

**DESIGN AND ANALYSIS OF A FAST TRANSIENT
VOLTAGE REGULATOR WITH ALL CERAMIC
OUTPUT CAPACITORS FOR MOBILE
MICROPROCESSORS**

By

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TABLE OF CONTENTS

ACKNOWLEDGEMENT	ii
ABSTRAK	vii
ABSTRACT	viii
LIST OF FIGURES	ix
LIST OF TABLES.....	xiii
LIST OF SYMBOLS	xiv
CHAPTER 1.....	1
1.0 Chapter Overview.....	1
1.1 Background	1
1.2 Switching Frequency of Voltage Regulator.....	3
1.3 The Need for Fast Transient Voltage Regulator.....	4
1.4 Problem Statement.....	6
1.5 Research Objective	7
1.6 Thesis Outline.....	7
CHAPTER 2.....	9
2.0 Chapter Overview.....	9
2.1 Fundamentals of Switching Voltage Regulator.....	10
2.2 Output Capacitor for Voltage Regulator.....	11
2.3 Power Delivery Architecture in Mobile Computer System.....	14
2.4 Voltage Regulator in the Power Delivery Network.....	15

2.5	Switching VR vs Linear VR.....	16
2.6	On-board VR vs On-Chip VR.....	17
2.7	Single-Phase VR vs Multi-Phase VR.....	18
2.8	Topology of Buck Converter.....	19
2.8.1	Power Stage of Buck Converter.....	19
2.8.2	Control Schemes and Techniques.....	20
2.8.3	Feedback Compensation.....	21
2.9	Output Impedance and VR Transient Response.....	22
2.10	Adaptive Voltage Positioning (AVP).....	24
2.11	Efficiency of Voltage Regulator.....	26
2.12	Chapter Summary.....	29
CHAPTER 3	30
3.0	Chapter Overview.....	30
3.1	Block Diagram of the Voltage Regulator Design.....	30
3.1.1	Controller.....	31
3.1.2	Driver.....	33
3.1.3	MOSFET.....	36
3.1.4	Current Sensing Network.....	37
3.1.5	Output LC Filter.....	39
3.2	Flow Chart of the Voltage Regulator Design.....	40
3.3	Design Specifications.....	42
3.4	Power Loss Calculator.....	43

3.4.1	MOSFET and Driver Losses	44
3.4.2	Inductor Losses	49
3.5	Design of Current Sensing Network.....	54
3.6	Determine the Number of MLCC Needed	54
3.7	Loop Gain Simulation Using MATHCAD	61
3.8	Output Impedance and Transient Simulation Using LTSpice	63
3.9	Measurement of Transient Response on Test Board	64
3.10	Chapter Summary	66
CHAPTER 4.....		67
4.0	Chapter Overview	67
4.1	Selection of Switching Frequency for Optimal Efficiency.....	68
4.2	Temperature Compensation of the Current Sensing Network	70
4.3	Selection of MLCC Type for Smallest Decoupling Area.....	71
4.4	Results of Output Impedance and Transient Simulation using LTSpice....	72
4.5	Loop Gain Response of the Voltage Regulator.....	80
4.6	Transient Response of the Voltage Regulator on Test Board	81
4.7	Chapter Summary	85
CHAPTER 5.....		86
5.0	Chapter Overview.....	86
5.1	Conclusion.....	86
5.1	Future Works.....	87
REFERENCES		89

APPENDIX A: Evaluation Module (EVM) of TPS59650	94
APPENDIX B: Schematic of TPS59650	95
APPENDIX C: Functional Block Diagram of MOSFET Driver TPS51601	96
APPENDIX D: Datasheet of Inductor MPT724-H1 Series	97
APPENDIX E: Online Datasheet of Multilayer Ceramic Capacitor GRM32ER60J107ME20	98

ABSTRAK

Keperluan untuk mereka bentuk pengatur voltan yang mempunyai tindak balas transien yang cepat didorong oleh kadar transien yang semakin meningkat daripada mikropemproses mudah alih. Oleh itu, mengoptimumkan frekuensi pensuisan pengatur voltan menjadi langkah penting untuk mencapai keseimbangan antara mengekalkan kecekapan pengatur voltan dan meningkatkan tindak balas transien. Kapasitor seramik berlapis telah menjadi lebih popular sebagai kapasitor output pengantara voltan disebabkan oleh saiznya yang kecil dan kos murah.

