



# **AN ULTRA-COMPACT THREE-PORT DC/DC CONVERTER**

By

**Amr Sayed Taha Meabed**

A thesis submitted to the  
Faculty of Engineering at Cairo University  
In Partial Fulfillment of the  
Requirements for the Degree of  
DOCTOR OF PHILOSOPHY

In

**Electrical Power and Machines Engineering**

**FACULTY OF ENGINEERING, CAIRO UNIVERSITY  
GIZA, EGYPT  
2017**

# **AN ULTRA-COMPACT THREE-PORT DC/DC CONVERTER**

By

**Amr Sayed Taha Meabed**

A thesis submitted to the  
Faculty of Engineering at Cairo University  
In Partial Fulfillment of the  
Requirements for the Degree of  
DOCTOR OF PHILOSOPHY

In

**Electrical Power and Machines Engineering**

**Under supervision of**

**Prof. Dr. Essam Mohamed Abul Zahab    Dr. Abdelmoamen Osama Mahgoub**

Electrical Power and Machines  
Department  
Faculty of Engineering, Cairo University

Electrical Power and Machines  
Department  
Faculty of Engineering, Cairo University

**FACULTY OF ENGINEERING, CAIRO UNIVERSITY  
GIZA, EGYPT  
2017**

# **AN ULTRA-COMPACT THREE-PORT DC/DC CONVE`RTER**

By

**Amr Sayed Taha Meabed**

A thesis submitted to the  
Faculty of Engineering at Cairo University  
In Partial Fulfillment of the  
Requirements for the Degree of  
DOCTOR OF PHILOSOPHY

In

**Electrical Power and Machines Engineering**

**Approved by the Examining Committee:**

**Prof. Dr. Essam El-Din Mohamed Abul Zahab**

**Main Supervisor**

---

**Prof. Dr. Khaled Aly El-Metwally**

**Member**

---

**Prof. Dr. Mohamed Bayoumy Abdel Kader Zahran**

**Member**

---

**FACULTY OF ENGINEERING, CAIRO UNIVERSITY  
GIZA, EGYPT  
2017**

# **Acknowledgements**

First of all, all thanks go to Allah, the most gracious and merciful for brewing me the reasons that led to completion of this work.

I like to express my deepest gratitude to Prof. Osama Mahgoub for his trust, insight, guidance, and support before, during, and after this work. He was the reason why this work started and also was the reason why this work completed.

I would like to express my deep sincere thanks to Prof. Esaam Abul Zahab for his understanding, support, and patience. His support and understanding were substantial and indispensable for this work to complete.

Finally, I must give the deepest thanks to my supervisor and co-worker Dr. Abdelmomen Mahgoub for his inspiration, help, and support. He provided me with the ideas, energy, and support from the start to the finish of this work.

# Table of Contents

<b>Chapter 1: Introduction .....</b>	<b>1</b>
1.1 Switch-Mode Power Supplies .....	2
1.2 Challenges Facing Switching Converters .....	4
1.2.1 Higher Efficiency Requirement .....	4
1.2.2 Higher Power Density Requirement .....	5
1.3 Thesis Outline .....	6
<b>Chapter 2: Application of Magnetic Shaking to Ferrite Core Transformers.....</b>	<b>7</b>
2.1 Introduction.....	7
2.2 Magnetic Materials .....	7
2.3 Origin of Ferromagnetism .....	8
2.3.1 Curie Temperature .....	9
2.3.2 Magnetization Process .....	11
2.3.3 The B-H Loop .....	12
2.3.4 Minor BH Loops .....	14
2.3.5 Permeability .....	14
2.4 Filter Inductor Design.....	15
2.5 Magnetic Material Used in SMPS Cores.....	16
2.5.1 Metal Alloys.....	16
2.5.2 Powdered Metal Cores .....	16
2.5.3 Ferrite Core .....	16
2.6 Magnetic Shaking .....	17
2.6.1 Using PSpice to Simulate the Effect of Magnetic Shaking .....	18
2.6.2 Obtaining BH Loop Using PSpice .....	18
2.6.3 Simulation of Magnetic Shaking Using PSpice.....	20
2.6.4 Boost Converter with Shaking .....	23
2.7 Experimental Work.....	25
2.7.1 The Power Amplifier .....	27
2.7.2 Integrator.....	28
2.8 Effect of Magnetic Shaking on the Ferrite Cores .....	32
2.8.1 Dependence of BH Curve On Amplitude, Frequency and Waveform of the Applied Shaking Field.....	34
2.8.2 Inserting Shaking Coil in A Boost Converter .....	34
<b>Chapter 3: DC Flux Compensation in SMPS Magnetic Cores .....</b>	<b>38</b>

