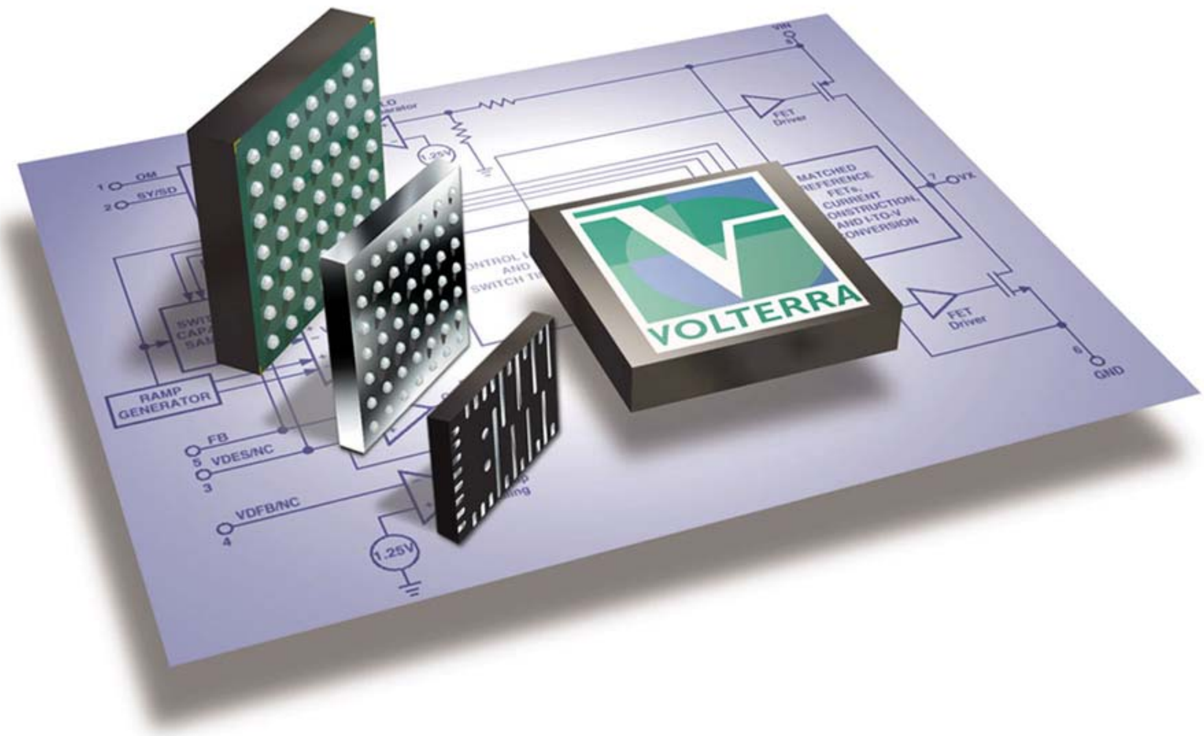

Investigation of DCR Current Sensing in Multiphase Voltage Regulators

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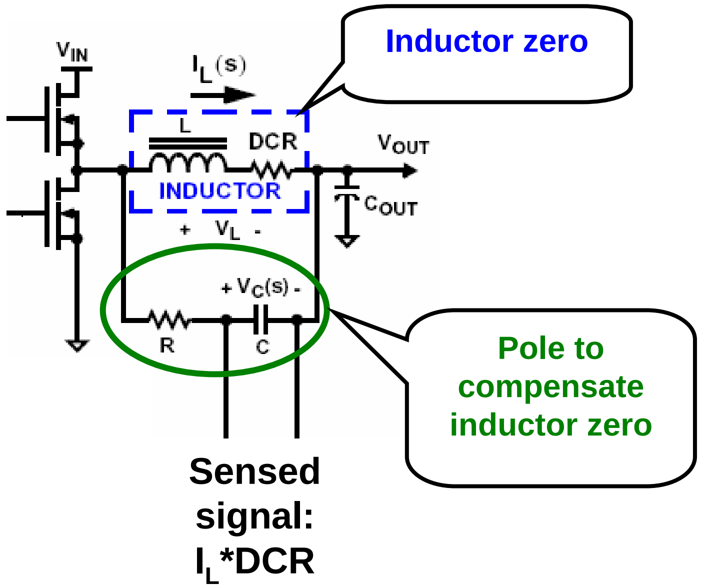
Background



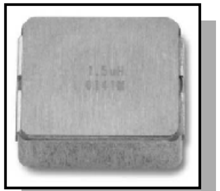
- Popular industry practice is to use inductor DCR to sense individual phase currents
- A thermistor is often used with this current sensing method to compensate for the temperature drift of the inductor DCR
- A typical current sense circuit arrangement is shown on the left
  - Tolerance of R or C does not affect sensed signal amplitude at DC
  - DCR tolerance affects accuracy of the sensed DC current and has a direct impact on the overall accuracy of the load line
- This presentation analyzes issues that arise from using the inductor DCR to measure individual phase currents in order to achieve a precisely controlled loadline

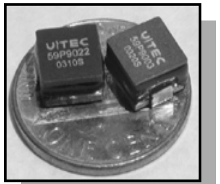
Experimental Setup

- To get a sense of DCR tolerances in a real application, five PCBs with 6 different inductors were machine assembled in a reflow oven
- Six different surface mount inductors were chosen to cover a wide range of inductor construction, DCR and inductance value
  - Two inductors had a winding construction with a relatively high inductance value and DCR
  - Two were single turn, medium inductance and medium DCR inductors (suitable for POL and medium to low frequency VRM applications)
  - Two were single staple, low inductance and low DCR inductors (suitable for high frequency VRM applications)
- Precise current was applied to each inductor and related voltage was measured using a precision voltmeter in order to accurately to determine the DCR
  - Current was applied in a fast pulse to avoid the temperature drift
  - Test board layout provided Kelvin sense points for each inductor