Walaupun topologi penukar buck kekal tidak berubah betahun-tahun, terdapat banyak inovasi dan kejayaan cemerlang dalam peringkat kuasa pengatur voltan dan teknologi kawalan. Selain itu, reka bentuk yang berorientasikan galangan keluaran dan AVP (Penempatan Voltan Automatik) telah diperkenalkan untuk menangani keperluan transien. Banyak kajian juga memberi tumpuan untuk meningkatkan kecekapan pengantara voltage terutama untuk system yang beroperasi dengan bateri.

Sebuah pengatur voltan bertindak balas laju yang mempunyai hanya kapasitor output seramik untuk mikropemproses mudah alih dicadangkan dalam kajian ini. Hasil kajian ini menunjukkan bahawa pengatur voltan yang direka adalah stabil dengan jenis dan bilangan kapasitor seramik berlapisan yang dicadangkan. Lebih penting lagi, keputusan transien juga adalah sehampir dengan keputusan simulasi di mana output pengantara voltan tidak mengalami kelanjakan dan kejatuhan voltan semasa dimuatkan dengan arus dinamik yang bermagnitud 10.5A dalam 1 μ s. Kesimpulannya, sebuah pengatur voltan dengan tindak balas laju yang mempunyai hanya kapasitor output seramik telah direka dan dianalisis and ia mempunyai tindak balas transien yang lebih baik berbanding dengan reka bentuk asal.

ABSTRACT

The need to have fast transient response of the voltage regulator is driven by the increasing current slew rate of the mobile microprocessor. Hence, optimizing the switching frequency of the voltage regulator becomes an important step to achieve a balance between preserving the efficiency of the voltage regulator and improving the transient response. Besides, output capacitor solution with multilayer ceramic capacitor has also become more popular due to its small size and cheap cost.

Over the years, even though the topology of the buck converter remains unchanged, there are plenty of innovations and breakthroughs in the power stage of the voltage regulator and controller technology. In addition, output impedance oriented design and adaptive voltage positioning (AVP) feature are also introduced to address the transient requirements. Apart from improving the dynamic response of the voltage regulator, many research works also focus on improving the efficiency of the voltage regulator, especially for battery-powered systems.

A fast transient voltage regulator with all ceramic output capacitors for mobile microprocessor is proposed in this study. The outcome of the study shows that the voltage regulator designed is stable with the proposed type and number of multilayer ceramic capacitors. More importantly, the actual transient results correlate well with the simulation results where minimal transient droop and overshoot are observed with a dynamic current load step with a slew rate of 10.5A per 1 μ s. In conclusion, a fast transient voltage regulator with all ceramic output capacitors is designed and analyzed which proven to have better transient performance compared to the original design on the test board.

LIST OF FIGURES

Figure 1.1: Key design requirements for power delivery circuits on mobile computer	2
Figure 1.2: Switching frequency of different voltage regulators [1]	3
Figure 1.3: Increasing number of transistors integrated into the processor according to Moore's law [2]	4
Figure 1.4: Trend of processor's current slew rate measured at the package pin [3] ..	5
Figure 1.5: Switching voltage regulator.....	11
Figure 2.1: Typical power delivery architecture in mobile computer system [4]	15
Figure 2.2: Power delivery network model [6]	16
Figure 2.3: Fundamental building blocks of a buck converter.....	19
Figure 2.4: Power stage of buck converter [14]	19
Figure 2.5: AVP load line programmable by the VR controller [34]	24
Figure 2.6: Illustration of benefits of AVP during transient event [35].....	25
Figure 2.7: Extended AVP (EAVP) to the full PDN network [37]	26
Figure 2.8: Typical efficiency curve of VR [39].....	27
Figure 2.9: The residency rate of different VR output currents and voltages in a notebook [5].....	28
Figure 3.1: Block diagram of the single-phase switching voltage regulator.....	31
Figure 3.2: Functional block diagram of TPS590650 from datasheet.....	32
Figure 3.3: Connections between the driver and the MOSFET	34
Figure 3.4: Timing diagram of dead-time control in TPS59601:	36

