Application Report

Step-Down (Buck) Converter Power Solutions for Programmable Logic Controller Systems

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ABSTRACT

A programmable logic controller (PLC) is an industrial computing system that is used to control manufacturing processes of assembly lines and other factory automation equipment that require a highly reliable control method and fault diagnosis. The PLC system is comprised of analog and digital input and output modules, a communication module, a CPU module, a control module, and a power supply. The modules within the PLC system contain of many different integrated circuit sub-systems requiring a power solution, such as an analog front-end (AFE), backplane communication, digital processing microcontrollers, FPGAs, wired or wireless interfaces, clocking, memory and user interfacing. PLCs operate in harsh, rugged manufacturing environments and require special attention when designing a non-isolated point-of-load power solution. Designers must consider the point of load bus architecture, solution size, thermal limitations, noise issues, and processor power concerns.

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1 Point-of-load Architecture Considerations

PLCs benefit from a DC/DC point of load power solution that supports the needs of advanced analog and digital integrated circuits, offers high efficiency with good thermal performance, and reduces the overall component count and cost. Point of load strategies can vary, but PLCs are usually provided a 24-VDC input supply from the power supply or occasionally a 12-VDC input. However, the line voltage is susceptible to input voltage transients that originate from motors or relays, causing excessive voltage spike which can damage the system. Voltage spikes also come from power transmission wires routed longer distances introducing parasitic inductance loops causing problems to the DC/DC converters. It is good design practice to account for unpredictable voltage spikes by choosing a DC/DC converter that withstands an additional 50% voltage rating, or 36 V, from a 24-V rail if no other line voltage conditioning exists in the system.

In almost all cases, 5-V and 3.3-V rails are used as secondary regulation rails from 24-V or 12-V source to power low-voltage sub-systems. Since newer microcontrollers, FPGAs, memory ICs, clocks, and AFEs operate with lower voltages, it is difficult to regulate a 1-V rail with a 24-V input while switching at a higher frequency, such as 1 MHz or above, to maintain a small form factor. As shown in Equation 1, to regulate 1 V from a 24-V input (4.2% duty cycle), the minimum controllable on time of the DC/DC converter must be lower than 40 ns when switching at 1 MHz to avoid noisy pulse-skipping.

$$Minimum \quad controllable \quad on - time \quad = \frac{Duty \quad Cycle}{Switching \quad Frequency} \tag{1}$$

2 Line Voltage Transients

Line transients can come from motors and relays in the system, and can cause an excessive voltage spike on the input voltage line. Voltage spikes can also come from power rails or signal transmission lines that are routed longer distances causing problems to the DC/DC converters or interface circuits. Because PLCs are employed on factory floors that may have motors or other inductive loads and loops, they are susceptible to line transient spikes. Figure 2-1 shows an example of a line voltage transient which may have a short duration, but can severely damage circuits inside PLCs without proper protection.

