Mixed-Signal Board Power Generation and Distribution

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One of the most common applications of mixed signal design at the board level is board level power generation and distribution. The difficulties involved with designing proper board-level power supplies are often underestimated because the nuances are misunderstood. Failure to understand the power requirements can lead to performance failure, missed schedules, and board respins. The sequence of design steps presented in this paper will allow the designer to properly estimate, generate, and deliver power to mixed-signal boards.

POWER SYSTEM DESIGN SEQUENCE

The power systems consideration is usually assumed to be a choice between a linear or switching DC/DC converter. A proper board level power system design should instead consist of the following carefully thought out sequence of Engineering steps.

1. Identify the power characteristics coming into the board.
2. Estimate the loading requirements for each voltage on the board and for each mode of operation.
3. Identify and list board level considerations other than DC voltages and currents such as DC and AC regulation, noise management, thermal management, cost, component size and future changes to the power requirements.
4. Make the basic power system decision of a linear regulator, switching DC/DC converter or combination of both.
5. Identify and mitigate the problems associated with the power system decision including performance resulting from component variations and parasitics.
6. Prepare a power distribution mechanism at the board level and layout board accordingly.
7. Verify design by testing the power system at the board level, verifying suppliers, layout, and temperature variations.

Each step in this sequence will now be reviewed to identify major design tradeoffs.

STEP 1: INPUT POWER CONSIDERATIONS

This paper assumes that the input voltage is a DC voltage generated either from a switching power supply or battery source remotely or on the board. The input voltage or power characteristics should identify the following:

- The DC voltage regulation for each voltage entering the board usually specified before the input connector of the board. The board designer must calculate additional voltage drops due to connectors, power MOSFET switches, fuses or other resistive elements in the current path that will reduce the voltage.
- The delivery characteristics or impedance of the input voltage. The voltage may be from a very low impedance backplane with ample decoupling or it may be from a long, inductive cable. When the delivery method is inductive (long cable) then large input capacitors may be required to create a stable voltage.
- The current allowed by each voltage or the total power allowed into the board. The input connector pins may limit this current. The total board power dissipation might be limited due to system thermal management budgets.
- The voltage ripple and noise characteristics.
- Voltage turn on and turn off timing and voltage sequencing timing.
- For battery inputs, the characteristics of the battery and charging system must be identified including the voltage range, the Equivalent Series Resistance (ESR), and the AC characteristics of the charger.

STEP 2: ESTIMATE THE LOAD CURRENTS AND CHARACTERISTICS

Load current characteristics consist of more than DC current ranges. The loading characteristics should include the range of current required and the transient specifications as well. For analog and digital circuitry, the load calculations will require knowledge of the operating characteristics shown in Figure 1.

Analog Circuit	**Digital Circuit**
• **Bias Currents** • **Drive Currents** • **RMS Power in passives** • **Icc maximum vs. typical** • **Limited current range** • **High slew rates**	• **Icc depends on** •**Fclock** •**Logic level inputs** •**Operating modes** •**Algorithm** •**Memory access/partition** •**ASICs = uW/MHz/gate** • **Wide current range** • **Large transient swings**

Figure 1 - Mixed Signal Load Current Characteristics

References 1-4 provide some insight into how and why digital ICs vary in current. Estimating the current in an analog component or section requires knowledge of bias currents, drive currents and the average power dissipation in the passive components. Bias currents specified on analog component data sheets can vary significantly from typical to maximum. A general rule in estimating analog bias current is to use 80% of the maximum current.

The load characteristics on each voltage can be qualified for the power system into four criteria as shown in Figure 2.