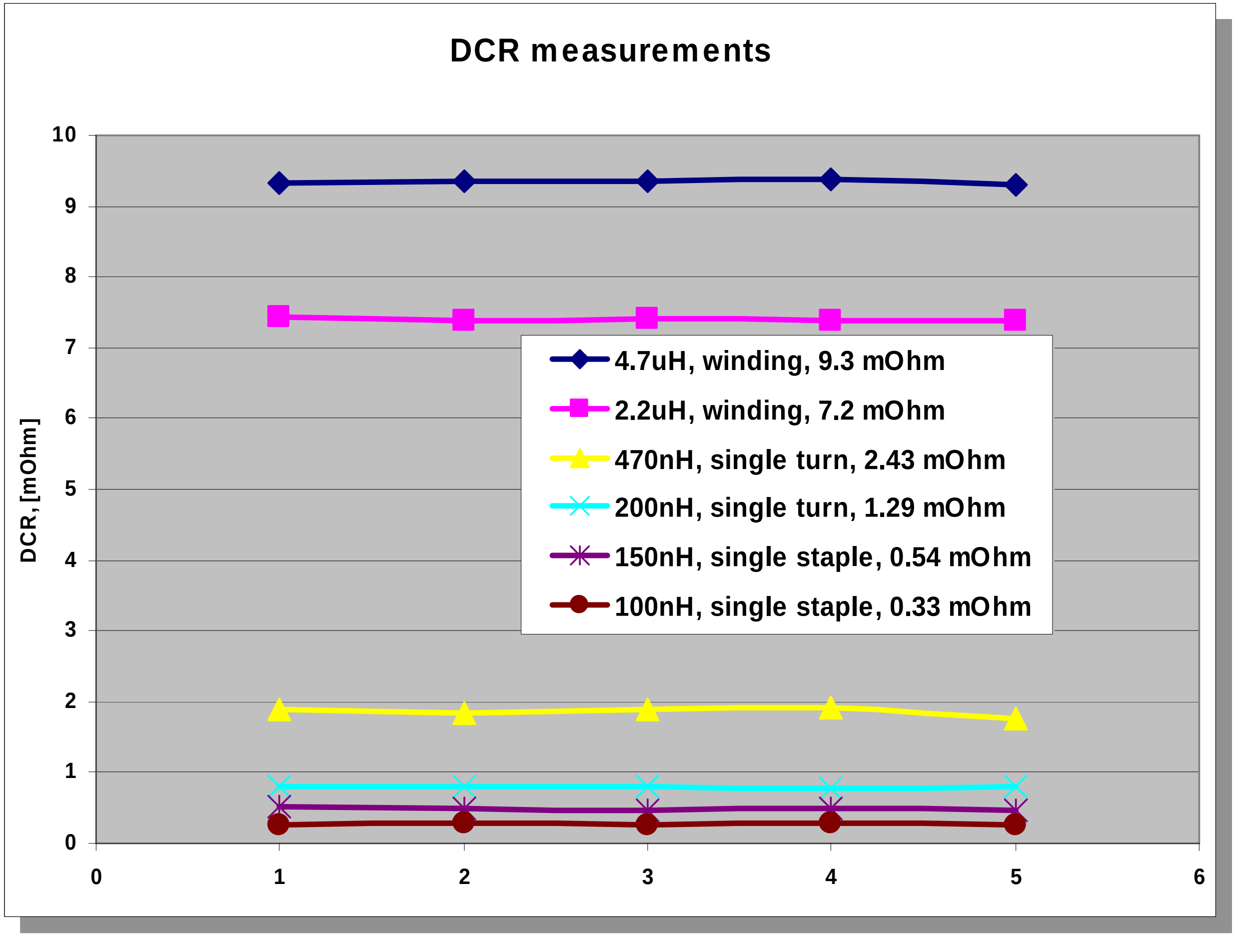
Tested Inductors

Inductor	Vishay IHLP-5050FD-4R7: 4.7uH, 9.3 mOhm	Vishay IHLP-5050CE-2R2-07: 2.2uH, 7.2 mOhm	Vitec 59P9052: 470nH, 2.43 mOhm	Vitec 59P9051: 200nH, 1.29 mOhm	Cooper FP4-150: 150nH, 0.54 mOhm	Vitec 59P9022: 100nH, 0.33 mOhm
Datasheet DCR	9.3	7.2	2.43	1.29	0.54	0.33
Board 1	9.32	7.43	1.89	0.797	0.508	0.2653
Board 2	9.35	7.38	1.84	0.793	0.489	0.2724
Board 3	9.34	7.41	1.89	0.803	0.479	0.2716
Board 4	9.39	7.39	1.91	0.788	0.483	0.2736
Board 5	9.31	7.38	1.75	0.797	0.475	0.2667
Average	**9.342**	**7.398**	**1.856**	**0.7956**	**0.4868**	**0.26992**
Max	**9.39**	**7.43**	**1.91**	**0.803**	**0.508**	**0.2736**
Min	**9.31**	**7.38**	**1.75**	**0.788**	**0.475**	**0.2653**
Range, %	0.856347677	0.67585834	8.620689655	1.885369532	6.778964667	3.074985181
Construction	Winding	Winding	Single turn	Single turn	Single staple	Single staple

