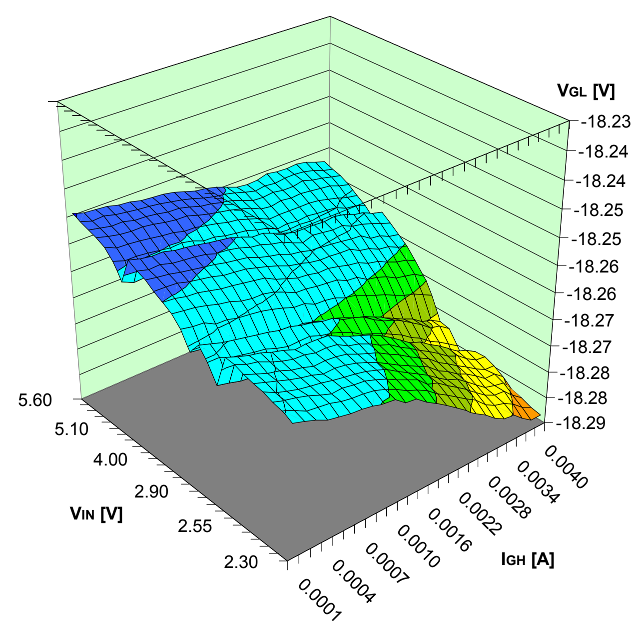


Fig. 11. Cross-Regulation at V_{GL} with variable load at V_{GH} and variable V_{IN}

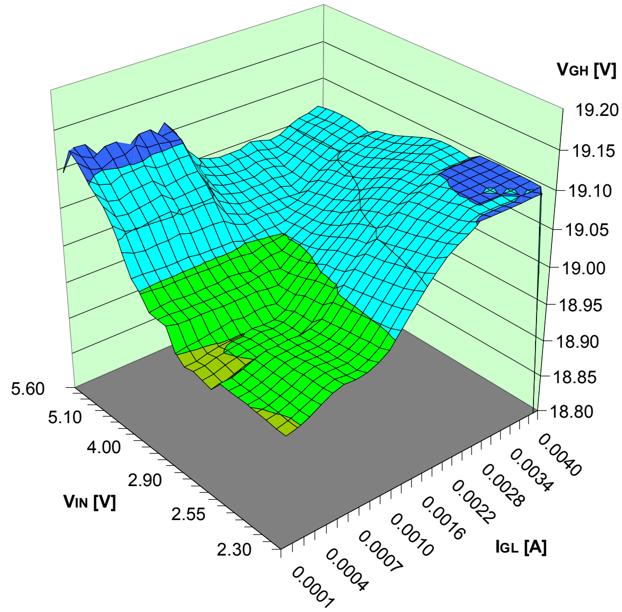


Fig. 12. Cross-Regulation at V_{GH} with variable load at V_{GL} and variable V_{IN}

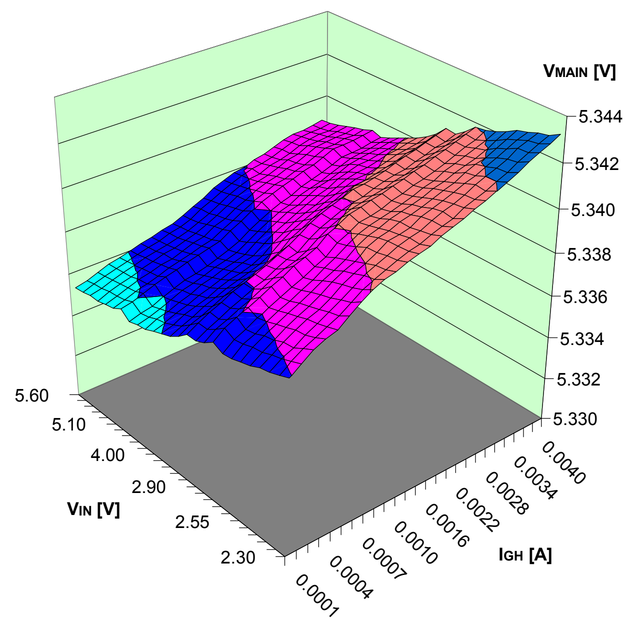


Fig. 13. Cross-Regulation at V_{MAIN} with variable load at V_{GH} and variable V_{IN}

To summarize one can say that, independent on the test conditions above, all outputs of the TPS6512X Single-Inductor Multiple-Output Boost Converter are regulated within 1%.

V. Conclusion

The TPS65120 Single-Inductor Multi-Output DC/DC converter in 16-pin 3X3 QFN package offers a very compact Power Supply solution to provide all Bias- and Supply voltages required by small Form-Factor TFT LCD Panels. Compared to Charge Pump or multi-inductor solutions with a large amount of external energy storage elements and high pin-cont packages just one inductor in 0805 package is used in a time-multiplexed way, managed by a State-Machine which controls the Power Stage switches and allows the hysteretic converter to run in a Pseudo Continuous Conduction Mode. This new CCM operation in combination with Multi-Output Converters allows up to two times the power-level conversion capability compared to standard DCM operation. The inductor peak current is regulated in an additional loop. The combination of Hysteretic Control of the individual channels and Adaptive Peak Current Control provides a good line- and load transient response while maintaining a relatively constant switching frequency and high efficiency over a wide supply voltage- and load current range with negligible cross-regulation.

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