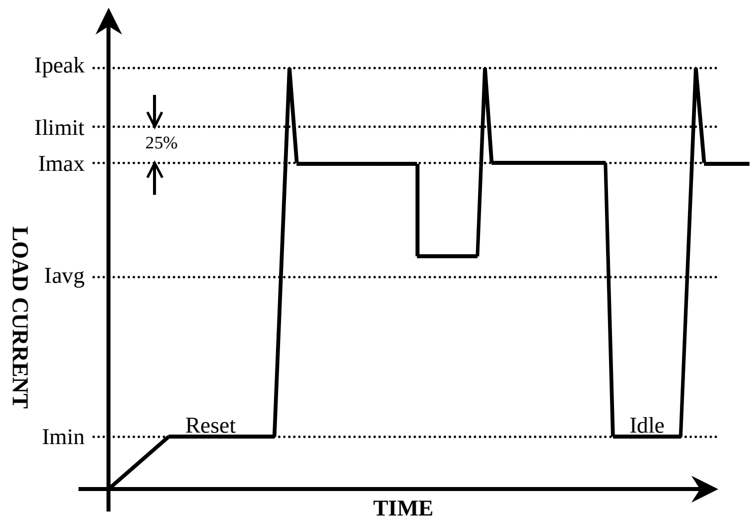

Figure 2 - Load Current Profile for Mixed-Signal Power System

- Minimum Current, *Imin* - Minimum operating current on any single voltage. The power supply must be stable and must maintain regulation under this condition. Pre-loading may be necessary.
- Average Current, *Iavg* - Power dissipation estimation for load power as well as efficiency of the power supply should be evaluated using this current. Reliability predictions might occur here as well.
- Maximum Current, *Imax* - Maximum operating current seen by the power supply. This may be a DC condition or a transient condition too long for capacitors to supply the current to the load. The power supply should be stable and should maintain regulation at this current. The short circuit current limit of the power supply, *Ilimit*, should exceed this value by 15-25%. All components in the power supply current path should be rated electrically for this current.
- Peak Current, *Ipeak* - This current is typically of a short enough duration that the output decoupling capacitors of the power supply can source this current while still maintaining regulation. This is typically the most difficult operating point to maintain regulation. The power supply output impedance characteristics must be chosen with this current in mind. (Reference 5).

STEP 3: IDENTIFY OTHER POWER SYSTEM REQUIREMENTS

Power system requirements consist of much more than supplying a fixed current at a regulated voltage. These system requirements should be considered prior to the board level architecture solution being defined.

Regulation - The total regulation at the load included effects from DC regulation of the power supply, voltage drop, transient load regulation and ripple voltage. A regulation budget as shown in Figure 3 must be established in order to insure the solution meets the load requirements.