3.1	Core Size Reduction .....	40
3.2	Core Design .....	43
3.3	Simulation Results .....	44
3.4	Experimental Work.....	48
<b>Chapter 4: A Three-Port Bidirectional Buck-Boost Regulator Optimized for Solar Lighting Applications.....</b>		<b>51</b>
4.1	Introduction.....	51
4.2	Power Circuit.....	51
4.3	Proposed Circuit Operation .....	54
4.4	Proposed Circuit Analysis: .....	57
4.4.1	Battery Charger Circuit Analysis.....	57
4.4.2	LED Driver Circuit Analysis .....	60
4.5	Converter Design .....	60
4.5.1	Battery Sizing.....	60
4.5.2	Solar Panel Sizing .....	61
4.5.3	Inductor Design.....	62
4.5.4	Output Capacitor Design.....	64
4.5.5	Transistor Design .....	64
4.6	Proposed Circuit Simulation.....	65
<b>Chapter 5: Conclusions and Future Work.....</b>		<b>70</b>
<b>References .....</b>		<b>72</b>
<b>Appendix A : Filter Inductor Design.....</b>		<b>74</b>
A.1	Filter inductor.....	74
A.2	Filter Inductor Design Constraints .....	76
A.2.1	Maximum flux density.....	78
A.2.2	Inductance.....	78
A.2.3	Winding area.....	78
A.2.4	Winding resistance .....	79
A.2.5	The core geometrical constant $K_g$ .....	79
A.3	A Step-by-Step Procedure .....	80
A.3.1	Procedure .....	81
A.3.1.1	Determine core size .....	81
A.3.1.2	Determine Air Gab Length.....	81
A.3.1.3	Determine number of turns.....	81
A.3.1.4	Evaluate wire size.....	81

A.4	Summary of key points .....	81
<b>Appendix B : Magnetics Design Tables .....</b>		<b>83</b>
B.1	Pot CoreData .....	83
B.2	EE CoreData.....	84
B.3	EC Core Data .....	85
B.4	ETD CoreData.....	86
B.5	PQCoreData .....	87
B.6	ETD39 Core Data.....	88
B.7	Ungapped.....	88
B.8	Gapped.....	88
B.9	Coil former and Yoke .....	89
B.10	Mechanical stress and mounting .....	89
B.11	Effects of core combination on AL value .....	90
B.12	Heating up .....	90
B.13	NiZn-materials .....	90
B.14	Processing notes.....	90

# List of Tables

Table 2.1: Curie Temperatures for Some Common Magnetic Materials.....	11
Table 2.2 Boost Converter Component Values .....	35
Table 3.1: Boost Converter Parameters .....	40
Table 3.2: Buck-boost regulator parameters.....	48
Table 4.1: Solar panel data at STC [21] .....	61
Table 4.2: LED module data.....	62
Table 4.3: Converter design parameters .....	62
Table A.1: Summery of Basic Quantities need in Inductor Design .....	80



# List of Figures

Figure 1.1: Schematic of a linear mode regulator .....	1
Figure 1.2: Block diagram of a switching regulator.....	3
Figure 1.3: Sever Power Systems [2] .....	4
Figure 1.4: Efficiency requirement for AC/DC Converter [5] .....	5
Figure 1.5: Microprocessor power consumption over the years [6].....	5
Figure 1.6: Power density roadmap [7] .....	6
Figure 2.1: BH characteristic of different materials .....	8
Figure 2.2: Magnetic domains .....	9
Figure 2.3: Domain walls [8].....	9
Figure 2.4: Magnetization of a ferromagnetic material. (a): External field = 0 (b): With external field applied .....	11
Figure 2.5: Magnetic moments rotation .....	12
Figure 2.6: The BH curve of initially un-magnetized material [8].....	13
Figure 2.7: BH loop of a magnetic material .....	13
Figure 2.8: Minor BH loops .....	14
Figure 2.9: Initial permeability of a material.....	15
Figure 2.10: Relation between BH loop width and permeability .....	15
Figure 2.11 Principle of Shaking Process.....	17
Figure 2.12: PSpice model of an inductor coupled with a core.....	18
Figure 2.13: BH loop for the inductor from PSpice simulation .....	19
Figure 2.14: PSpice model used to obtain minor BH loops .....	19
Figure 2.15: Minor HB loops from PSpice simulation .....	20
Figure 2.16: PSpice model with no shaking applied .....	21
Figure 2.17: Simulation result in case of no shaking applied.....	21
Figure 2.18: PSpice model with 0.05A shaking current applied.....	22
Figure 2.19: Simulation result with 0.05A shaking current .....	23
Figure 2.20: PSpice model for the boost converter .....	24
Figure 2.21: Inductor Current in case of no shaking .....	24
Figure 2.22: Inductor Current with shaking applied .....	25
Figure 2.23: Schematic of the experimental setup .....	26
Figure 2.24: Power amplifier schematic diagram.....	27
Figure 2.25: S-Domain representation of the pure integrator.....	28
Figure 2.26: Finite DC gain integrator .....	30
Figure 2.27: PSpice model to compare the response of the pure integrator and the finite DC gain integrator .....	31
Figure 2.28: Frequency response of the pure integrator and the finite DC gain integrator .....	31
Figure 2.29: Finite DC gain integrator with offset nulling.....	32
Figure 2.30: DC BH curve of the ferrite core used in the experiments. The x-axis is showing the current to represent the applied magnetic field.....	33
Figure 2.31: BH curve of the ferrite core with and without magnetic shaking .....	33
Figure 2.32 BH Curve of the ferrite core without and with shaking averaged .....	34
Figure 2.33 BH curve of the core with sinusoidal shaking current .....	35
Figure 2.34 BH curve of the core with square wave shaking current .....	35