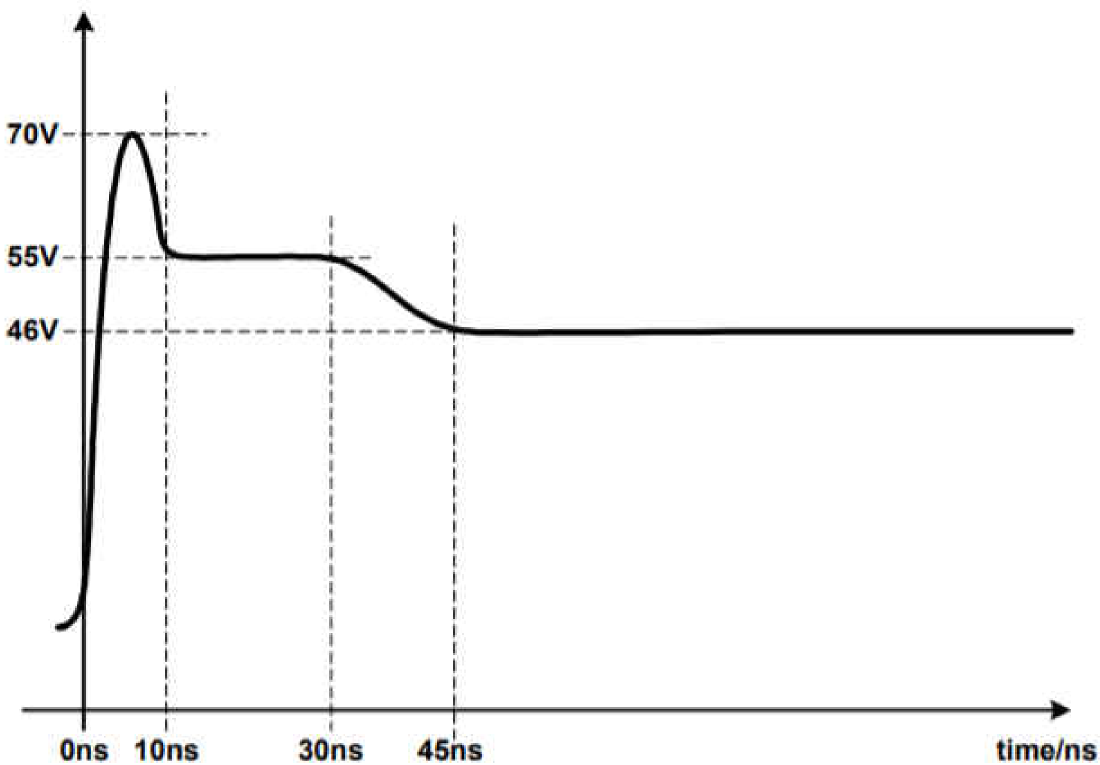

Figure 2-1. Example of a Fast Line Voltage Transient That Can Damage PLC Circuits

A protection circuit, or clamping circuit shown in Figure 2-2 would typically be used for protecting the load from voltage spikes. The diode D2 is used to set the clamp voltage and a pass FET is used to allow the current to flow to the load protected. Unfortunately, these circuits take up space and require more additional circuitry. As semiconductor process technology advances, suppliers are able to offer higher input voltage converters to integrate components and save space. It is true that a 28-V converter rated at 3 A is a less expensive than a 60-V, 3-A converter with the same MOSFET resistance. But the reliability and space savings of a higher rated converter is worth the small added price. Instead of relying on voltage protection circuits, non-isolated synchronous buck converters with integrated FETs are available with ratings up to 100 V to protect downstream circuits.

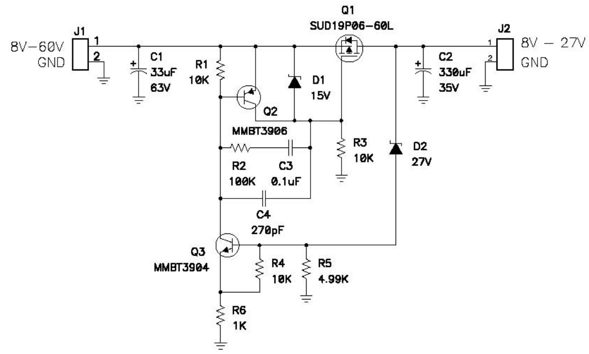

Figure 2-2. Discrete Voltage Clamping Circuit

3 Thermal limitations and power budgets

Because PLCs operate in harsh factory environments, they are enclosed in a cabinet where airflow is either constricted or unavailable. In many cases, the use of a cooling fan is prohibited due to the presence of dust, corrosive elements, or other material limitations. Integrated circuits dissipate heat when operating, especially power management devices, so it is important to choose a high efficient power solution to minimize heat. System long-term reliability is degraded under excessive thermal stressing. Heat also affects the accuracy of any analog sensing circuitry. There is a good chance that the amount of power is limited from the 24-V source supplied to the PLC. Reducing the power dissipation of the point-of-load power solution will increase the power budget of a module and allow the PLC to be differentiated in the marketplace. Additional available power allows faster microprocessor clocking speeds, higher accuracy accurate data converters, or additional memory to improve the performance of the PLC against the competition. Harsh factory environments may experience extreme ambient temperature. It is more useful to specify and rate DC/DC converters by their minimum and maximum junction temperature rather than their ambient temperature. Many DC/DC converters are rated at 150C maximum junction temperature to provide more thermal headroom. An operating temperature range parameter is available within the parametric search engine of step down converters which makes it easy to select products with high operating temperature capability.

Operating a DC/DC converter at peak efficiency is an excellent way to minimize the conduction and switching losses of the DC/DC converter's power MOSFETs. The efficiency of the 2-A TPS54218 design de-rated to 0.5 A is shown in Table 3-1 compared to the 0.5-A TPS62231 using Webench®. Obviously, the smaller MOSFETs of the TPS62231 allow a smaller package size, and the higher frequency allows smaller passive components for smaller solution size. However, the TPS54218 saves 140mW of energy, maximizing efficiency and improving thermal performance in applications that have limited airflow or constrained power budgets. The efficiency of TPS54218 can be further optimized as shown in Figure 3-1. Peak efficiency is about 93% around 0.5A at the knee of the curve which represents the optimal point between switching and conduction losses.