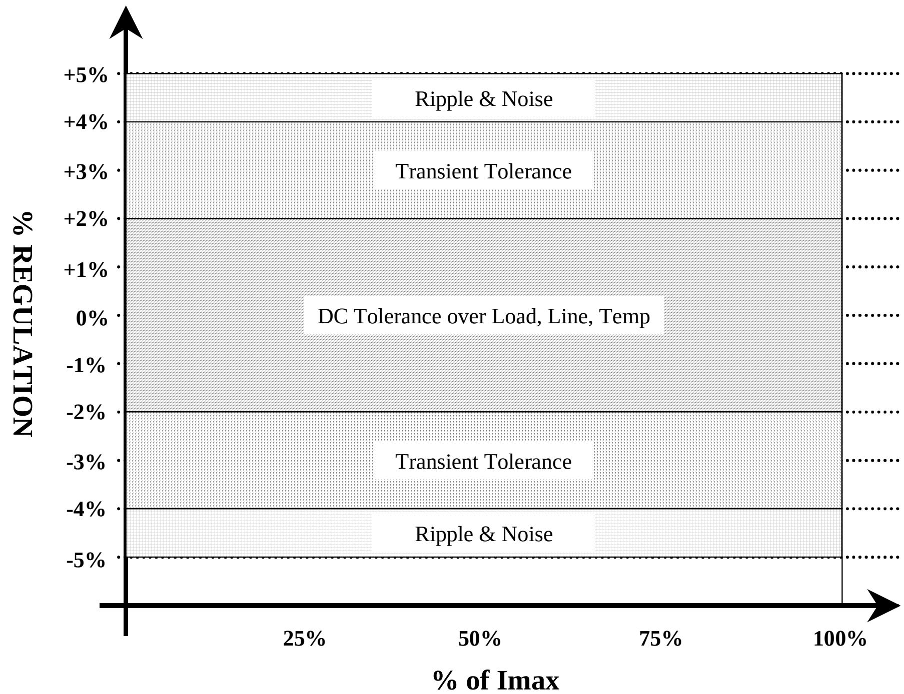

Figure 3 - Total Regulation Budget Required by Load

DC Regulation at the load - Variation in the output voltage, relative to the nominal, is a function of DC level changes in the input voltage (Line Regulation), the output current (Load Regulation) and the operating temperature. The regulation of a power supply is highly dependent on the quality of its reference voltage, usually incorporated within the linear or switching controller IC. Both linear regulators and switching regulators are excellent in this category with typical performance better than 2%. Regulation is measured at the output of the power supply but is most critical at the circuit it is powering. Remote sensing should be utilized to improve DC regulation at the load when the power source is not very close to the load.

Transient Load Requirements - The time changing characteristics of the load must be well understood in order to choose the appropriate power system and components. The transient load characteristics should include how much (ΔI) and how fast (di/dt) the load current changes and should include both low-to-high and high-to-low transitions. The power supply's ability to react to the load current changes are characterized by the peak voltage excursion, recovery time and recovery characteristics (overshoot and ringing).

Designers often rely on wide bandwidth linear regulators to supply fast transient load currents, but neglect to calculate the transient effects on the input capacitors. No matter what the power solution, sufficient on-board capacitors are required at the input or the output to supply large transients while maintaining regulation. Reference 5 sufficiently addresses transient regulation design concerns.

Noise Management - Ripple must be managed to insure regulation requirements, but proper noise management requires awareness of the entire frequency band. The mixed-signal components and circuits should be reviewed to determine an acceptable voltage (RMS) vs. frequency profile, as shown in Figure 4. This profile will guide the designer in the choice of architecture, components and filters.

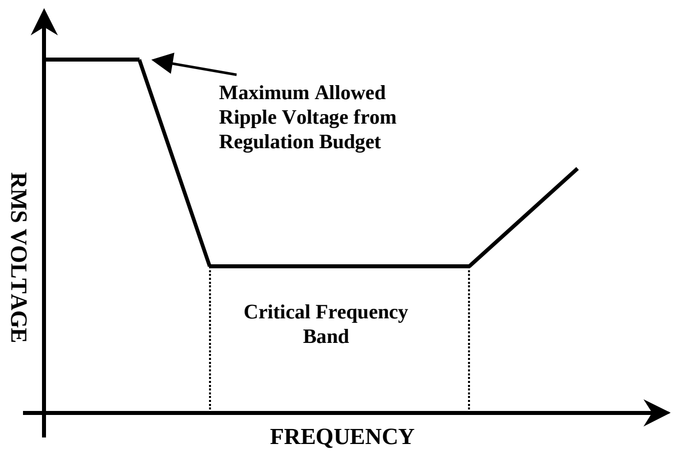

Figure 4 - Acceptable AC Noise Profile at the Load

Several characteristics of power supplies, ripple rejection, PARD, input ripple and pass-through noise, should now be considered relative to the requirement of Figure 4.

Ripple Rejection, also known as audiosusceptibility, is the ability of a power supply to prevent AC noise from getting to the output of the power supply from the input of the power supply. Ripple rejection is closely related to the open loop response of a power supply and is much better in a linear regulator than in a switching regulator since linear regulators typically have a much wider bandwidth.

PARD is defined by the switching power supply industry as the total peak-to-peak voltage over a specified bandwidth, typically 20MHz. This is enough for the designer to insure the regulation requirements are made, but it does not define the frequency spectrum (energy or voltage vs. frequency). Linear regulator noise specification, in $\mathrm{nV}/\sqrt{\mathrm{Hz}}$ is more useful because noise at a particular frequency, F1, can be determined by

$$\mathrm{Noise@F1\,in\,nv(rms)} = \mathrm{F1}^2 \bullet \mathrm{nV}/\sqrt{\mathrm{Hz}}$$

Input ripple of a switching power supply is an effect of the input capacitors sourcing and sinking large current values. The level of the switched current, the quality of the input capacitors, and the impedance of the power delivery system determine the input ripple. Input ripple is a concern to the designer because that input voltage may be common to other power circuits.