Figure 3.5: Current sensing network using DCR sensing topology	38
Figure 3.6: Load step response for different REQ.CSENSE to LOUT/DCR ratios: (a) REQ.CSENSE = Lout / DCR, (b) REQ.CSENSE > Lout / DCR, (c) REQ.CSENSE < Lout / DCR	39
Figure 3.7: Flow chart to design a fast transient response voltage regulator with all- MLCC output capacitors	41
Figure 3.8: Categories of power loss in the voltage regulator.....	44
Figure 3.9: Depiction of turn-on and turn-off path of the HS FET	46
Figure 3.10: Switching waveforms of HS FET: (a) During turn-on (b) During turn- off.....	46
Figure 3.11: Reverse recovery loss in HS FET during turn-on.....	47
Figure 3.12: (a) B-H loop of the inductor (b) CCM inductor current waveform (c) DCM inductor current waveform [50]	51
Figure 3.13: Impedance versus frequency plots for the three shortlisted MLCC	56
Figure 3.14: DC biasing effect on the three shortlisted MLCCs	56
Figure 3.15: Output impedance: (a) Voltage regulator without output capacitors, Z_{vr} (b) Output capacitors, Z_c	58
Figure 3.16: Output impedance of the voltage regulator with output capacitors	59
Figure 3.17: Output impedance versus frequency plots of the voltage regulator without capacitor, output capacitors, and the equivalent output impedance.....	60
Figure 3.18: Control Loop for the controller TPS59650	62
Figure 3.19: Schematic of the voltage regulator mode for LTSpice simulation	64
Figure 3.20: Setup of the hardware for transient response measurement on the voltage regulator test board	65

Figure 3.21: Mini-slammer connection at the output terminal of the voltage regulator for transient tests.....	65
Figure 4.1: Calculated efficiency of the voltage regulator with different switching frequency at 5.9 mΩ AVP load line.....	69
Figure 4.2: Comparison between the measured and calculated efficiency curves of 495 kHz	70
Figure 4.3: Load line of the voltage regulator versus temperature.....	71
Figure 4.4: MLCC number and MLCC area in relation to switching frequency of the voltage regulator for different MLCC type	72
Figure 4.5: 40 pieces of 22 μF MLCC are needed to achieve an output impedance lower than the specified 5.9 mΩ load line.....	73
Figure 4.6: 23 pieces of 47 μF MLCC are needed to achieve an output impedance lower than the specified 5.9 mΩ load line.....	74
Figure 4.7: 7 pieces of 47 μF MLCC are needed to achieve an output impedance lower than the specified 5.9 mΩ load line.....	75
Figure 4.8: Full frequency range response of the output impedance of the voltage regulator with 7 pieces of 47 μF MLCC	76
Figure 4.9: Comparison of output capacitor area with different type of MLCC.....	77
Figure 4.10: Droop response of the voltage regulator during load step.....	78
Figure 4.11: Overshoot response of the voltage regulator during load release	79
Figure 4.12: Bode plot of the control loop of the voltage regulator	80
Figure 4.13: Top layer view of the test board	81
Figure 4.14: Bottom layer view of the test board	82

Figure 4.15: Droop response of the voltage regulator with original output capacitors	83
Figure 4.16: Droop response of the voltage regulator with seven pieces of 100 μ F MLCCs	83
Figure 4.17: Overshoot response of the voltage regulator with original output capacitors	84
Figure 4.18: Overshoot response of the voltage regulator with seven pieces of 100 μ F MLCCs	84
Figure A.1: Power system block diagram of TPS59650 EVM	94
Figure A.2: Illustration of TSP59650 EVM test board	94
Figure B.1: Original controller schematic of TPS59650 on EVM	95
Figure B.2: Original driver and power stage implementation on TPS59650 EVM ..	95

