

Non-Intrinsic Differential-Mode Noise in Switching Power Supplies and Its Implications to EMI Filter Design

Song Qu

Thesis submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

Master of Science
in
Electrical Engineering

Dan Y. Chen
Dusan Borojevic
Alex Q. Huang

February 12, 1999
Blacksburg, Virginia

Keywords: NIDM, Switching Power Supplies, EMI, Filter

Non-Intrinsic Differential Mode Noise in Switching Power Supplies and Its Implications to EMI Filter Design

Song Qu

ABSTRACT

Electromagnetic Interference (EMI) problems in switching power supplies have been traditionally treated with cut-and-try approaches. In recent years, advancement has been made to better understand the problems and minimize the cut-and-try portion of the design process. However, there are still phenomena difficult to explain in many practical design situations. Often, the problems may be solved by luck but many puzzles remain unsolved. If not fully understood, these puzzles are very likely to come back to haunt the designers.

According to the conventional theory, there are two modes of noise: the Differential-Mode (DM) noise and the Common-Mode (CM) noise. Recently, a new noise-coupling mode called Non-Intrinsic Differential-Mode (NIDM) noise was uncovered accidentally in the process of explaining certain EMI filter action [1]. This phenomenon has never been thoroughly studied. The focus of the present thesis is to investigate the NIDM phenomenon and its implications to practical EMI filter design issues.

The generation mechanism and basic characteristics of this phenomenon will be briefly reviewed, which is crucial to the understanding of the remaining parts of the research. Two essential diagnostic tools are introduced. One is the DM/CM noise separator and the other is the zero-span mode operation of a spectrum analyzer.

The results of the investigation will be presented. The results will be presented using practical examples, which tie the phenomenon to filter design issues. In some examples, explanations are given to dispel the puzzles commonly encountered in the practice.

A filter design procedure is suggested for off-line power supplies. This procedure incorporates the NIDM phenomenon into an existing design procedure. Only first-order and second-order filter topologies are included in the discussion.

Acknowledgments

I wish to express my deepest and sincerest appreciation to Dr. Dan Y. Chen, my academic advisor and the principle investigator of this project. His extensive knowledge and insightful thinking inspired the fundamental concept of the present thesis. His constant guidance and encouragement have helped me get through so many difficulties in the research process.

I would like to express my gratitude to Dr. Dusan Borojevic and Dr. Alex Q. Huang, members of my advisory committee for the enlightening suggestions and valuable encouragement.

I also want to extend my appreciation and best wishes to the excellent faculty, staff and students of CPES/VPEC, who have made my stay an unforgettable and enjoyable one.

Last, but not the least, my thanks go to my wife and my parents for their love, support, and understanding, which have made this work possible.

Table of Contents

Chapter 1 Introduction	1
1.1 Background and Motivations	1
1.2 Outline of Thesis	3
Chapter 2 Non-Intrinsic Differential-Mode Noise	4
2.1 Review of Conventional Conducted EMI Theory	4
2.1.1 CM Noise	6
2.1.2 DM Noise	7
2.2 Diagnosis Tools for Conducted EMI	8
2.2.1 Noise Separator	9
2.2.2 Zero-Span Mode of Spectrum Analyzer	11
2.3 Generation of Non-Intrinsic Differential-Mode Noise	13
2.3.1 Description of NIDM Phenomenon	13
2.3.2 NIDM Noise Generation Mechanism	15
2.3.2.1 Rectifier Diodes On	15
2.3.2.2 Rectifier Diodes Off	17
2.4 Basic Characteristics of NIDM	20
2.4.1 Dependency of NIDM on Line Voltage	20
2.4.2 Dependency of NIDM on Load Current	21

Chapter 3 Implications of NIDM to EMI Filter Design	23
3.1 Asymmetrical vs. Symmetrical DM Chokes	23
3.1.1 Description of Phenomenon	25
3.1.2 Effect of Asymmetrical DM Choke	27
3.1.3 Effect of Symmetrical DM Choke	29
3.2 Effect of X Capacitor on NIDM	31
3.3 Position of X Capacitor in Filter	38
3.3.1 Asymmetrical Inductor with X Capacitor	38
3.3.1.1 X Capacitor on EUT Side	40
3.3.1.2 X Capacitor on LISN Side	44
3.3.2 Symmetrical Inductor with X Capacitor	46
3.4 Effect of CM Choke on NIDM	50
3.5 Determination of Balancing Cap (X Cap) Value.....	53
 Chapter 4 EMI Filter Design Incorporating NIDM	 58
4.1 Basis for EMI Filter Design	58
4.1.1 Noise Source Impedance	58
4.1.2 Possible Filter Topologies	59
4.2 Determine the Position of X Capacitor	63
4.3 EMI Filter Design Procedure	65