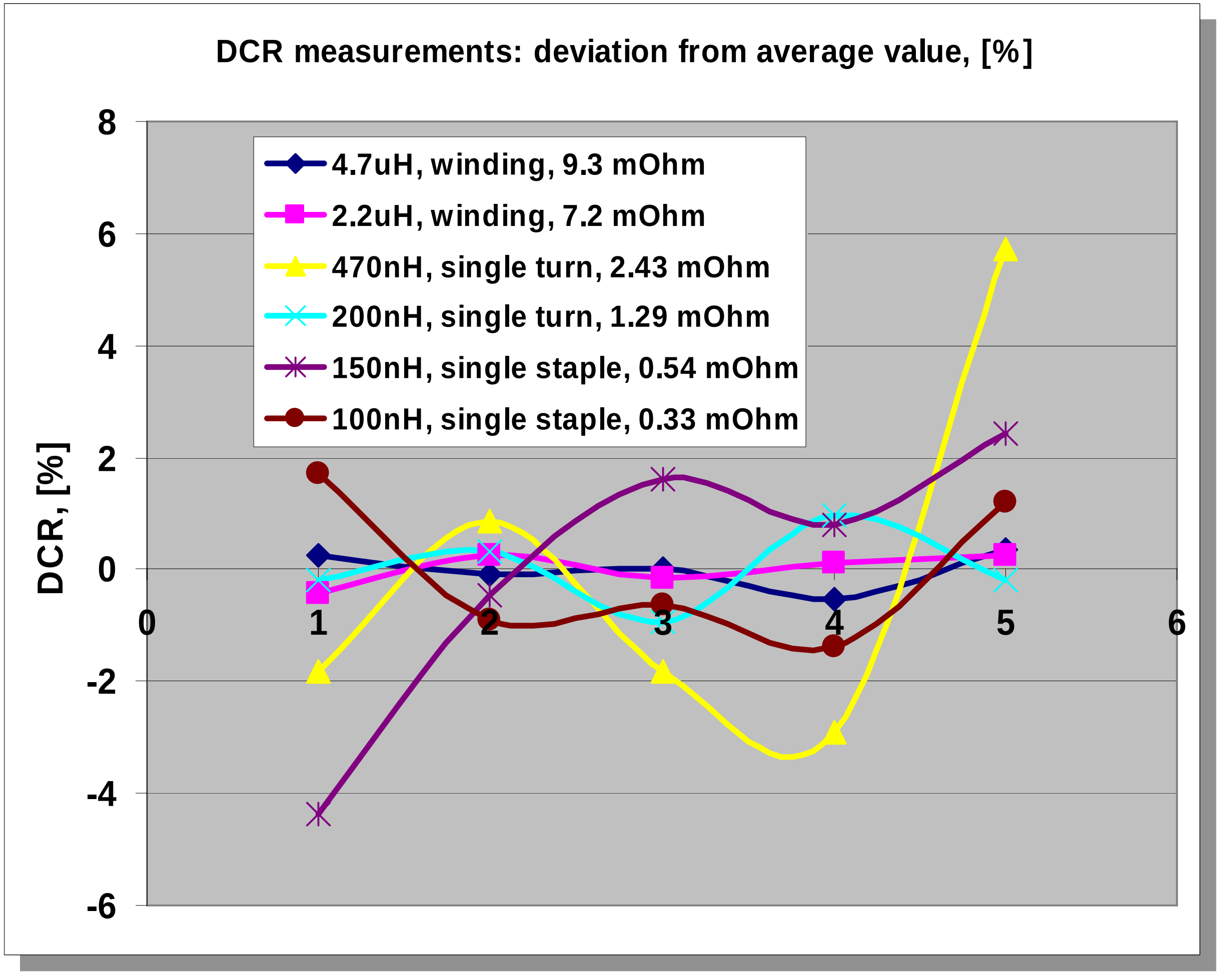



Measured DCRs



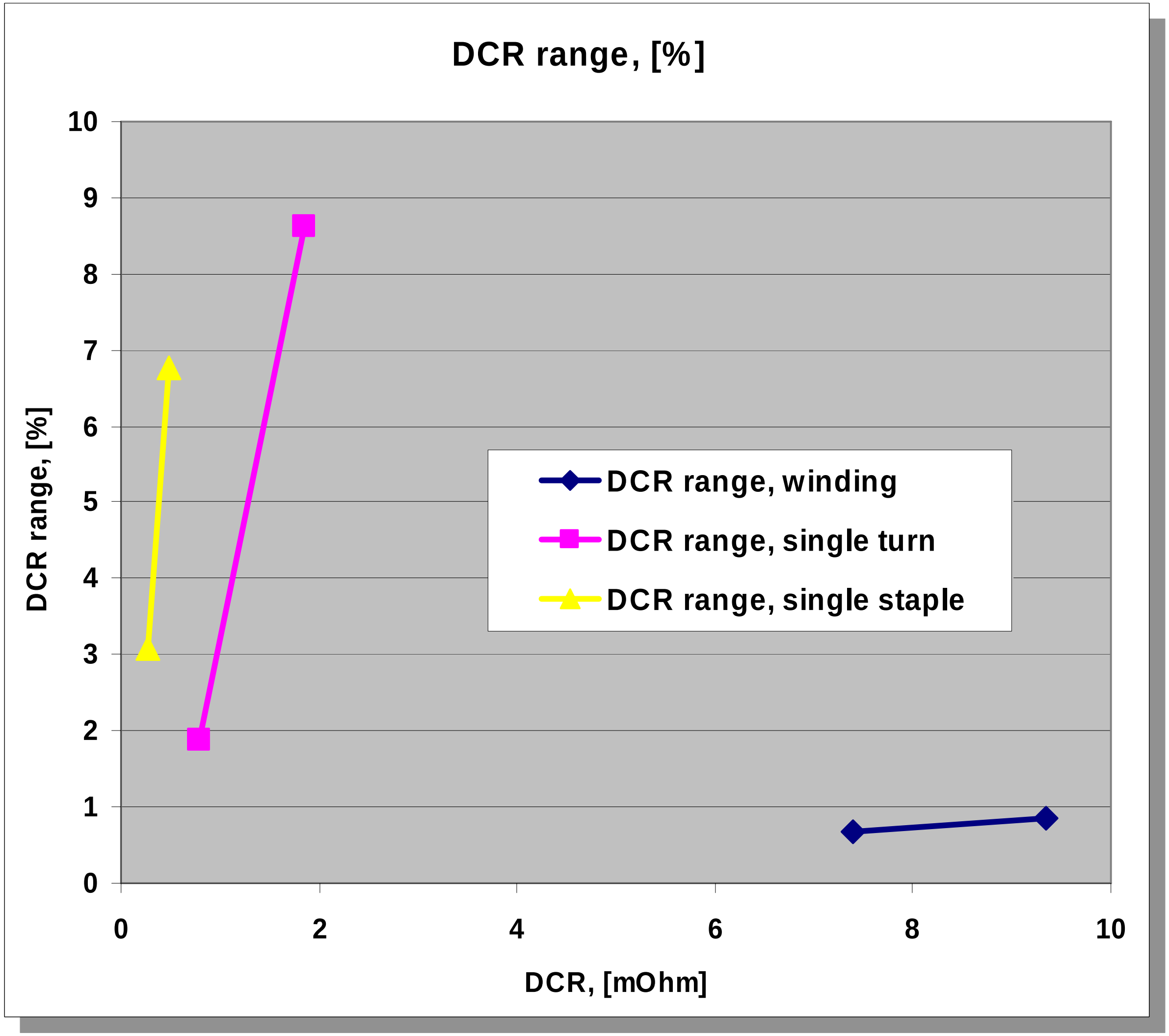
- Notice that inductor DCR value advertised in the part datasheet can be different from the "effective DCR" on a PCB which may include tolerances associated with solder attachment and pad layout