Table 3-1. 5-V Input, 1.8-V Output, 0.5-A Comparison

Device	**η**	Pd (W)	Rds(on)	Frequency	Solution Size
TPS54218	87%	0.13	20 mΩ/20 mΩ	1.125 MHz	122 mm^2
TPS62231	80%	0.27	600 mΩ/350 mΩ	3 MHz	23 mm^2

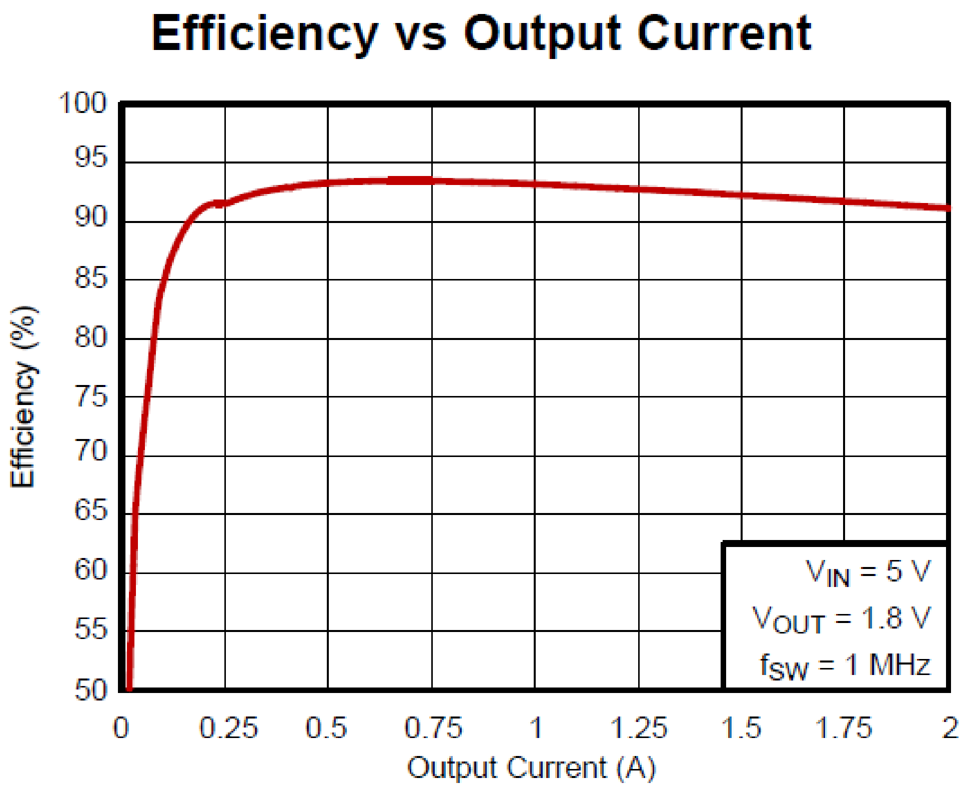

Figure 3-1. Efficiency Curve of TPS54218

4 Isolation Improving Electrical Noise Immunity

PLCs use data transmission systems, such as RS485, but other communication protocols may be employed, such as Profibus, Profinet, or Ethernet. The remotely located nodes of a communication network usually draw their supply from different points in the electrical installation system. A remotely located power source can experience large ground potential differences due to multiple, non-standardized grounding techniques, which cause multiple ground paths and loops. A ground loop is created when providing a direct connection from a ground wire between the transmitter ground and a remote receiver ground. Ground loop currents can be extremely high, because they connect different ground potentials via low-impedance wiring. As a result, high loop currents induce voltages into transmission signal wires causing signal distortion and data errors. Breaking ground loops through galvanic isolation not only prevents loop currents, but is the most reliable method to solve high ground potential differences. Galvanic isolation allows the input, which is referenced to the ground from the input side, to be independent from the ground at the output side, which significantly enhances the common mode rejection and improves noise performance. It is important to have an area on the circuit board that is "isolated" from potentially noisy grounds, and the most popular technique is to implement a 5-V input to 5-V output thru an isolation barrier.