Figure 2.35: BH curves of the material under different shaking levels.....	36
Figure 2.36: Inductor Current without shaking .....	37
Figure 2.37: Inductor current with shaking .....	37
Figure 2.38: Photo of the experimental setup.....	37
Figure 3.1: Operating point on the BH loop when inductor current comprises a DC component ( $H_{DC}$ ) and an AC component ( $\Delta H$ ) .....	38
Figure 3.2: BH loop with DC flux removed.....	39
Figure 3.3: Converter inductor with no DC bias .....	39
Figure 3.4: Inductor with bias winding added.....	40
Figure 3.5: Buck-boost Converter .....	40
Figure 3.6: CCM Steady-state inductor current .....	41
Figure 3.7: Inductor current at the boundary between CCM and DCM.....	41
Figure 3.8: AC inductor current .....	44
Figure 3.9: PSpice model of the buck-boost converter with DC bias .....	45
Figure 3.10: Inductor current without DC bias .....	45
Figure 3.11: Inductor current with DC bias.....	46
Figure 3.12: BH loop without DC bias.....	47
Figure 3.13: BH loop with DC bias.....	47
Figure 3.14: Experimental setup.....	48
Figure 3.15: Photo of the experimental setup.....	49
Figure 3.16: Inductor current without DC bias .....	49
Figure 3.17: Inductor current with DC bias.....	50
Figure 4.1: Solar street lighting system block diagram.....	51
Figure 4.2: Power circuit for the conventional solar street lighting system.....	52
Figure 4.3: Block diagram of standard three-port converter .....	52
Figure 4.4: Three-port converter proposed in [17].....	53
Figure 4.5: Power circuit of the proposed three-port converter .....	54
Figure 4.6: Proposed circuit in charging mode .....	54
Figure 4.7: Proposed circuit in LED driver mode .....	55
Figure 4.8: Charging mode.....	57
Figure 4.9: Charging mode - Mode (1) .....	57
Figure 4.10: Charging mode - Mode (2) .....	58
Figure 4.11: Supply current waveform.....	59
Figure 4.12: Filter capacitor current.....	59
Figure 4.13: Converter waveforms in charging mode.....	63
Figure 4.14: PV panel PSpice model.....	66
Figure 4.15: Battery PSpice model.....	66
Figure 4.16: Simulation Model.....	67
Figure 4.17: Steady-state output voltage .....	67
Figure 4.18: Steady-state inductor current .....	68
Figure 4.19: Average transistor losses.....	68
Figure 4.20: Average power loss of standard MOSFET .....	69
Figure A.1: Filter inductor employed in a continuous conduction mode buck converter: (a) circuit schematic, (b) inductor current waveform.....	75
Figure A.2: Filter inductor: (a) structure, (b) magnetic circuit model.....	75
Figure A.3: Filter Inductor Minor B-H loop .....	76

Figure A.4: Filter inductor equivalent circuit.....	76
Figure A.5: Filter inductor: (a) assumed geometry, (b) magnetic circuit.....	77
Figure A.6: The winding must fit in the core window area.....	78

# List of Symbols

$A_c$	Core Cross Sectional Area
$A_w$	Wire Area
$B$	Magnetic Flux Density
$B_{max}$	Maximum Flux Density
$B_r$	Remanence
$B_{sat}$	Saturation Flux Density
$C$	Capacitance
$f_s$	Switching Frequency
$f_{shaking}$	Shaking Frequency
$H$	Magnetic Field
$H_c$	Coercivity
$H_{ext}$	Externally Applied Field
$H_m$	Main Winding Field
$H_s$	Shaking Field
$i_-$	Inverting Input Terminal Current
$i_+$	Non- Inverting Input Terminal Current
$I_1$	Minimum Inductor Current
$I_2$	Peak Inductor Current
$I_a$	Average Load Current
$i_c$	AC Current Component
$I_{DC}$	DC Current Component
$i_L$	Instantaneous Inductor Current
$I_L$	Average Inductor Current
$I_{max}$	Maximum Average Inductor Current
$I_{mpp}$	Maximum Power Point Current
$I_o$	Average Output Current
$i_R$	Resistance Current
$I_s$	Average Supply Current
$I_{sc}$	Short-Circuit Current
$K$	Core Coupling
$k$	Duty Cycle
$K_g$	Core Geometrical Factor
$k_{max}$	Maximum Duty Cycle
$k_{min}$	Minimum Duty Cycle
$K_u$	Winding Fill Factor
$L$	Inductance
$L_c$	Critical Value of the Inductance
$l_g$	Air Gap Length

