Digital Power Eases Designer's Burden

DC-DC conversion with Auto-control^{TM}

Regulation of supply rails, from a control perspective is traditionally the domain of analog integrated circuits. But current trends in power conversion are moving the industry to smaller and more efficient power architectures. The requirement to intelligently manage the multiple power rails under these constraints of space and efficiency is driving the industry towards research, development and adoption of digital power control and power management solutions.

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The economics of IC design support the adoption of digital power control because the cost reduction of digital circuits is more rapid over time, leading to cost parity of digital and analog power control ICs, with digital solutions ultimately being cheaper. Factoring in the requirement for advanced power management, which is a digital function, the economics of IC design point to increased demand for digital power controllers and therefore they are expected to be a very significant proportion of the market (greater than 40%) by 2011.

Taken together, these trends indicate that there is significant potential for the development of power control technologies which harness uniquely digital techniques in order to deliver improvements in power system design. Indeed, such improvements have been looked forward to for some time. Now it is time to deliver.

We will examine DC-DC conversion from a control perspective, introducing key differences compared to analog techniques, looking at key control issues such as robustness and finally introducing truly adaptive Auto-controlTM technology which uses digital processing to deliver improved control.

Overview of Digital Power Control

Figure 1 illustrates a typical digital DC-DC converter, comprising of the power stage, output voltage V_{OUT} (y) sampling ADC, digital error amplifier / compensator, and digital Pulse-Width-Modulation (PWM).

There are several differences between analog and digital DC-DC converters, some of the most significant are:

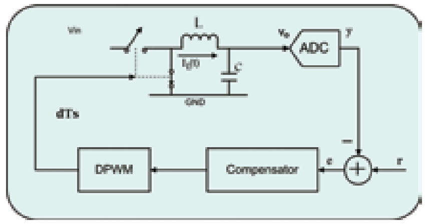

Figure 1: Typical Digital DC-DC Converter.

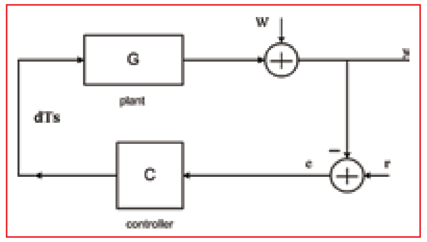

Figure 2: Representation of a feedback control system.

a) The output voltage (y) as seen by the control loop is quantized in voltage. This means the output voltage is known to the resolution and accuracy of the ADC.

b) The output voltage is sampled in time and therefore is only known at the sampling instants.

c) The Digital Pulse-Width-Modulation (DPWM) is quantized in time and therefore discrete quantized pulse widths are available. The interaction between the DPWM's quantized levels and those of the ADC can result in limit cycling whereby the DPWM's pulse width never settles to a steady state. This results in a limit-cycle on VOUT, the amplitude of which is dependent on several factors and is a function of the DPWM's resolution.

d) The ADC requires some time to convert the VOUT reading into a digital value, adding to delay in the loop.

e) The compensator adds to the loop delay because it requires some time to compute the duty-cycle following each ADC reading.

The delays inherent in a digital PWM control loop place a bound on the achievable control bandwidth which in turn affects the control response and therefore the deviation in the transient response to a load current step. The maximum control bandwidth achievable when a control loop has a delay of Td is approximately:

$$f_{\max} \approx \frac{1}{2\pi T_d}$$

Intuitively this makes sense; the control loop cannot react to a disturbance until the ADC has measured it and the controller has calculated a response. In the meantime the output voltage will continue on its trajectory giving a minimum achievable voltage deviation to the load transient and equivalently, a maximum achievable control bandwidth.

This means that in a typical digital DC-DC converter where the ADC sample rate is the same as the switching frequency, and there is a one cycle delay from ADC sample to DPWM update the maximum achievable control bandwidth is:

$$f_{\max} \approx \frac{f_{sw}}{2\pi}$$

In reality the delay inherent in PWM modulation must also be taken into account, reducing the maximum achievable bandwidth even further.

Clearly the transport delay is an important figure of merit for a digital DC-DC converter. It is as low as 400ns for Powervation's technology.

The Role of Control

Consider the controller depicted in Figure 2 where the compensator and plant are represented by C and G respectively. The role of control is to ensure the output (y), tracks the reference (r), in the presence of a) unknown disturbances and b) uncertainty regarding the parameters (or structure) of the power stage. Feedback control facilitates this through high loop gain.