LIST OF TABLES

Table 2.1: Common surface-mount (SMD) capacitors.....	12
Table 2.2: Trend of target impedance in desktop workstation [33].....	24
Table 3.1: Design specifications for single-phase switching voltage regulator	43
Table 3.2: MOSFET parameters of CSD87350Q5D.....	48
Table 3.3: Driver parameters of TPS51604	49
Table 3.4: Inductor part number used for different switching frequency in power loss calculation	51
Table 3.5: Power loss calculation formula for PFM mode and PWM mode	52
Table 3.6: Component values of the current sensing network	54
Table 3.7: Original output capacitor configuration for GPU rail on the test board...	55
Table 3.8: Proposed shortlisted large capacitance multilayer ceramic capacitor to replace the tantalum polymer capacitors.....	55
Table 3.9: RLC parameter of the shortlisted MLCCs.....	60
Table 3.10: Number of MLCC needed and MLCC area for 100uF, 47uF, and 22uF MLCCs with different switching frequency.....	61

LIST OF SYMBOLS

AC	Alternating current
A _{CS}	Gain of current sense amplifier
AVP	Adaptive voltage positioning
B _{max}	Maximum flux density
C _{boot}	Bootstrap capacitor
CCM	Continuous conduction mode
C _{droop}	Droop setting capacitor
C _{DS}	Drain-to-Source capacitance
C _{GD}	Gate-to-Drain capacitance
C _{GS}	Gate-to-Source capacitance
C _{in}	Input capacitance
C _{ISS}	Input parasitic capacitance of MOSFET
CMC	Current mode control
C _{OSS}	Output parasitic capacitance of MOSFET
C _{out}	Output capacitance
CPU	Central processing unit
C _{RSS}	Transfer parasitic capacitance
CSN	Negative current sense feedback terminal
CSP	Positive current sense feedback terminal
C _{VDD}	Input capacitance for supply voltage V _{DD}
dB	Decibel
DC	Direct current

DCM	Discontinuous conduction mode
DCR	Parasitic resistance of the inductor
DRVH	High-side MOSFET driver signal
DRVL	Low-side MOSFET driver signal
ESL	Equivalent series inductance of the capacitor
ESR	Equivalent series resistance of the capacitor
ET	Volt-second balance of the inductor
F _{CO}	Bandwidth of the voltage regulator
FET	Field effect transistor
FOM	Figure of merit
F _{SW}	Switching frequency
F _Z	Frequency of zero
GFB	Ground feedback terminal
G _L	Loop gain
G _M	Gain of error amplifier
GPU	Graphic Processing Unit
I _{DIODE}	Diode current
HS	High-side
I _{DRVH}	Driver signal current
I _{max}	Maximum load current
IMVP7	Intel mobile voltage positioning – 7
I _{out}	Output current
I _{q5V_controller}	5V quiescent current of the controller
I _{q3.3V_controller}	3.3V quiescent current of the controller
I _{q5V_driver}	5V quiescent current of the driver

$I_{q3.3V_driver}$	3.3V quiescent current of the driver
I_{rr}	Reverse recovery current
I_{sat}	Saturation current of inductor
I_{step}	Dynamic current step of the load current
L_o	Output inductance
L_{out}	Output inductor
LS	Low-side
L_{VR}	Series inductor for voltage regulator model
MLCC	Multi-layer ceramic capacitor
MOSFET	Metal oxide field effect transistor
N-Ph	Number of phase
NVDC	Narrow direct current voltage
PCB	Printed circuit board
P_{core_PWM}	Core loss of inductor in PWM mode
PDN	Power delivery network
PFM	Pulse frequency modulation
PWM	Pulse width modulation
Q_G	Gate charge of MOSFET
Q_{GD}	Gate-to-Drain charge of MOSFET
Q_{GS}	Gate-to-Source charge of MOSFET
Q_{TH}	Gate charge of MOSFET at threshold point
Q_{OSS}	Output charge of MOSFET
Q_{rr}	Reverse recovery charge of MOSFET
Q_{SW}	Gate charge at switch point voltage
R_{cs}	Equivalent current sense resistance