Deviation from Average



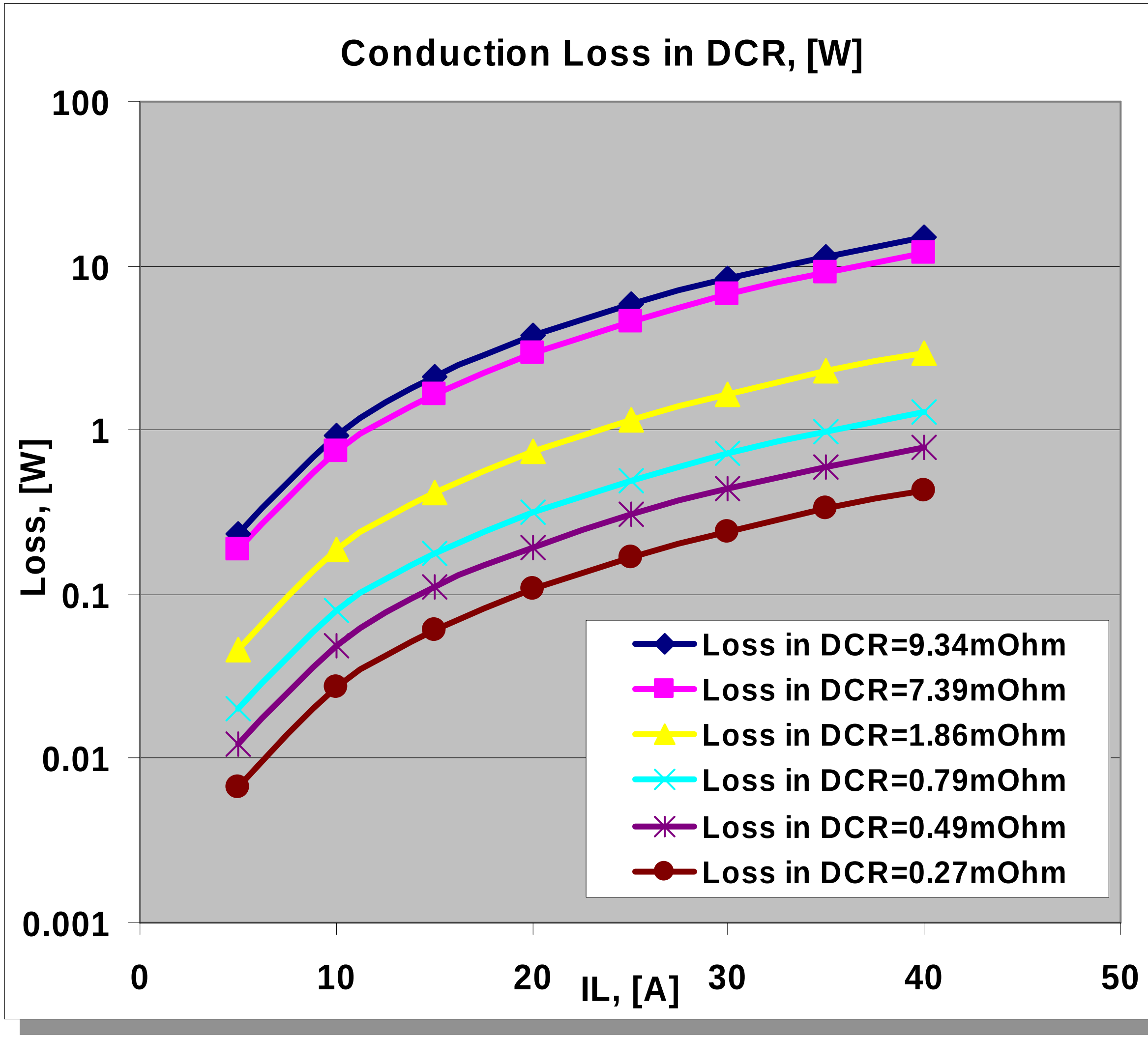
- Deviation from the average DCR value for all inductors is plotted in [%]
- The smallest deviation belongs to inductors with highest DCR
- The second inductor (2.2uH) is a special current sense inductor with a 5% DCR tolerance. It has the best controlled DCR

Range of Deviation

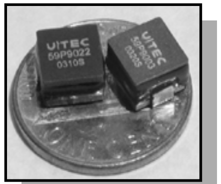


- The (total) range of deviation is extracted from the previous plot. Each point in the figure on the left corresponds to five measured inductors
- Clearly, inductors with largest DCR have the smallest tolerance range
- Smaller DCRs (for higher efficiency) are generally harder to control; inductor construction seems to play a role as well

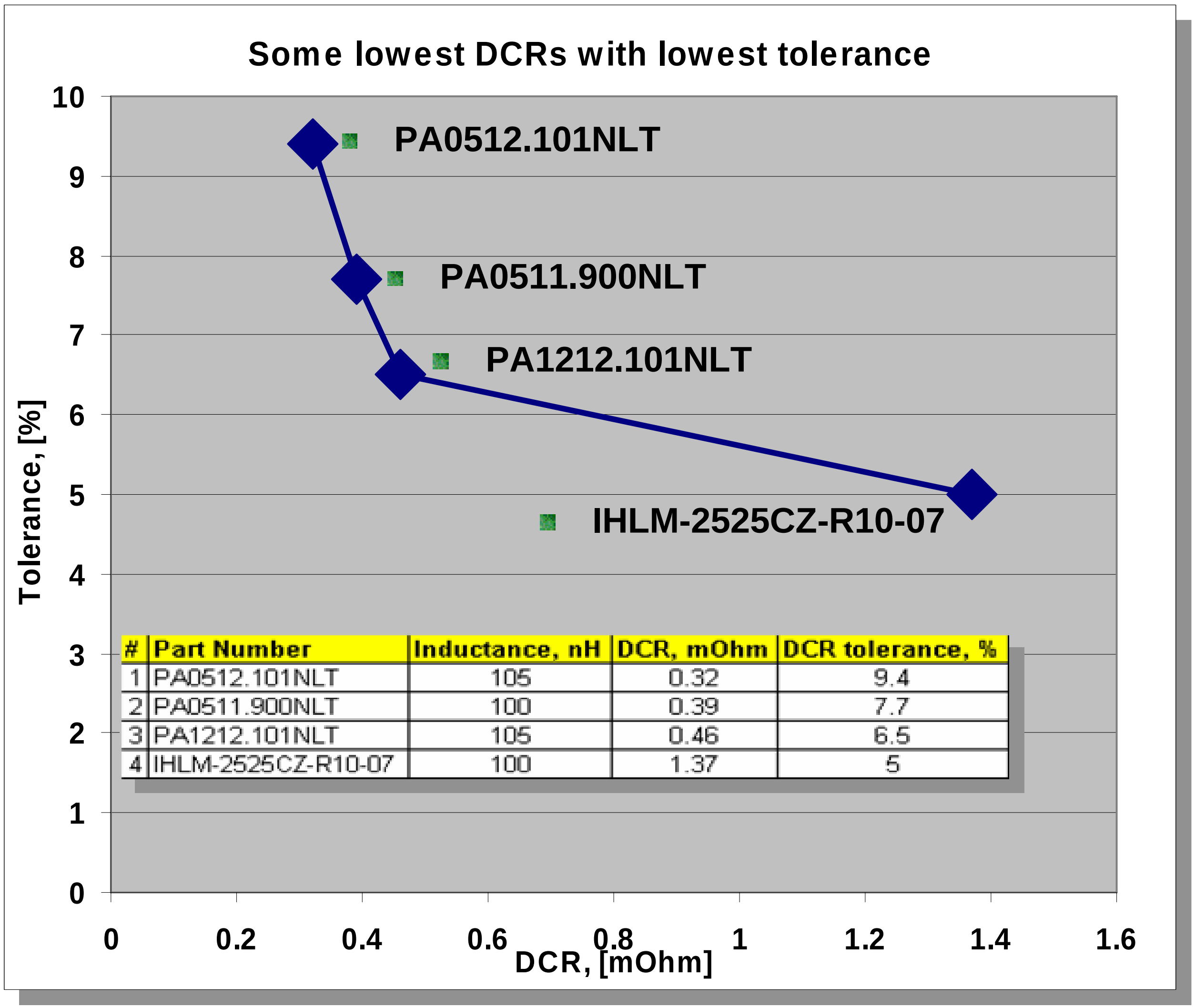
The Need for Low DCR



- Low DCR is an important factor for higher efficiency
- Plot on the left shows conduction loss for the average value of measured DCRs as a function of current
- In a 4 or 5 phase 150A VR solution, current could reach 40A per phase