However, the gain must roll-off at high frequencies in any physically realisable system. This is illustrated in Figure 3, where the loop gain is shown as CG. As CG rolls off we can see there are conflicting requirements between loop stability and robustness. For example, to ensure that the loop is insensitive to a high degree of plant uncertainty requires high loop gain up to a high bandwidth. However, the loop gain must roll-off at high frequencies in order to ensure loop stability, with lower bandwidth systems being more stable. Therefore there is a fundamental trade-off between loop stability and robustness versus uncertainty regarding the power stage. In practice control loops are designed with lower bandwidths so they are stable despite plant uncertainty. Robustness is achieved by ensuring a high phase margin.

Robustness

Loop phase margins, gain margins and crossover frequencies are typically designed conservatively when robustness is considered in physical systems. This comes about because the control loop is particularly sensitive to inaccuracies in the dynamic modelling of the power stage as the loop gain rolls off and crosses 0dB.

We can view phase-margin as a measure of robustness against delay uncertainty at the 0dB crossover frequency, i.e. high phase margin systems can tolerate more uncertainty in loop delay without being unstable. The amount of additional delay a loop can tolerate (Tmax), for a given phase

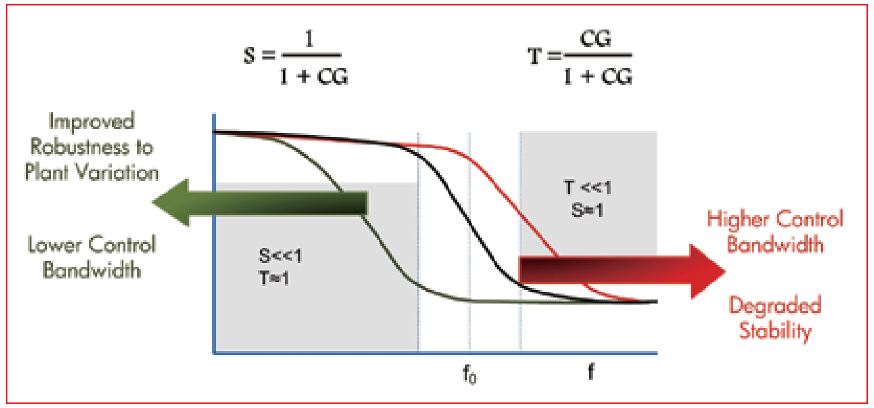

Figure 3: Conflicting requirements of Sensitivity and Robustness as the Loop Gain (CG) rolls off versus frequency.

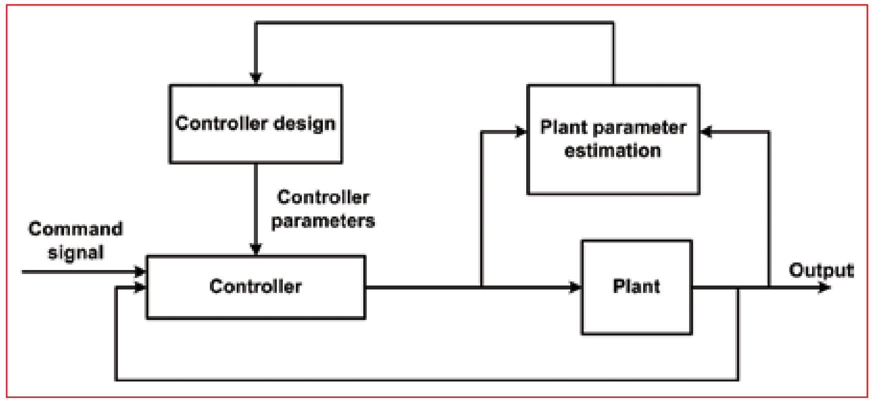

Figure 4: Typical adaptive self-tuning regulator.