R_{damp}	Damping resistor for MOSFET driver signal
$R_{\text{driver_sink}}$	Internal sinking resistance of driver
$R_{\text{driver_source}}$	Internal sourcing resistance of driver
R_{droop}	Droop setting resistor
$R_{\text{ds(on)}}$	Drain-to-source resistance of MOSFET
R_{g}	Internal gate resistance of MOSFET
R_{LL}	Load line
R_{load}	Output loading resistance
SMD	Surface mount device
SMT	Surface mount technology
SVID	Serial voltage identification
SW	Switch node
T_{DEAD}	Dead time
$T_{\text{DLY(fall)}}$	Delay time for falling edge
$T_{\text{DLY(rise)}}$	Delay time for rising edge
T_{off}	OFF time
T_{on}	ON time
T_{period}	Period
T_{rr}	Reverse recovery time
T_{slew}	Slew time
V_{c}	Control voltage
$V_{\text{DIODE_LS}}$	Forward voltage drop of body diode of low-side MOSFET
V_{DRIVE}	Driver voltage
V_{DS}	Drain-to-source voltage
VFB	Voltage feedback terminal

V_{GS}	Gate-to-Source voltage
$V_{GS(th)}$	Gate-to-Source threshold voltage
V_{in}	Input voltage
VMC	Voltage mode control
V_o	Output voltage
V_{out}	Output voltage
VR	Voltage regulator
V_{SP}	Switch point voltage
Z_c	Impedance of output capacitor
Z_{droop}	Impedance of droop setting RC components
Z_{out}	Output impedance
Z_{target}	Target impedance
Z_{vr}	Output impedance of voltage regulator

CHAPTER 1

INTRODUCTION

1.0 Chapter Overview

Chapter 1 is the introductory chapter of this study. First of all, Section 1.1 provides the background of the study and also listed down the five important criteria for a good voltage regulator in mobile segment. Section 1.2 explains the trend of switching frequency in the industry and the challenges to optimize the switching frequency to achieve a balance between good transient performance and good efficiency. Section 1.3 justifies the need to design a fast transient voltage regulator with optimized number of output capacitor in order to keep the solution size small and cheap. The problem statement and research objective are presented in Section 1.4 and Section 1.5 respectively. Last but not least, Section 1.6 provides the thesis outline.

1.1 Background

Non-isolated DC-DC voltage regulator is the key component of power delivery network in a modern computer system. It is used to step down the high DC input voltage to a well regulated lower output voltage which is consumed by platform devices. Out of all the platform devices, the design of the voltage regulator for the processor is most demanding and challenging because the quality of the power delivery network to the processor determines the overall performance of the system.

There are many key parameters which dictates the quality of a voltage regulator design. In fact, the importance of each parameters can be varied across different industry and segments. Figure 1.1 depicts the key parameters for a good voltage regulator design for mobile system such as laptop.

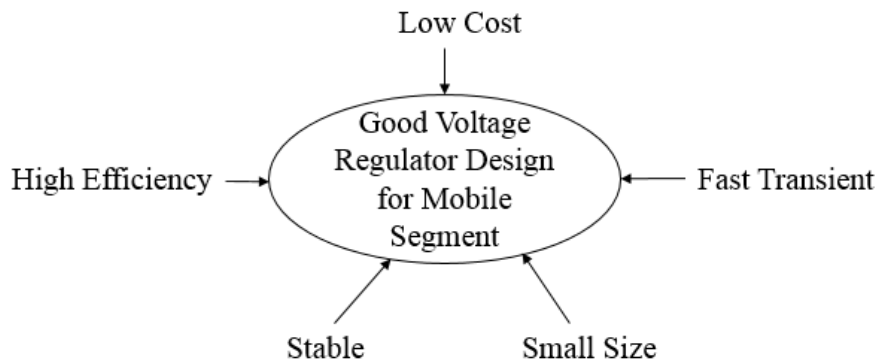


Figure 1.1: Key design requirements for power delivery circuits on mobile computer