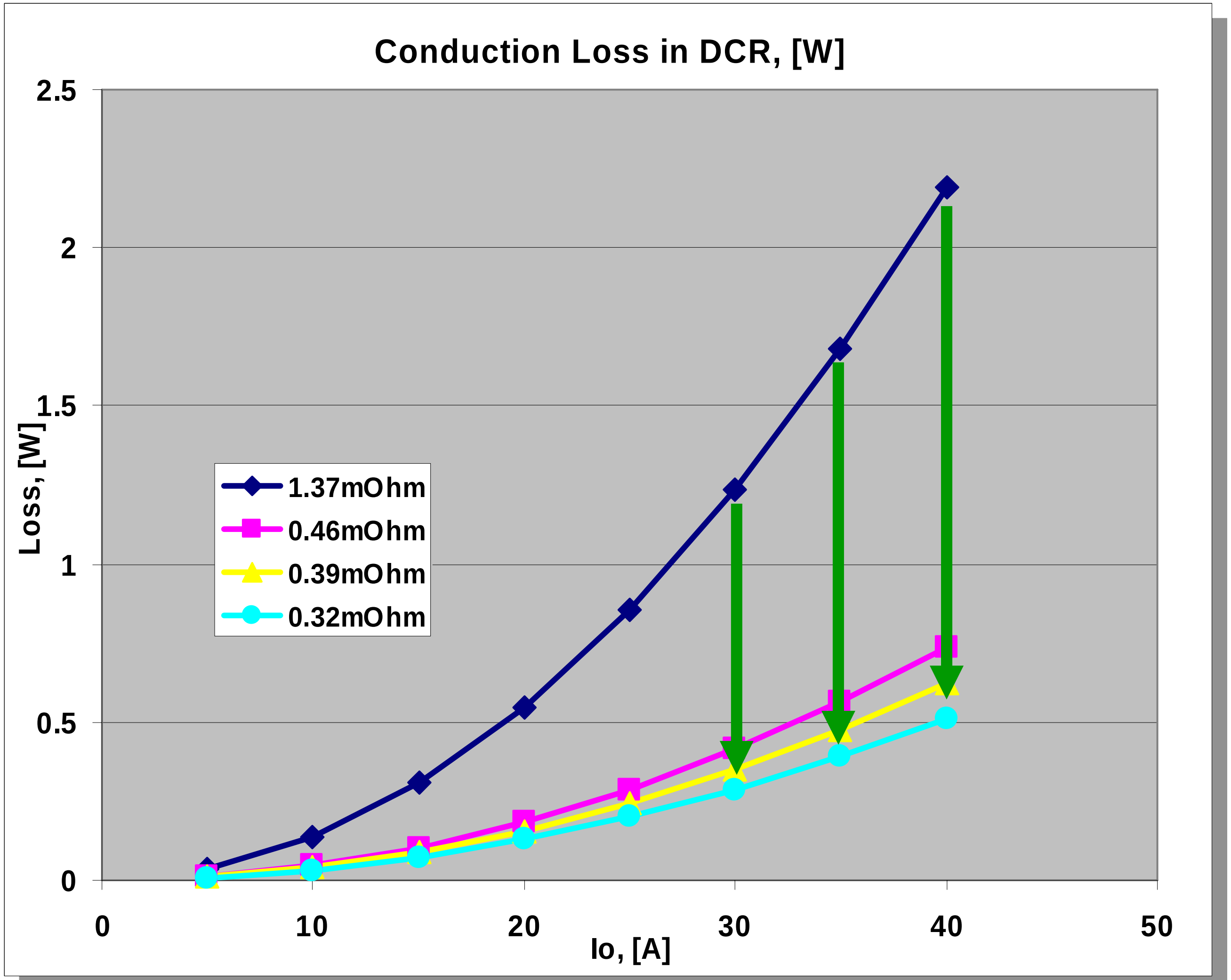
Low DCR and Low DCR Tolerance



#	Part Number	Inductance, nH	DCR, mOhm	DCR tolerance, %
1	PA0512.101NLT	105	0.32	9.4
2	PA0511.900NLT	100	0.39	7.7
3	PA1212.101NLT	105	0.46	6.5
4	IHLM-2525CZ-R10-07	100	1.37	5

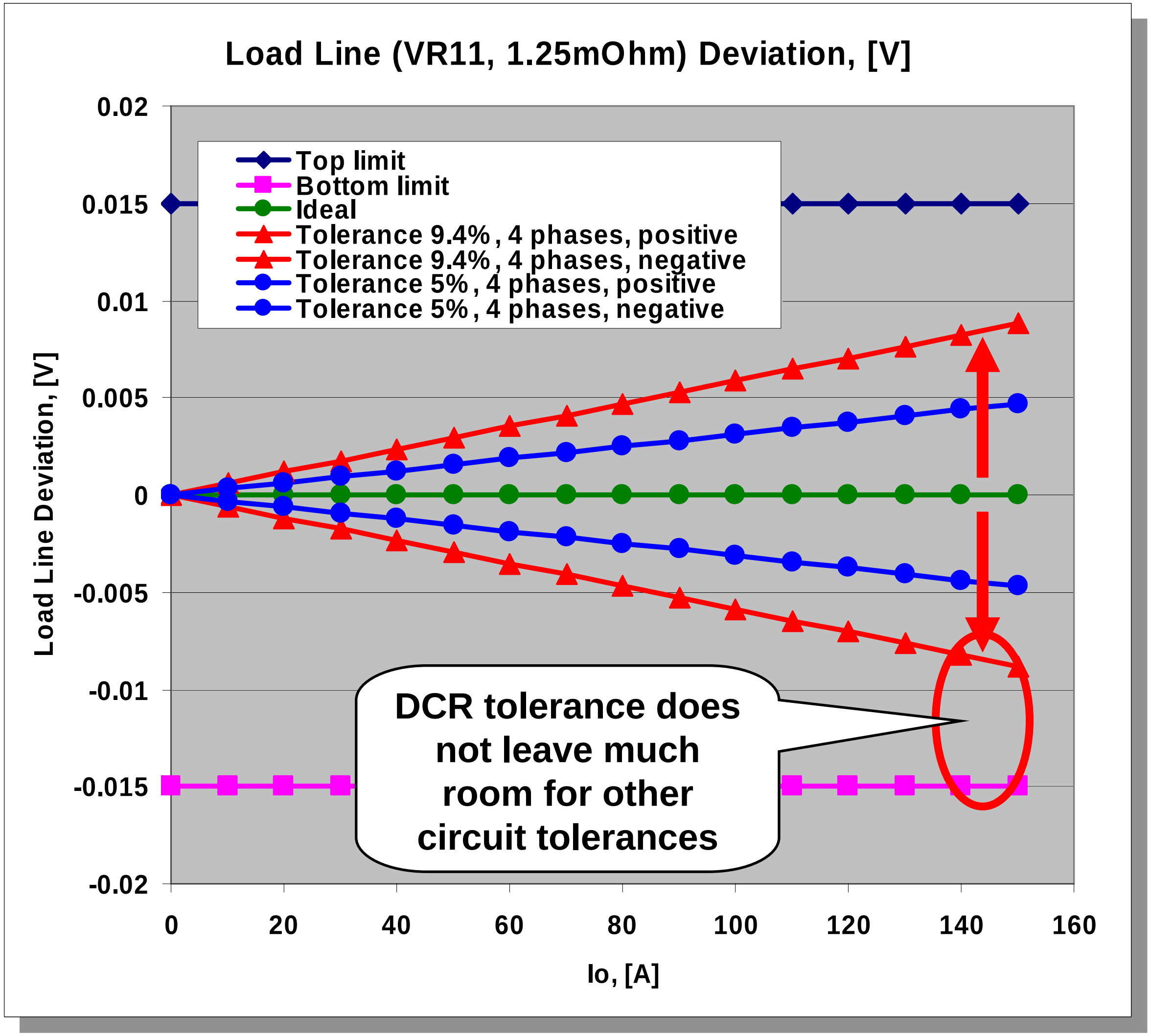
- An exhaustive search was conducted to find inductors with lowest DCR value and lowest DCR tolerance at the same time
- It is possible that other (better) parts are or will be available, but parts analyzed in this work represent best in class inductors we could find at the time of printing

