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

Electrical Power and Machines Department
Faculty of Engineering, Cairo University

Dr. Abdelmoamen Osama Mahgoub

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

List of Tables

List of Figures

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 Gab 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_1	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_1	Winding number 1
W_A	Core Windows Area
η	Efficiency
μ	Magnetic Permeability
μ_i	Initial Permeability
μ_o	Free space Permeability
μ_r	Relative Permeability
μ_D	Differential Permeability
ϕ	Magnetic Flux
ϕ_{DC}	DC Component of the Flux
ϕ_{AC}	AC Component of the Flux
ϕ_{total}	Total Flux
ΔV_C	Capacitor Voltage Ripples
ΔB	Change in Flux Density
ΔH	Change in Magnetic Field
ΔI	Inductor Current Ripples
$\mathcal{R}_c$	Core Magnetic Reluctance
$\mathcal{R}_g$	Air Gab Magnetic Reluctance
ρ	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.