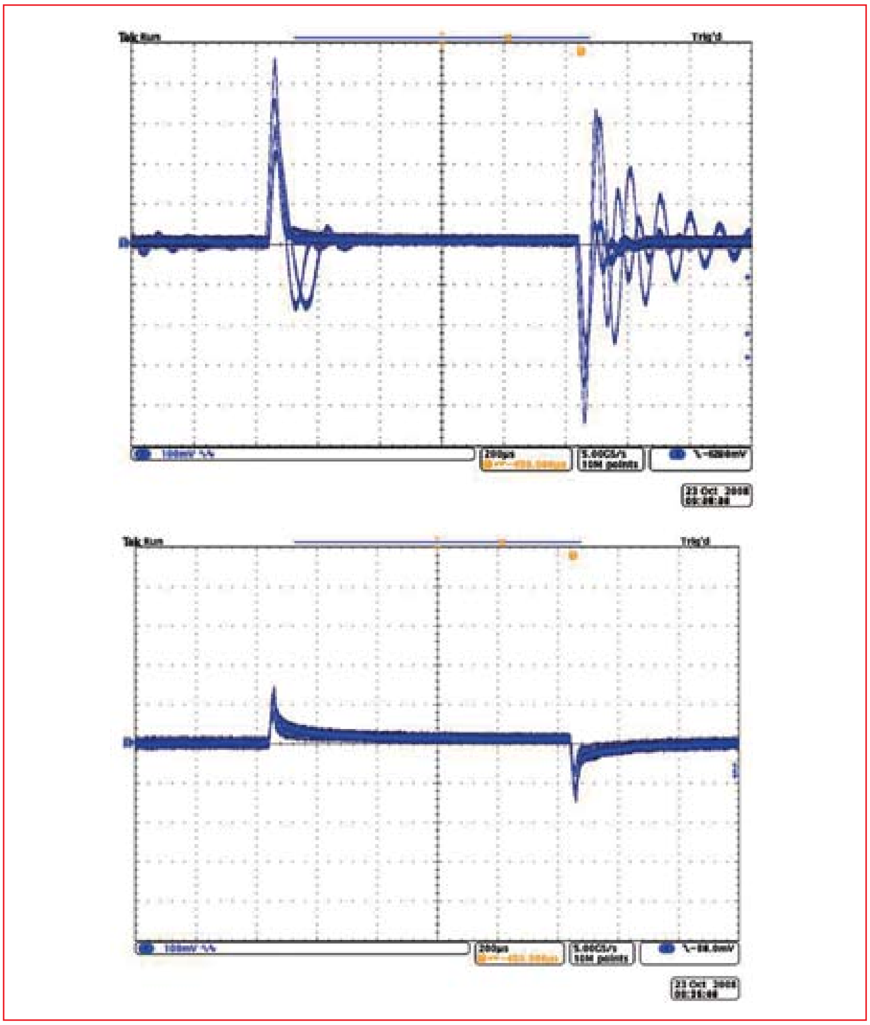

Figure 5: (a) Varying load step response as L and C vary in a DC-DC converter; (b) Improved robustness to variation when controlled with Powervation's Auto-controlTM technology.

margin (PM, in radians) and crossover frequency (ωc in rad/s) is given by:

$$T_{\max} = \frac{PM}{\omega_c}$$

Therefore, loops with higher phase margin or lower crossover frequency are more robust against uncertainty in loop delay. Similarly we can view gain-margin as a measure of robustness against gain uncertainty at crossover, i.e. high gain margin systems can tolerate more uncertainty in gain at crossover without being unstable.

Adaptive Control

A typical adaptive control system is illustrated in Figure 4, whereby the parameters of the plant are estimated by the 'plant parameter estimation' block and the controller is designed on-the-fly by the 'controller design' block to meet some pre-determined requirements such as closed loop pole locations.

One of the main advantages of adaptive control is that plant uncertainty is reduced by the parametric estimation. As the uncertainty in the control system is reduced it becomes more robust, and the limitations on control performance to achieve robustness are relaxed. As such the loop can maintain high gain up to as high a bandwidth as stability will allow.

Traditionally gain and phase margins are chosen to yield a compromise between performance and stability. By using adaptive control high gain margins and high phase margins are not required in order to ensure loop stability. Therefore, higher performance control is possible.

Powervation has developed Auto-controlTM technology which brings true adaptive control to DC-DC conversion for the first time. The benefits of Auto-control such as improved robustness, maximum performance and ease of design are all made available through this technology.

Figure 5 illustrates the improved robustness compared to a fixed controller which is achieved automatically with Auto-controlTM.

Summary

As trends in power conversion move the industry towards power architectures which are smaller and more efficient, the requirement to intelligently manage the multiple power rails under these constraints of space and efficiency is driving the industry towards the adoption of digital power control and power management solutions. There is significant potential for the development of power control technologies which harness uniquely digital techniques in order to deliver improvements in power system design. Using traditional control techniques gain and phase margins are chosen to yield a compromise between performance and stability. By using Auto-controlTM, high gain margins and high phase margins are not required in order to ensure loop stability. Therefore, higher performance control can be achieved and unprecedented ease of use can be delivered as designers are freed from the burden of loop compensation.

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