First of all, the voltage regulator must be stable under all possible operating conditions, and this is the most important and fundamental requirement. Secondly, fast transient response of the voltage regulator has become more and more important as the mobile processor load current switches at a much higher slew rate nowadays. A fast reacting and stable voltage regulator is able to keep the output voltage under the specified regulation window even when high current transient event happens. A fast transient voltage regulator can also bring significant cost and area benefit to the voltage regulator solution. The reason is when the voltage regulator can react fast enough to high frequency transient, significant amount of output capacitors can be saved. This directly translates to less design cost and board area occupied.

Efficiency is another key metric to gauge the quality of the voltage regulator in a mobile computer system. A voltage regulator with good efficiency has low power

loss which is translated to prolonged battery life for a battery-powered system. In addition, an efficient voltage regulator requires only simple thermal solution. In a greater extent, the whole system can be designed in a chassis with no fan at all. In fact, fan-less design is very much a requirement in thin and light-weight laptop design such as Intel's Ultrabooks.

1.2 Switching Frequency of Voltage Regulator

Typical design specifications for a switching regulator includes input voltage range, output voltage, maximum output current, and worst case magnitude of the dynamic output current. Switching frequency is the key design parameter that has direct impact to the transient performance and efficiency of the voltage regulator. Figure 1.3 below shows the typical switching frequency for different power converters in the market. For the case of voltage regulator residing in a mobile computer system, the switching frequency ranges from 200 kHz to 1 MHz. In fact, the trend for switching frequency of voltage regulator has been increasing steadily over the years.



Figure 1.2: Switching frequency of different voltage regulators [1]

High switching frequency is good for transient performance and reducing size of the passive components such as inductor and capacitors of the voltage regulator. However, too high of a switching frequency will degrade the efficiency of the voltage regulator and increase the risk of control loop instability. Hence, voltage regulator designer faces a great challenge to find the suitable switching frequency in order to meet both the efficiency and transient performance targets.

1.3 The Need for Fast Transient Voltage Regulator

Moore's law propelled the semiconductor industry to double the number of transistors integrated into the processor every 18 to 24 months as shown in Figure 1.4 below. In addition, advancement of semiconductor manufacturing process also helps to reduce the supply voltage to the processor to sub-1V in the most recent processors.

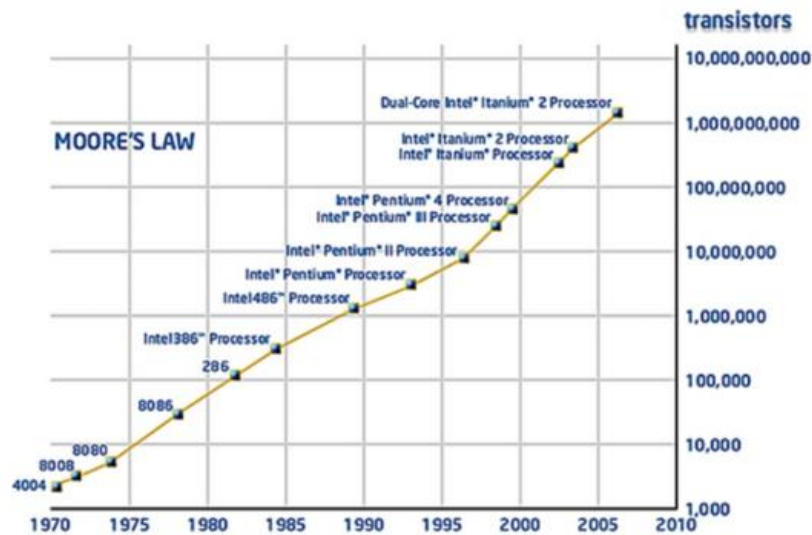


Figure 1.3: Increasing number of transistors integrated into the processor according to Moore's law [2]

However, current demand for processors is increasing year-over-year due to aggressive integration strategy and increasing complexity of circuit blocks inside the processor. Besides, computational frequency of the processor will always be pushed higher from one generation of processor to the next. Together with incremental power saving states being introduced to the processor C-states, the current profile of the processor becomes more dynamic in nature. Figure 1.5 below shows that the trend of the current slew rate of processor is increasing year-over-year when new generation of processors are released.