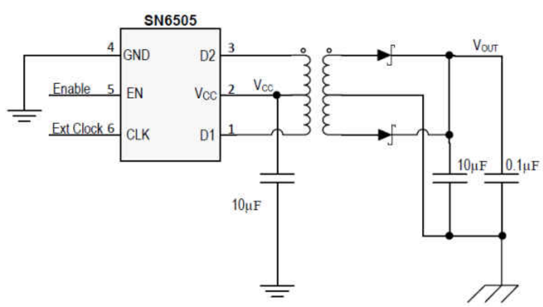

Figure 4-1. Push-Pull Transformer Driver

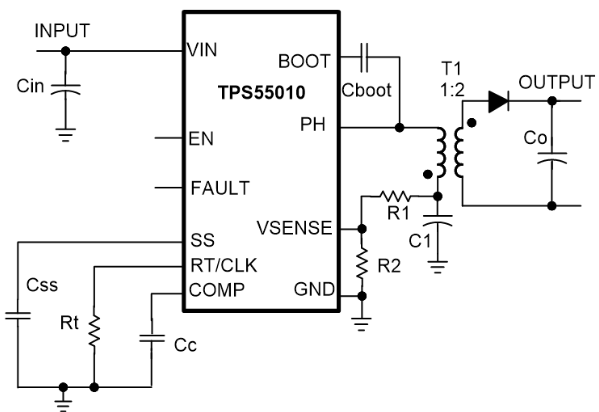

Figure 4-2. Fly-Buck Regulator

There are several solutions that can be used to create an isolation barrier using a transformer. The push-pull transformer driver in Push-Pull Transformer Driver operates at a 50% duty cycle, so the transformer coil must be designed accordingly to accommodate a specific input and output voltage. The push-pull circuit also runs open-loop, so there is no feedback mechanism. In some cases, a linear regulator is needed on the secondary side to provide better output voltage regulation. The fly-buck regulator, also known as an asymmetrical half-bridge, is shown in Figure 4-2 has same transfer function as a standard buck regulator, but uses a transformer, similar to the flyback converter. The LC of the buck regulator uses C1 for the output bulk capacitor and the primary side of the isolated transformer, T1. The output voltage is reflected to the secondary side and is derived from the turns-ratio of the transformer. R1 and R2 set the duty cycle of the ½ bridge, which allows more flexibility in choosing an off-the-shelf transformer turns-ratio to accommodate the input and output voltages. Also note that the fly-buck's frequency can be adjusted with the RT pin and also synchronized to a wide range of switching frequencies. The fly-buck here is limited to about 2 W, because high currents flowing thru the diode on the secondary side can limit regulation due to losses. Opto-couplers are not needed for either topology.

The TPS55010 is an example of a low voltage fly-buck. This device has higher efficiency than the push-pull with lower $R_{ds(on)}$ and also uses primary side feedback to allow flexibility with the magnetics. The frequency can be programmed from 100 kHz to 2MHz and synchronized to an external clock with the clock pin. However, the TPS55010 requires loop compensation, since this is a current mode controlled converter. However, a design calculator on the web that can aid in selecting the compensation components based on the transformer and capacitor selections. For higher efficiency, more output current, and better regulation accuracy, the fly-buck is a better alternative than a push-pull.

The SN6505 is a low noise push-pull driver for designing isolated supplies. It's an easy-to-use 6 pin device and uses fewer components than a fly-buck. The device is offered with 2 different switching frequencies, 140 kHz and 400 kHz, and can be synchronized to an external clock. It also features a built-in spread spectrum dithering circuit to help with EMI emissions.

5 Voltage Regulation Accuracy

As the process technology advances, the FPGAs, micro-controllers, and ASICs require tighter voltage accuracy and lower operating voltages for their core rails. The processor's datasheet may specify the voltage tolerance as a percentage or as a value in mV, which includes DC, AC and ripple variations over the entire operating temperature range. Any voltage outside of this range is not recommended and the processor can behave unexpectedly. Designers much also consider the tolerance of the resistor divider used by the DC/DC converter, the routing and trace losses of the circuit board, and also the variations of the application, like the input voltage variations, temperature swings, and fast changes in the load. All of these contribute to the accuracy of the DC/DC converter. Many designers will want head-room or margin to make sure the solution is always within the tolerance expectation of the processor.

It is important to check the initial feedback voltage accuracy of the DC/DC converter in the data sheet rather than the front page. Table 5-1 shows the regulated feedback voltage specification of the TPS54218, which is a 2.95 to 6-V, 2-A converter, and shows that the reference accuracy is ±8 mV or ±1% over input voltage and temperature variations. The total output voltage accuracy is improved by choosing tighter tolerance resistors. If more headroom is needed, designers can choose 0.1% or 0.5% resistors1, even though they may cost a little bit more. The additional headroom will allow the total ±3% or ±5% output voltage variation to be met with less bulk and bypass capacitance.