Related Conduction Loss



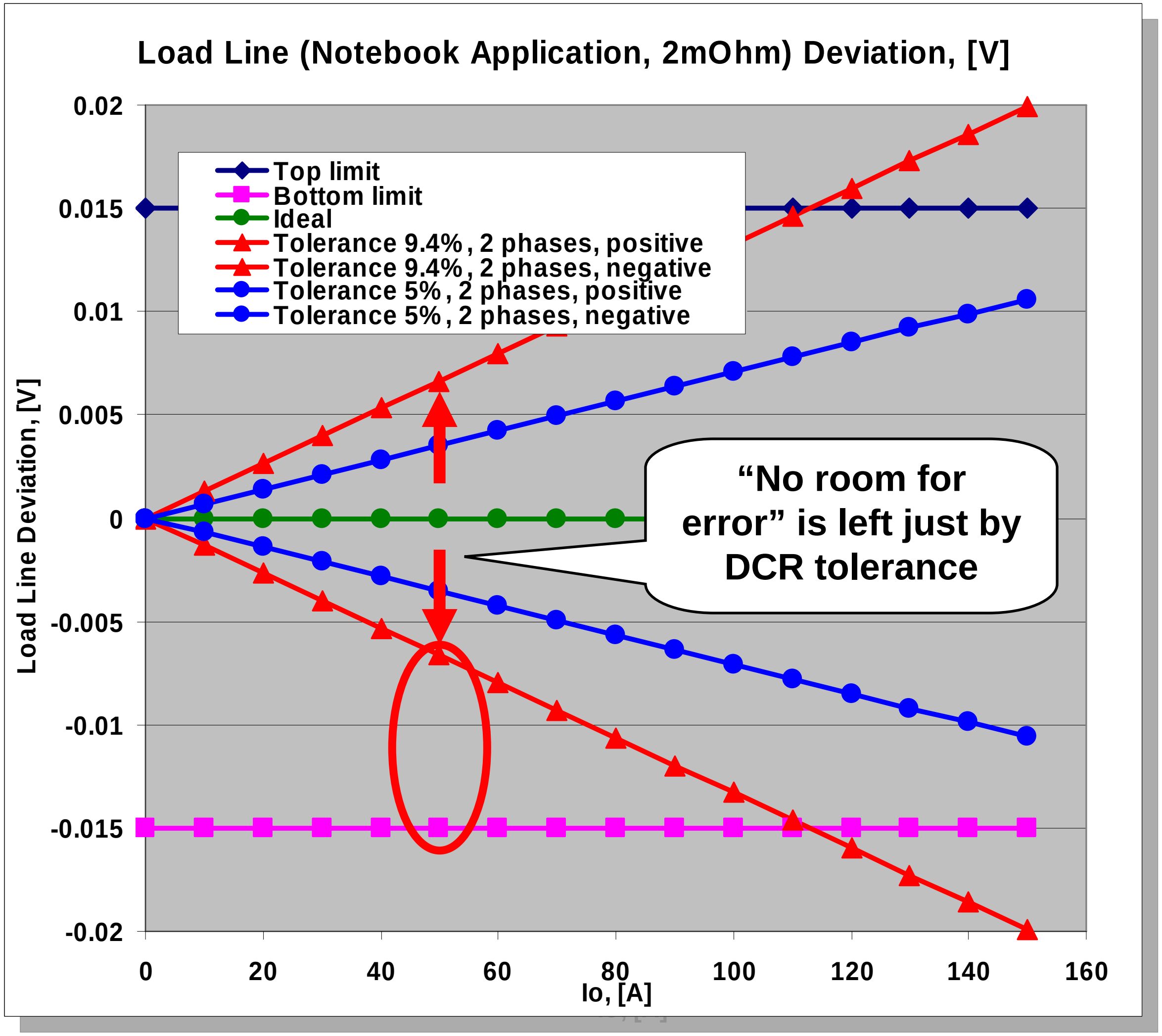
- Clearly, the lowest possible DCR is the objective from an efficiency point of view (0.32mOhm in this case)

