DESIGN, MODELING AND IMPLEMENTATION OF IMPROVED POWER QUALITY SWITCHED MODE POWER SUPPLIES FOR ARC WELDING APPLICATIONS

SWATI NARULA

DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
HAUZ KHAS, NEW DELHI – 110016, INDIA
DECEMBER, 2015

DESIGN, MODELING AND IMPLEMENTATION OF IMPROVED POWER QUALITY SWITCHED MODE POWER SUPPLIES FOR ARC WELDING APPLICATIONS

by

SWATI NARULA

Department of Electrical Engineering

Submitted
in fulfillment of the requirements of the degree of
Doctor of Philosophy
to the

INDIAN INSTITUTE OF TECHNOLOGY DELHI

DECEMBER, 2015

CERTIFICATE

This is to certify that the thesis entitled **"Design, Modeling and Implementation of Improved Power Quality Switched Mode Power Supplies for Arc Welding Applications,"** being submitted by **Ms. Swati Narula** for the award of the degree of **Doctor of Philosophy** is a record of a bonafide research work carried out by her in the **Department of Electrical Engineering** of **Indian Institute of Technology Delhi**.

Ms. Swati Narula worked under our guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to our knowledge has reached the requisite standard. The results obtained herein have not been submitted to any other University or Institute for the award of any degree.

(Dr. G. Bhuvaneswari)
Professor
Department of Electrical Engineering
Indian Institute of Technology Delhi
Hauz Khas, New Delhi–110016, India.

(Dr. Bhim Singh)
Professor
Department of Electrical Engineering
Indian Institute of Technology Delhi
Hauz Khas, New Delhi–110016, India.

Dated:

New Delhi

ACKNOWLEDGEMENTS

I express my deepest gratitude and indebtedness to **Prof. G. Bhuvaneswari** and **Prof. Bhim Singh** for providing me the lifetime opportunity to do Ph.D work under their supervision. Working under them, has been a wonderful experience, which has provided me a deep insight into the world of research. Their sagacity and vision have played a vital role in guiding me throughout the research. Continuous monitoring, useful discussions, valuable guidance and time management by them was an inspiring force for me to complete this work. From time to time, they encouraged me for excelling in my work and it is their quest for excellence that has actuated me to improve my work and constantly introspect myself.

My sincere gratitude is reserved for all the SRC members **Prof. Sukumar Mishra, Prof. T.S. Bhatti** and **Dr. N. Senroy** who have been a part of the evaluating team of experts, providing me their valuable insights, suggestions and encouragement throughout my research work. My sincere thanks to **Prof. Bhim Singh, Prof. G. Bhuvaneswari, Prof. B.P. Singh, Prof. S.S. Murthy, Prof. M.L. Kothari** and **Prof. Sukumar Mishra** for their valuable inputs during my course work which helped me to enrich my knowledge.

I am grateful IIT Delhi for providing me the research facilities. Thanks are due to **Mr. Gurucharan Singh, Mr. Amit Kumar, Mr. Satey Singh Negi, Mr. Srichand, Mr. Puran Singh** and **Mr. Jagbir Singh**, lab. staff of Power Electronics and PG Machines labs. For their sustained help and co-operation rendered to carry out my dissertation work.

I extend my special thanks to the fellow research scholars **Mr. B. Amarendra Reddy, Mr. E. Vargil Kumar, Mr. T. Chandrasekhar, Md. Junaid, Mr. Raghavendra, Ms. Geeta Pathak, Ms. Yashi Singh, Ms. Nupur Saxena, Mr. Chinmay Jain, Mr. Ikhlaq Bohru, Mr. Rajan Kumar Sonkar, Mr. Rahul Pandey** and **Mr. Aniket Anand**. My sincere thanks are due to **Dr. Shikha Singh, Dr. Anmol Ratan Saxena, Dr. R. Kalpana, Dr. Sandeep Madishetti, Dr. Vashist Bist, Dr. N.K. Swami Naidu, Dr. Sabharaj Arya, Dr. M. Rajesh. Dr. Ashish Srivastava, Dr. V. Rajogopal** and **Dr. Shailendra Sharma** who have given me immense moral support and shown exemplary attitude and dedication for research.

Words cannot express the feeling and gratitude I have for my father **Mr. S.P. Narula** and mother **Mrs. Ranju Narula** for their constant encouragement, support and personal sacrifices they made to push me forward to allow me to reach new levels of excellence. I thank my sisters

for their support and love that allowed me to complete my PhD work. Once again, I bow to all those who directly or indirectly helped me but whose names are left out.

Last but not the least I'm beholden to almighty for their blessings to help me to raise my academic level to this stage. I pray for their benediction in my future endeavors. May their blessings be showered on me for strength, wisdom and determination to achieve in future goals also!