4.3 Design Example	72
Chapter 5 Conclusions and Future Work	85
5.1 Conclusions	85
5.2 Future Work	87
Reference	88
Vita	89

List of Figures

Fig.1-1 Conducted EMI Measurement Setup	2
Fig.2-1 A Typical Switching Power Supply Circuit	5
Fig.2-2 Noise Path of CM Noise	6
Fig.2-3 Noise Path of DM Noise	8
Fig.2-4 Principles of Noise Separator	10
Fig.2-5 Spectrum Analyzer Display of EMI Noise	12
Fig.2-6 DM Emission Measurement Result	13
Fig.2-7 DM Noise Displayed in Zero-Span Mode	14
Fig.2-8 Rectifier Diodes On; Switch being Turned Off	16
Fig.2-9 Rectifier Diodes On; Switch being Turned On	17
Fig.2-10 Rectifier Diodes Off; Switch being Turned Off	18
Fig.2-11 Rectifier Diodes Off, Switch being Turned On	19
Fig.2-12 NIDM at Different Line Voltages	21
Fig.2-13 NIDM at Different Load Currents	22
Fig.3-1 Test Setup of Asymmetrical Filter	24
Fig.3-2 Asymmetrical DM Choke vs. Symmetrical DM Choke	26
Fig.3-3 Noise Path Models with Asymmetrical DM Choke	27
Fig.3-4 DM Noise with Asymmetrical DM Choke (Zero-Span Mode)	29
Fig.3-5 Noise Path Models with Symmetrical DM Chokes	30
Fig.3-6 Balancing Noise Paths with X Capacitor	33

Fig.3-7 Effect of X Capacitor on NIDM (Zero-Span Mode)	34
Fig.3-8 Effect of X Capacitor on NIDM (Normal Operation Mode)	35
Fig.3-9 Effect of X Capacitor on CM Noise	37
Fig.3-10 Two Asymmetrical DM Filter Topologies	39
Fig.3-11 Noise Path Model: Asymmetrical DM Choke, X Cap on EUT Side	41
Fig.3-12 DM with Asymmetrical Choke and X Cap on EUT Side	42
Fig.3-13 DM with Asymmetrical Choke and 0.33 μ F X Cap on EUT Side	43
Fig.3-14 Noise Path Model: Symmetrical Choke and X Cap on LISN Side	44
Fig.3-15 DM with Asymmetrical Choke and X Cap on LISN Side	45
Fig.3-16 Noise Path Model with X Cap on EUT Side	47
Fig.3-17 Noise Path Model with X Cap on LISN Side	48
Fig.3-18 DM Noise with Symmetrical Choke and X Cap	49
Fig.3-19 Experiment Setup for CM Choke Effect	50
Fig.3-20 Effect of CM Choke on NIDM (Zero-Span Mode)	51
Fig.3-21 Effect of CM Choke on DM Noise	52
Fig.3-22 X Capacitor on LISN Side	53
Fig.3-23 X Capacitor on EUT Side	54
Fig.3-24 Impedance of X Cap Affects NIDM Attenuation	56
Fig.3-25 Same X Cap on LISN and EUT Side	57
Fig.4-1 Equivalent Model of Noise Sources	59
Fig.4-2 Effective Filter Topologies for CM Noise	60

Fig.4-3 Effective Topologies for IDM Source	61
Fig.4-4 Available EMI Filter Topologies	63
Fig.4-5 Comparison of X Cap on LISN Side and on EUT Side	64
Fig.4-6 Flow Chart of Old Design Procedure	66
Fig.4-7 Flow Chart of New Design Procedure	71
Fig.4-8 Baseline Noise	74
Fig.4-9 First-Order Filter Topology	75
Fig.4-10 Determine Corner Frequencies of First-Order Filter	77
Fig.4-11 Second-Order Filter Topology	78
Fig.4-12 Determine Corner Frequencies of Second-Order Filter	80
Fig.4-13 Filter Design Results	81
Fig.4-14 Conducted EMI Emission with Filter	83
Fig.4-15 Design Result from Old Procedure	84