Pass through noise is the noise generated at the load, by high-speed digital clocks for instance, which passes through the power supply from the output to the input. Like input ripple, it too can effect circuits that share a common input voltage bus.

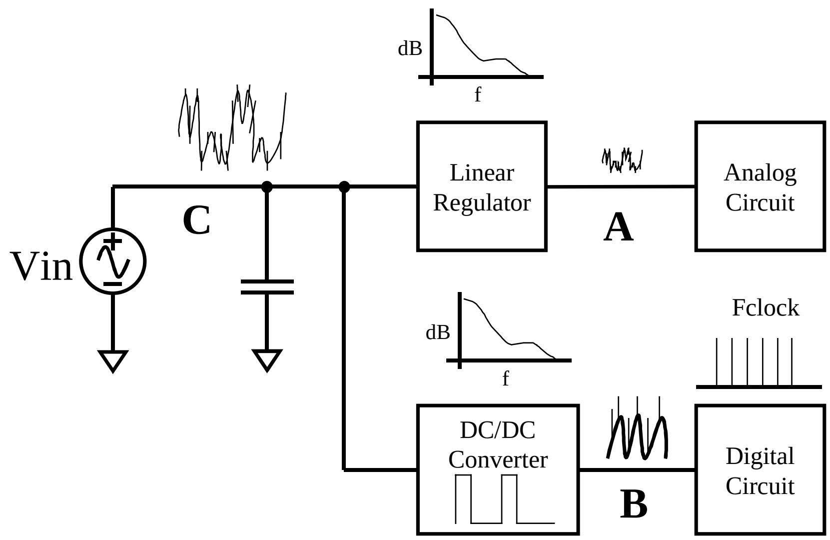

Figure 5 - A typical mixed signal Board using Linear and Switching Regulators

Figure 5 illustrates the noise management issue. The sensitive analog load at point A requires a noise profile similar to that shown in Figure 4. In order to insure the noise is kept to an acceptable range at point A, the rest of the system must be understood. The noise component at point B consists of three sources: the high-speed digital clocks, the output noise and ripple of the DC/DC converter and the input noise and ripple not rejected by the DC/DC converter. The noise components at point C consists of three sources: point B noise passing back through the DC/DC converter, input voltage ripple from the DC/DC converter, and input noise from the input voltage source. The linear regulator must therefore reject all of these components in order to meet the requirements at point A. Additional filtering must be added in the circuit if the linear regulator cannot meet these requirements.

<u>Protection</u> - Overcurrent, short circuit, overvoltage and thermal protection methods should be included for protecting the load circuit, the power supply itself and the input power source(s). There are various methods of achieving each of these with both linear and switching regulators.

<u>Thermal Management</u> - Thermal management includes (a) insuring that the board itself does not exceed a heat dissipation level defined by the system and (b) no component on the board is stressed due to localized heat dissipation.

Board power dissipation is the sum of the average load power, power supply losses and the distribution losses in paths such as connectors and copper runs. When calculating board power dissipation, it is often (but not always) adequate to use the average load current rather than the maximum load current. When calculating individual component dissipation, the component's maximum operating current should be used.

The average load power dissipation is determined by the sum of all the board level voltages times the average current for each voltage

$$Pavg = \sum (Vout \cdot Iavg)$$

The power dissipation, not the efficiency of the power supply, is the characteristic that determines whether the power solution is feasible. The relationship between the two is given by

$$Efficiency = \frac{Pout\ (Power\ Delivered\ to\ Load)}{Pin\ (Power\ input\ to\ system)} = \frac{Pout}{Pout + Pdissipated}$$

Therefore, for each power supply on the board, the power dissipated is

$$Pdissipated = \frac{Pout}{Efficiency} - Pout$$

Power distribution losses, typically between 1%-2% of the total power delivered, result from carrying current through connectors and copper etch.