$l_m$	Mean Magnetic Path Length
$mT$	Milli Tesla
$N$	Number of Turns
$P_{cu}$	Copper Losses
$P_{loss}$	Power Losses
$P_{max}$	Maximum Power
$P_{out}$	Output Power
$Q_c$	Capacitor Charge
$R_F$	Feedback Resistance
$R_L$	Load Resistance
$S$	Laplace Variable
$S_1$	Switch number 1
$T$	Periodic Time
$t_I$	On Time
$V_c$	Capacitor Voltage
$V_{cc}$	Bias Supply Voltage
$V_{in}$	Input Voltage
$V_{mpp}$	Voltage at Maximum Power
$V_o$	Output Voltage
$V_{oc}$	Open Circuit Voltage
$V_s$	Supply Voltage
$W_I$	Winding number 1
$W_A$	Core Windows Area
$\eta$	Efficiency
$\mu$	Magnetic Permeability
$\mu_i$	Initial Permeability
$\mu_o$	Free space Permeability
$\mu_r$	Relative Permeability
$\mu_D$	Differential Permeability
$\phi$	Magnetic Flux
$\phi_{DC}$	DC Component of the Flux
$\phi_{AC}$	AC Component of the Flux
$\phi_{total}$	Total Flux
$\Delta V_C$	Capacitor Voltage Ripples
$\Delta B$	Change in Flux Density
$\Delta H$	Change in Magnetic Field
$\Delta I$	Inductor Current Ripples
$\mathcal{R}_c$	Core Magnetic Reluctance
$\mathcal{R}_g$	Air Gab Magnetic Reluctance
$\rho$	Conductor Resistivity

# List of Abbreviations

AC	Alternating Current
BJT	Bipolar Junction Transistor
CCM	Continuous Conduction Mode
DC	Direct Current
DCM	Discontinuous Conduction Mode
eHEMT	Enhancement mode High Electron Mobility Transistor
EMI	Electromagnetic Interference
FG	Function Generator
GaN	Gallium Nitride
HID	High Intensity Discharge
HPS	High Pressure Sodium
IC	Integrated Circuit
IT	Information Technology
LED	Light Emitting Diode
MLT	Mean Length per Turn
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
op-amp	Operational Amplifier
PV	Photovoltaic
SiC	Silicon Carbide
SMPS	Switch Mode Power Supply
STC	Standard Test Conditions

# Abstract

The need for compact size DC power sources is increasingly rising. Several industrial and information technology (IT) sectors demand power supply designers to reduce the overall power supply size while increasing its efficiency. All power supply subsystems are subject to intensive research where their size and efficiency are optimized. The inductive components represent a significant percentage of the total power supply volume. The most common technique to reduce their size is by increasing the switching frequency either directly or through interleaving. In the current work, a different approach is followed. In this work, the core permeability is increased instead. Improving relative permeability of the ferrite cores used in switch-mode power supplies (SMPS) is a challenging task to reduce the requirements of the core size in the circuit. Two methods are introduced in this work. The first method is magnetic shaking that is widely used in shielding applications. An AC component is added to the core of the winding used in SMPS. The relative permeability is improved, causing the inductance of the coil to increase. However, the method is facing some technical difficulties to be integrated in the power circuit. Another method is also introduced by adding a DC magnetic field component equivalent to the DC flux component of the main winding in SMPS. This brings the operating point from the non-linear near saturation region to the more linear region. This not only keeps the inductance constant, but also causes a significant increase in its value. As a result, the core size is dramatically reduced. The principle is explained and the method is verified to reduce the inductor ripple and size requirement.

Another approach is taken to reduce the overall power supply size. Optimizing the number of components is another desired issue in power supply topologies. Reducing the component count results in board size reduction and power density improvement. In the current work, a low component count three-port buck-boost converter is proposed. This converter has only two active components and three passive components. The converter is optimized for renewable energy utilization where energy is stored in batteries for some period and discharged into the load in another period. Solar street lighting is a typical application. The proposed circuit was analyzed, simulated, and proved well suited for the application.