(Swati Narula)

ABSTRACT

In the process of achieving increased energy efficiency, power density and reliability, switch mode power supplies (SMPSs) have become an accepted part of the electronic systems. SMPSs are now standard equipment for the majority of our industrial and home appliances due to their ruggedness, efficacy, low cost, compactness and reliability. As a result of their performance, SMPSs are widely used in the most applications to provide an efficient and effective source of power. Moreover, with recent advances in semiconductors, magnetic and passive technologies make the SMPS an ever more popular choice in many electronic equipments such as for computers, LEDs, net-books, chargers, motor drives, telecommunication tower power supplies, military equipment, aerospace applications etc. and the demand is ever-increasing. Most of these power supplies utilize AC-DC converters at the front end that are either diode bridge or phase controlled rectifiers. Although these SMPSs are highly efficient, due to their non-linear behavior they draw highly distorted current resulting in low power factor (PF) and high total harmonic distortion (THD). This deterioration in power quality (PQ) leads to increased system losses, degrading the shelf-life of electrical equipments, high electromagnetic interference, etc. With the all pervasive nature of these SMPSs, distribution systems face escalated PQ issues which affect the other equipment in the electrical systems. The proliferation of SMPS in industrial applications has accentuated the PQ issues faced by utilities and consumers making the research on improved PQ utility interface come to the forefront and to look for a possible opportunity to mitigate the associated PQ problems. The increasing awareness about PQ and adverse effects of harmonics pollution have persuaded the power supply manufacturers to maintain THD and PF within the permissible levels which are imposed by international standards, such as IEEE-519 and IEC-61000. In fact, these standards have enforced a constraint on the new electronic devices coming up these days in terms of maintaining a reasonable input PQ. Therefore, an emphasis is laid on the development of simple, economical and energy efficient SMPSs having high PF, low CF and reduced input current harmonics. Certainly, cost, size, design simplicity etc. are amongst the challenging constraints to deal with the goal to mitigate the input PQ issues.

Arc welding is amongst the widely used and efficient welding processes in many industries. However, arc welding power supplies (AWPSs) are considered as a potential source of harmonics. This work is an endeavour to develop an AWPS with improved power factor and less

current harmonic content at the utility interface. The AWPSs that are currently available in the market are devoid of power factor correction and input PQ improvement. An enhancement in the performance of AWPSs is required to achieve good process controllability, portability, improved efficiency and better PQ. Simplicity has always been one of the main features of medium and high capacity SMPSs. This constrains them to use a diode bridge rectifier (DBR) followed by a bulky DC link capacitor at the front end. The second stage usually comprises an isolated DC-DC converter. However, this type of conventional SMPS draws a highly distorted, harmonic rich, peaky input current having a poor PF at the AC mains leading to deterioration of the system performance. With significant variations in the load, it draws a highly non-sinusoidal input current at low PF resulting in a poor converter operation. This research work presents different methods of improving the PQ at the point of common coupling (PCC) for single-phase and three-phase AC mains fed AWPSs. It provides a thorough analysis of the converters and investigates to provide suitable utility interfaces for both types of AWPSs. As a result, with concise analysis and design approach, high performance improved PQ AWPSs with stiffly regulated output voltage along with overcurrent handling capability have been designed, simulated and developed in single-phase and three-phase configurations.

Various single-stage and two-stage PFC-converters which have been classified into DBR based, bridgeless, interleaved, multilevel, modular and multipulse converter configurations for single-phase and three-phase systems have been designed, modeled and implemented in hardware to improve the PQ at the PCC. The single-stage SMPSs are preferred because of their advantages like high power density, simple control, high efficiency, reduced size and load sharing capability. However, two-stage power supplies are ideal for higher power ratings and enhanced control on output parameters. Besides, the control strategy of the PFC converters also plays a vital role in deciding the overall performance, complexity, cost and size of SMPS. In this work, most of the PFC converters have been designed to operate in discontinuous conduction mode (DCM), however, PFC converters of higher power rating function in continuous conduction mode (CCM). Ultimately, the output voltage and output current of the power supply are regulated depending on the loading conditions. Pulse width modulation (PWM) technique has been utilized for the switching of high frequency switches used in PFC converters. During the arc welding process, the load variations happen very rapidly over a wide range. This causes several problems such as spattering, poor weld bead quality, instability of arc length, etc. So, it is

expected of a good AWPS to work efficiently during light load as well as overload conditions. AWPS stands out as a special entity as compared to other power supplies because over-current limiting capability is mandatory for welding applications. The performances of the PFC converters in the AWPS are evaluated during their steady state operation, load variation and short circuit at the output terminals.