Impact of DCR Tolerance on Load Line Accuracy in a Server/Desktop Application



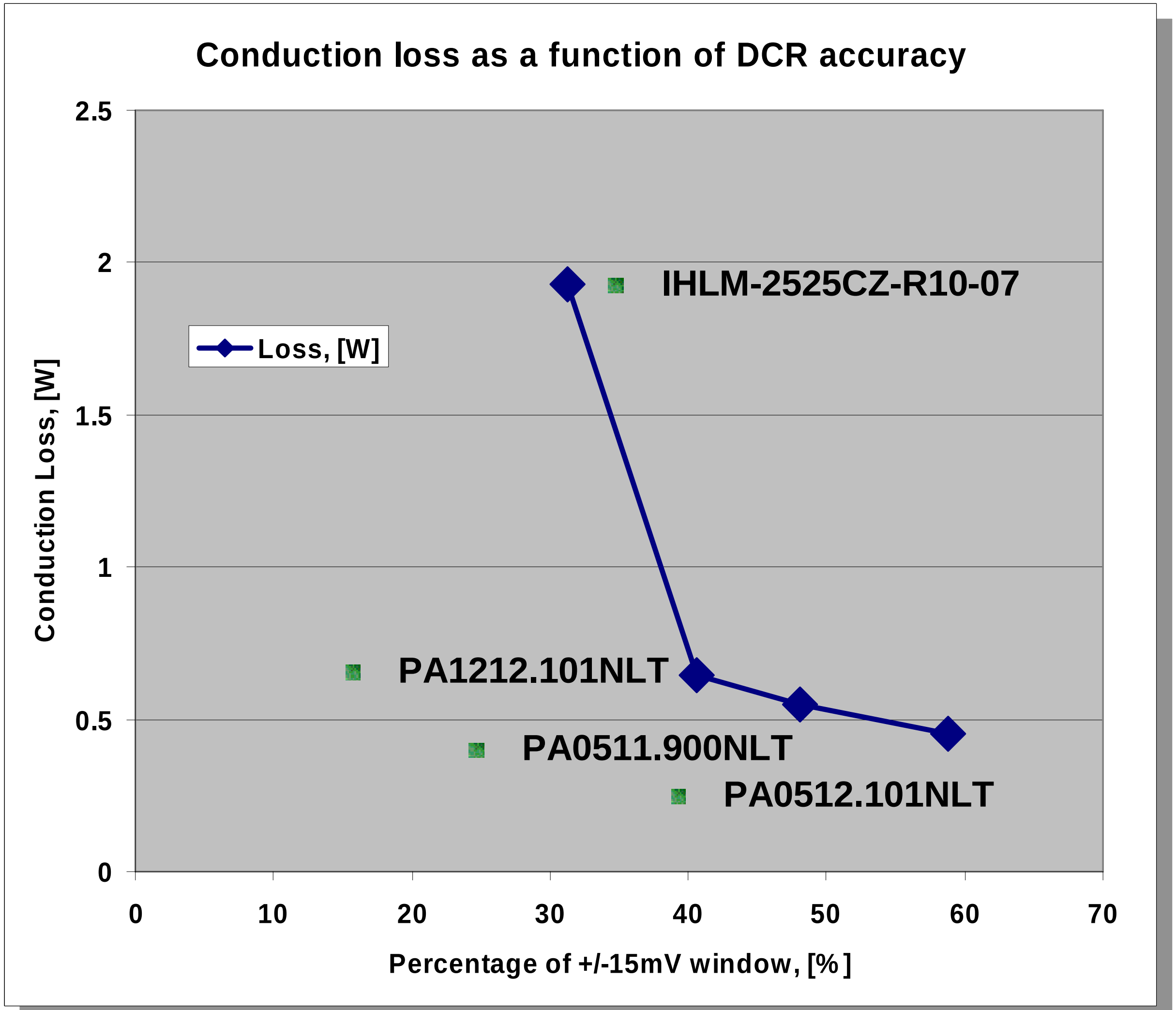
- The impact of DCR tolerance on a 4 phase VR11 solution with a 1.25mOhm loadline and a +/-15mV total tolerance window was calculated for several typical DCR tolerances
- Load line variation due to DCR tolerance is calculated as a sigma of DCR tolerance divided by a square root of the number of phases
- The best inductor from an efficiency point of view (DCR=0.32mOhm) but with a +/-9.4% DCR tolerance, would use up approximately 59% of the total tolerance window
- The best inductor from an accuracy point of view (+/-5% DCR tolerance) but with a 1.37mOhm DCR, would still use up almost one third of the total tolerance window

Impact of DCR Tolerance on Load Line Accuracy in a Notebook Application



- The impact of DCR tolerance on a 2 phase, 50A notebook-like solution with a +/-15mV total tolerance window was calculated for several typical DCR tolerances
- Load line variation due to DCR tolerance is calculated as a sigma of DCR tolerance divided by a square root of the number of phases
- Smaller number of phases has a noticeable impact on expected statistical load line tolerance
- The best inductor from an efficiency point of view (DCR=0.32mOhm) but with a +/-9.4% DCR tolerance, would use up almost 50% of the total tolerance window

Accuracy or Efficiency

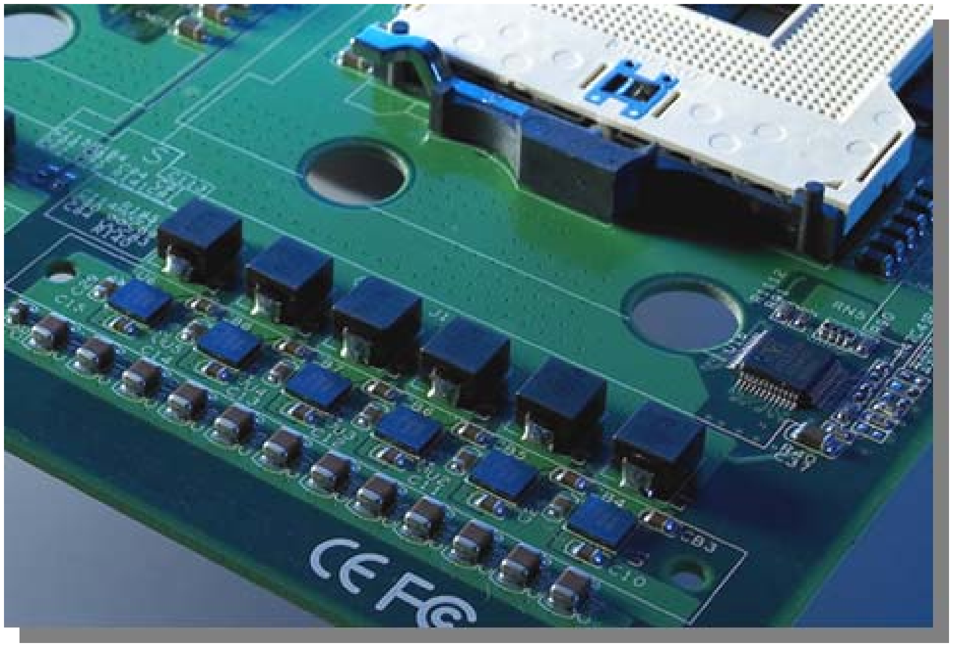


- DCR conduction loss was calculated for a typical four phase 150A VR11 application (1.25mOhm load line, +/-15mV total tolerance window)
- Plot on the left shows the efficiency vs accuracy tradeoff
  - Power loss in the inductor DCR is plotted as a function of the percentage of loadline window consumed by the DCR tolerance
- Data shows that decreasing conduction loss beyond a certain point results in a significant penalty in solution accuracy