Table 1 - General Comparison of Linear Regulators and Switching DC/DC Converters

Advantages	Disadvantages
Linear Regulator	
Low input noise	Poor efficiency
Low output noise	Ballast resistors required for load sharing
Wide Bandwidth Loop - Ripple Rejection	Limited input voltage range for given power dissipation
Fast Transient Response	Transient load is passed to input capacitors
Good DC regulation with Load, Line, Temperature	Load Noise Passthrough
Short circuit and thermal protection (most parts)	No electrical isolation
Simple to design in system	Difficult thermal management
Easy sequencing	Can only provide voltages lower than the input voltage
No overshoot at start up	
Switching DC/DC Regulator	
Excellent Efficiency possible	Lower Bandwidth typically
Electrical Isolation possible	Stability highly dependant on external components
Load Sharing possible	Beat frequencies or high noise for multiple switchers
Current limiting possible	Input Noise
Wide Range input voltage	Output Noise
Can create voltages higher or lower than the input voltage	Radiated Noise
Multiple outputs possible	Difficult for beginner designers

STEP 4: CHOOSE LINEAR REGULATORS, SWITCHING REGULATORS OR BOTH

A decision is now required as to how each board voltage is generated. Table 1 can be used as an aid in determining whether a linear regulator or switching regulator should be used.

STEP 5: IDENTIFY PROBLEMS AND MITIGATE

No power supply is perfect when all the system requirements are considered. Problems associated with every power solution must be identified and mitigated. Some common problems and solutions are listed in Table 2.

STEP 6: POWER DISTRIBUTION AND LAYOUT

Three important rules to use when designing the power solution on a mixed signal board are to separate power and ground planes, properly locate the power supply and to filter appropriately. Reference 4 provides a good introduction to power supply layout and power distribution when multiple voltages and loads are involved, such as for a mixed signal board.

Ground and power plane separation is demonstrated by Figure 6. Both the analog and digital circuits must share a system ground, typically common at the input connector. When the sections have no commonly grounded components, the ground planes should only be connected at the input power source, increasing the impedance between the two circuits. When the analog and digital circuits share a common component such as an A/D converter with one ground pin, then the two sections should be connected with a narrow piece of etch, or even by connecting each plane to the pin of that component. A narrow connection creates the required DC connection but introduces a high frequency resistance, R_{HF}, between the sections. Ferrite beads can improve this technique.