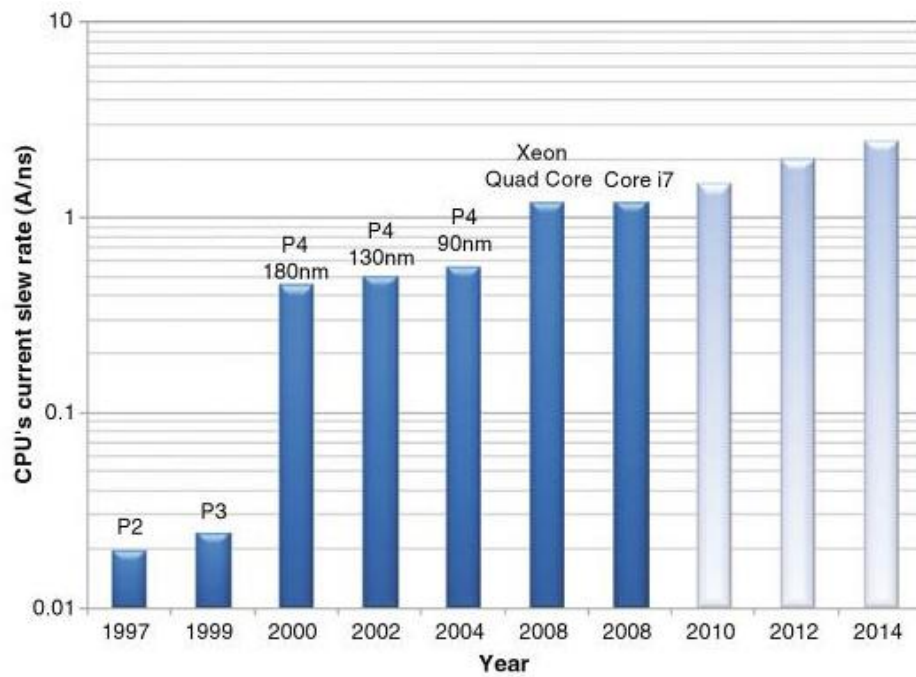


Figure 1.4: Trend of processor's current slew rate measured at the package pin [3]

The industry is trying to catch up with the high current slew rate of the processor current load by developing voltage regulator with high switching frequency. However, as mentioned in section 1.2, the switching frequency range for voltage regulator is limited in order to preserve the efficiency and stability. The other design solution to address the high current slew rate is to design with huge number of output

capacitors. Unfortunately, design with too many output capacitors will increase the product cost and consume huge amount of board area. This is not a favorable solution for mobile segment. As a result, this situation poses a great challenge to the voltage regulator designer.

1.4 Problem Statement

Fast transient voltage regulator is very much needed to address droop and overshoot caused by the high current slew rate of the processor. Increasing the switching frequency of the voltage regulator is a way to improve the transient response. However, on-board voltage regulator has limited switching frequency range. Besides, too high of a switching frequency will result in poor efficiency. Hence, this situation challenges the voltage regulator design to optimize both the switching frequency and efficiency at the same time.

Secondly, size of the voltage regulator has always been too huge driven by increasing power demand of the mobile processor. This renders the overall mobile computing product to be heavy, bulky, costly, and unattractive. With AVP feature introduced, now the voltage regulator designer has the option to design with all ceramic output capacitors in order to present an area and cost effective solution. However, design with all ceramic output capacitors requires thorough analysis and engineering judgment so that the solution presented is stable and meets the design specifications.