Load Line Accuracy

- As it was shown in previous slides, a small variation in DCR value causes a potentially significant loadline variation. The main reason is that the DCR determines the slope of the sensed signal as a function of current, so load line error will grow in absolute terms as the current per phase increases
- Load line window for VR11.x applications (+/-15mV) is specified to include all circuit tolerances, not just the DCR. Load line error analysis has to include offsets, gain tolerance and CMRR in both voltage and current error amplifiers. Loosing a big portion of the tolerance window to DCR errors puts serious pressure on the tolerance of all the other circuit contributors, generally increasing silicon cost
- In order to keep overall load line in spec, solutions with DCR sensing often have to choose inductors with acceptable DCR accuracy instead of inductors with the lowest possible DCR. This limitation of DCR current sensing adversely impacts solution efficiency and cost
- Decreasing DCR adversely impacts current sense Signal-to-Noise ratio making the offset of the current sense amplifier a proportionally more significant error contributor in the overall load line accuracy. The severity of the problem is illustrated in the article “System Accuracy Analysis of the Multiphase Voltage Regulator Module” published at APEC 2003. The aforementioned work shows that a 5mV offset of the current error amplifier causes a 5-7mV error in the output voltage for a DCR of 1.2mOhm. If we were to apply the same error analysis to a 0.32mOhm DCR inductor, the load line error due to current error amp offset would proportionally increase approximately 4 times

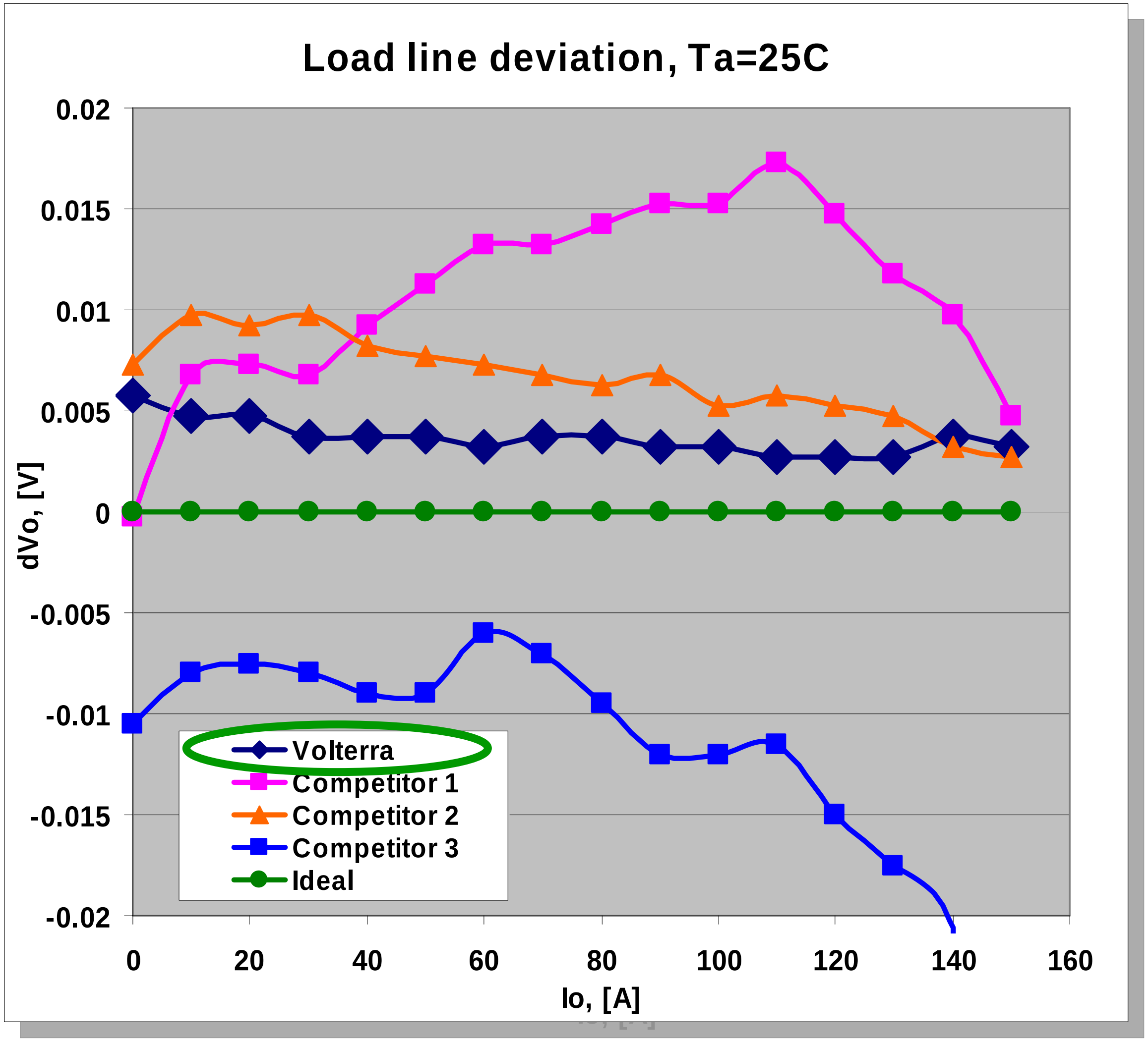
Integrated Power Stage from Volterra



- Production motherboard example
  - Single staple inductors with the lowest possible DCR are used to maximize efficiency
  - DCR tolerance does not impact VR accuracy allowing independent efficiency and cost optimization

- Volterra integrated power stage uses patented and proprietary current sense technology
  - Integrated into each power stage
  - Lossless
    - No external sense resistors needed
    - Lowest possible DCR inductors can be used for best efficiency without any accuracy penalty
  - Inherently thermally compensated
  - High speed
    - No noise or external filtering issues
  - No layout difficulties with routing sensitive current sense traces
  - No Signal-to-Noise ratio limitations due to inductor DCR value
  - Now applied to patented Volterra Coupled Inductor technology

Load Line Accuracy Comparison



- Volterra and several other competitive VR solutions were evaluated for load line accuracy by an independent source
- Volterra integrated solution shows the most consistent performance with a load line that is closest to ideal

Conclusion

- **DCR current sensing requires a tradeoff between system efficiency, accuracy and cost**
  - DCR current sensing noticeably decreases total system accuracy as DCR is lowered for better system efficiency because inductor manufacturers cannot simultaneously achieve low DCR, tight DCR tolerance and low part cost
  - With very low DCR inductors, PCB assembly and sensing parasitics can significantly impact current sense accuracy
  - Thermal DCR compensation with all its limitations is required for loadline accuracy further increasing solution complexity and cost
  - Decreasing DCR decreases the current sense signal amplitude making the offset at the input of current error amplifier a proportionally larger contributor to the overall loadline error
  - Decreasing DCR makes current sense Signal-to-Noise ratio worse for the current sense amplifier; noise in the current signal may lead to non-monotonic or irregular loadline, increased output voltage ripple and even lower efficiency if it causes irregular switching
  - For a given output current, number of phases plays a significant role in the overall loadline tolerance analysis
- **More advanced current sense and control techniques enabled by Volterra technology can achieve better solution accuracy while remaining insensitive to DCR value, tolerance and assembly parasitics. This allows Volterra to independently optimize solution efficiency, accuracy and cost**