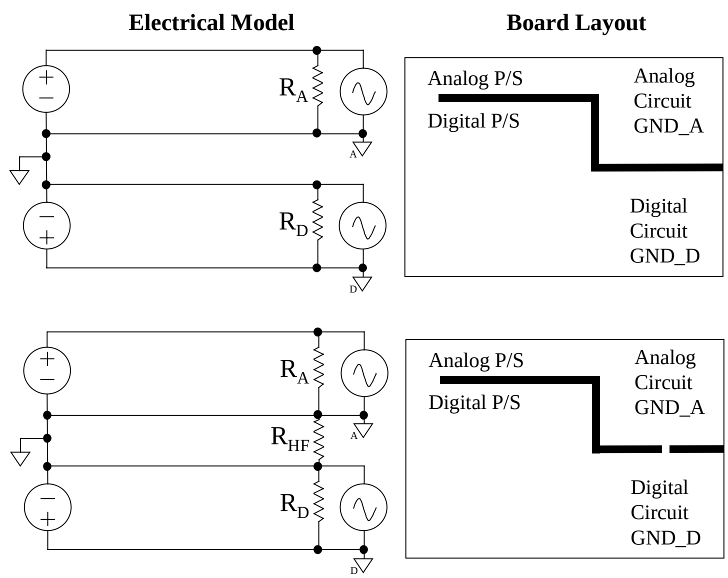

Figure 6 - Mixed Signal Board Power and Ground Planes

Table 2 - Common Board Level Power System Problems and Solutions

Problem	Explanation	Possible Solutions
DC Accuracy is inadequate at the load	The power supply accuracy is poor or the location results in voltage drops effecting the tolerance at the load	• If possible use an external precision reference at the power supply • Use remote sensing to improve accuracy at the load
Wide range input voltage with Linear Regulator	A Linear Regulator may be chosen for noise reduction purposes, but will be very dissipative when the input voltage is at the highest value	• Pre-regulate with a switching regulator and deliver load current with low noise linear regulator. Use appropriate filtering • If the load current does not vary significantly, use a power resistor in series with the input voltage to share power dissipation with the linear regulator
Linear Regulators dissipate too much power	A single linear regulator may dissipate too much power, but multiple linear regulators can't share current	• Partition the circuits to so that each linear regulator supplies only one section of circuitry, dissipating manageable power • Use ballast load sharing resistors • Use thermal feedback to reduce current when necessary
Load Sharing is required	Current to a load may be delivered from two or more identical power supplies in order to manage size or heat on the board. Power supplies do not share current naturally	• Use current mode switching regulators that share current to approximately 25%. • Use ballast resistors on the output of the supplies (ballast resistors dissipate power) • Use active current sharing techniques
Ripple Rejection is not adequate	A linear or switching power supply bandwidth is too low to reject high frequency noise detrimental to the load.	• Use a current mode switching regulator with better ripple rejection • Filter (LC or RC) the high frequency noise. Filter the input of a linear regulator. Filter the output of a switching regulator. Use ferrite beads for additional performance
Output Noise of DC/DC Converter	Sensitive analog circuitry cannot tolerate DC/DC ripple and noise	• Input and output LC filters on the DC/DC converter • Use elegant soft switching techniques to reduce high frequency noise, but not ripple
Input Noise if DC/DC Converter	The same input voltage supplies sensitive analog circuits and digital circuits. The DC/DC ripple on the input passes to the analog circuitry.	• Input LC filter at the DC/DC converter • More capacitance at the DC/DC converter input • Choose the DC/DC converter switching frequency to be out of the critical bandwidth
Load Noise Passthrough	Noise from load (digital clocks) can pass through LDO from output to input, to sensitive circuits	Add a ferrite bead to the output of the Linear regulator blocking high frequency noise.
Transient Regulation	The transient load is causing the voltage to go outside the regulation window	• Maximize the bandwidth of the power solution • Add high C, low ESR and low ESL capacitors to the power supply output. Use tantalum, aluminum and ceramic capacitors to reduce power supply impedance • Add high frequency ceramic capacitors at the load.
Transient Load ringing	The power supply response to the transient load is causing ringing at critical frequencies	• Ringing is the sign of an under-damped power supply loop. Increase the phase margin of the loop.
Transient Load passthrough	The transient load at the output of a power supply results in a transient input current as well.	• Add a LC input filter to the power supply. Add high C, low ESR and low ESL capacitors at the input.
Beat Frequencies	Two or more switching power supplies vary in frequency result in low level frequencies on board	• Synchronize the switching power supplies to a common frequency

The location of the power supply should be chosen to improve noise management. Switching power supplies create both conducted and radiated noise. Therefore, the power supply should be placed as far away from critical circuitry as possible. This may require more decoupling capacitors at the load. Sensitive circuitry on the mixed signal board and on adjacent boards should not be placed where radiated noise can cause problems. Mechanical shielding can be used to shield radiated emissions.

On board filters such as LC filters are used for two purposes: (a) prevent noise from leaving the circuit it originates in and (b) prevent noise from any source from entering a sensitive circuit. In both cases the filter should be placed close to the circuit mentioned. Parasitic elements, unit variation, supplier variation and temperature effects of passive filters should be reviewed to design an effective filter.

STEP 7: VERIFY THE DESIGN AND SUPPLIERS

The electrical design of the power system in a mixed signal environment does not stop with simulation or even breadboarding. The physical layout and component parasitics are such important factors for proper operation that they should be part of the design verification process. Passive components can vary significantly between suppliers and with changes in temperature. Therefore, the design should be tested with various suppliers' parts and over the expected operating temperature.

References:

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