Several non-isolated and isolated DBR based as well as bridgeless converter configurations have been investigated to mitigate the PQ issues associated with AWPSs. Bridgeless converter configurations have been realized to minimize the conduction losses of the converter and to improve thermal utilization. These DBR based and bridgeless converters have been designed, modeled and implemented in hardware to verify their performance during various operating conditions. Further, interleaved converters have been explored to increase the power rating of the SMPS and to reduce the input current ripple. By interleaving the PFC converters, the input current is bifurcated into two or more, therefore devices of reduced rating can be utilized. Hardware results also have been presented to validate the advantages of interleaving technique.

In the case of three-phase AWPSs, multilevel, multipulse and modular converter configurations are presented. For the multi-level case, three-level converter has been used at the front end for PFC and isolated DC-DC converter has been used at the rear end for voltage scaling. The overall configuration ensures that the output voltage remains constant and output current is limited during the overload conditions. The simulated performances have also been verified experimentally on the developed prototype. In any power electronic circuit, lower order harmonics are dominant and form the majority of the harmonic content present in the AC mains current. An 18-pulse AC-DC converter configuration, that would eliminate until 17th harmonic, has been explored and analyzed for arc welding applications. With an increase in the pulse number, the cost and complexity of the overall system also increases. An 18-pulse converter turns out to be optimal because of fairly manageable level of complexity despite eliminating most of the lower order harmonics. Hence, an 18-pulse converter based AWPS has been designed, modeled and implemented to validate its viability and proficiency. The modular configuration utilizes single-phase modules to form three-phase power supply. The aim of this configuration is to make the SMPS robust and flexible in terms of maintenance and power expandability. Various isolated DC-DC converter configurations have been designed, modeled and simulated to reduce the input current THD and to achieve unity PF at the input AC mains.

The major contribution of this thesis is two-fold: (i) input PQ improvement by using PFC converters in single-phase and three-phase configurations and (ii) voltage regulation and over current limit at the output end. Therefore, AWPSs having improved PQ with output voltage and current regulation have been designed, modeled and implemented using single-stage and two-stage PFC converters for single-phase and three-phase systems. The performance of the power supply has been investigated over wide range of loads. A substantial improvement in PQ indices has been achieved under varying loads apart from regulating the output voltage stiffly and limiting the current appreciably even under short circuit conditions.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS/SYMBOLS

AWPS	Arc Welding Power Supply
BL	Bridgeless
CCM	Continuous Conduction Mode
CF	Crest Factor
CSC	Canonical Switching Cell
DBR	Diode Bridge Rectifier
DCM	Discontinuous Conduction Mode
DF	Distortion Factor
DICM	Discontinuous Inductor Current Mode
DPF	Displacement Power Factor
DSP	Digital Signal Processor
FB	Full Bridge
HFT	High Frequency Transformer
IEC	International Electrotechnical Commission
PCC	Point of Common Coupling
PF	Power Factor
PFC	Power Factor Correction
PI	Proportional Integral
PQ	Power Quality
PWM	Pulse Width Modulation
SEPIC	Single Ended Primary Inductance Converter
SMPS	Switched Mode Power Supply
SPS	Sim Power System
THD	Total Harmonic Distortion

C_f	Input Filter Capacitor (F)
C_o	Output Filter Capacitor (F)
D	Duty Ratio
f_b	Switching Frequency of Non-Isolated Front-End Converter (Hz)

f_s	Switching Frequency of Isolated Converter (Hz)
ΔI_o	Ripple Current (A)
I_b	Output Current of First Stage (A)
I_o	Output Current (A)
i_s	Supply Current (A)
i_{sa}, i_{sb}, i_{sc}	Supply Currents in Three-Phase System (A)
k_{pi}, k_{ii}, k'_{pi}, k'_{ii}	Proportional and Integral Gains of Current Controllers
k_{pv}, k_{iv}, k'_{pv}, k'_{iv}	Proportional and Integral Gains of Voltage Controllers
L_f	Input Filter Inductor (H)
L_m	Magnetizing Inductance of HFT (H)
L_o	Output Filter Inductor (H)
n	HFT Turns Ratio
N_1	Number of Turns of Primary Winding of HFT
N_2	Number of Turns of Secondary Winding of HFT
P_{in}	Input Power (W)
P_o	Output Power (W)
R_o	Resistive Load at the Output (Ω)
ΔV_o	Ripple Voltage (V)
V_b	Output Voltage of First Stage (V)
$v_{L\text{-}L}$	Line-to-Line Voltage (V)
V_o	Output Voltage (V)
v_s	Supply Voltage (V)
v_{sa}, v_{sb}, v_{sc}	Supply Voltages in Three-Phase System (V)