Table 5-1. Feedback Voltage Regulation as Shown in the TPS54218 Data Sheet

Parameter	Test Condition	Min.	Typ.	Max.	Unit
Voltage Reference	2.95 V ≤ V_{VIN} ≤ 6 V, –40°C <TJ < 150°C	795	803	811	mV

It is always wise to place the DC/DC converter as close to the load as possible. Often times layout constraints, connectors, and board density requirements interfere

6 Solution Size

To keep the total DC/DC converter solution small, external components can be either integrated or optimized for the application. Non-isolated power modules have become more popular over the last few years due to the higher level of integration and ease of use, as well as the optimization of the inductor to occupy less space. The power module in Figure 6-1 is offered in 3 different current limit variations with the same pinout to provide a scalable power solution.

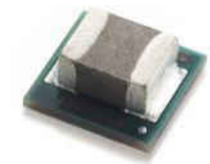

Figure 6-1. TPS82130 Power Module in μSIP package

7 Complete Solution

The DC/DC converters in Table 7-1 are ideal for powering PLCs and sub-systems. These converters feature high efficiency, good thermal performance, and tight VFB accuracy. Devices with the same package are pin compatible for design flexibility unless noted with a different feature in the comment column. Texas Instrument also has a wide variety of products and reference designs to solve design challenges for PLC applications5. Reference designs, such as the discrete power solution for AM437x Sitara family show possible ways of integrating TI devices into such sub-systems.

Table 7-1. Suggested Step-Down Converters and Modules for PLC

Device	Iout (A)	Input Voltage (V)	Package	Comment
High Transient DC/DC				
LM76003	3	3.5-60	4 × 6mm QFN	Low Iq, Synchronous
LMZ36002	2	4.5-60	10 × 10mm QFN	Power Module
LM46002	2	3.5-60	HTSSOP	Low Iq, Synchronous
LM46001	1	3.5-60	HTSSOP	Low Iq, Synchronous
LM5166	0.5	3.5-65	3 × 3mm SON	Low Iq, Synchronous
LM5165	0.15	3.5-65	3 × 3mm SON	Low Iq, Synchronous
24-V Rail				
LMZM33606	6	3.5-36	10 × 10mm QFN	Power Module
LM73605	5	3.5-36	4 × 6mm QFN	Low Iq, Synchronous
LMZM33603	3	4.0-36	7 × 9mm QFN	Power Module
LMR33630	3	3.8-36	2 × 3mm QFN / 8 HSOIC	Low Iq, Synchronous
LMZM33602	2	4.0-36	7 × 9mm QFN	Power Module
LMR33620	2	3.8-36	2 × 3mm QFN / 8 HSOIC	Low Iq, Synchronous
LMZM23601	1	4.0-36	3.8x3 uSIP	Power Module
LM43601	1	3.5-36	16HTSSOP	Low Iq, Synchronous
LMZM23600	0.5	4.0-36	3.8x3 uSIP	Power Module
LM43600	0.5	3.5-36	16HTSSOP	Low Iq, Synchronous
12-V Rail				
TPS54424	4	4.5-17	3.5 × 3.5mm QFN	Frequency synchronization
TPS62148	2	3.0-17	2 × 3mm QFN	Tracking
TPS82130	3	3.0-17	2.8.3mm uSIP	Power Module
TPS82140	2	3.0-17	2.8.3mm uSIP	Power Module
TPS82150	1	3.0-17	2.8.3mm uSIP	Power Module
3.3/5V rail				
TPS54618	6	2.95-6.0	3 × 3mm QFN	Frequency synchronization
TPS54418	4	2.95-6.0	3 × 3mm QFN	Frequency synchronization
TPS62823	3	2.4-5.5	1.5 × 2mm QFN	Small solution w/ 470nH
TPS54218	2	2.95-6.0	3 × 3mm QFN	Frequency synchronization
TPS62822	2	2.4-5.5	1.5 × 1.5mm QFN	Small solution w/ 470nH
TPS62821	1	2.4-5.5	1.5 × 2mm QFN	Small solution w/ 470nH
Isolated				
SN6505	1	2.25-5.5	SOT23-6	Push-Pull
TPS55010	1	2.95-6.0	3x3mm QFN	Fly-Buck
LM5161	1	4.5-100	HTSSOP	Fly-Buck
LM5160A	2	4.5-65	4 × 4mm SON	Fly-Buck
DCPA series	1W	4.5-5.5	PDIP / SOP	Power Module + or +/- 5, 12, 15Vout

8 References

1. Calculating Efficiency, Arvind Raj, SLVA390; 2010
2. Improving thermal performance of a module, Sandra Horton and Chris Glaser, SLYT724; 2017
3. For more information on single board computers, please visit the end equipment page on the TI website - http://www.ti.com/solution/plc-controller

9 Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Revision * (September 2018) to Revision A (July 2021)	Page
• Updated the numbering format for tables, figures and cross-references throughout the document	2

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