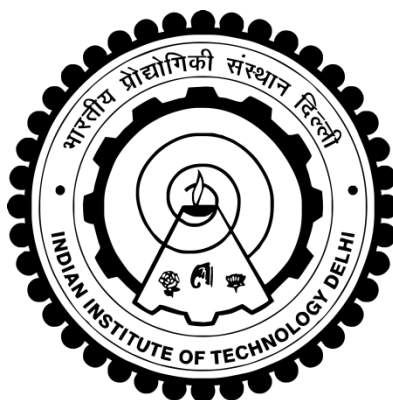


DESIGN, CONTROL AND IMPLEMENTATION OF GRID TIED SOLAR ENERGY CONVERSION SYSTEMS

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JULY 2016**

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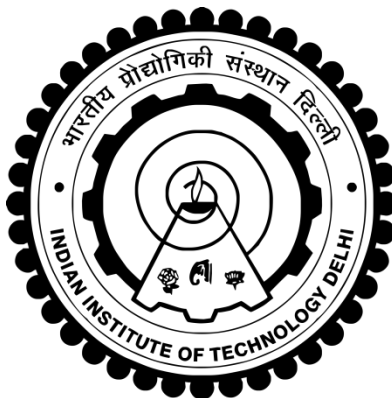
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Submitted

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

to the



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CERTIFICATE

It is certified that the thesis entitled “**Design, Control and Implementation of Grid Tied Solar Energy Conversion Systems**,” being submitted by **Mr. Chinmay Jain** for award of the degree of **Doctor of Philosophy** in the Department of Electrical Engineering, Indian Institute of Technology Delhi, is a record of the student work carried out by him under my supervision and guidance. The matter embodied in this thesis has not been submitted for award of any other degree or diploma.

Dated: July 28, 2016

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Chinmay Jain

ABSTRACT

The rapidly vanishing conventional energy sources (fossil fuels) have put an alarming energy crisis situation in front of the world. Moreover, the deteriorating environmental conditions have moved world's attention towards nonconventional green energy sources. Amongst the various available renewable energy sources, the SPV (Solar Photovoltaic) generation systems are gaining importance because of abundance of sun, low maintenance, modular structure and possibility of small generation plants at the roof tops. The SPV generation systems can be broadly classified into two main categories which are standalone and grid interfaced. The energy storage systems (generally batteries) are the inherent requirement of the standalone systems to match the instantaneous power balance, which adds to the extra cost and frequent maintenance in the standalone system. Therefore, battery-less grid interfaced SPV generation systems are more preferred where the grid is available.

The increasing energy crisis has not only given promotions to renewable energy sources but also to the efficient electrical equipment. Most of these equipments use power electronic converters to achieve high efficiency and compact structure. However, the rapid increase in power electronic converter based loads has given rise to serious power quality problems such as poor power factor, harmonics in AC mains current, neutral current, voltage distortion etc. in the distribution system. Therefore, the energy crisis and the power quality problems are the two prime issues of the modern distribution system.

This research work aims at the design, control and implementation of various single-phase and three-phase system configurations for SECSs (Solar Energy Conversion systems). All the system configurations are simulated in MATLAB based environment and the laboratory prototypes of them are built to validate the simulation results. This research work mainly focuses on the SPV

generation systems connected in the distribution system. In order to deal with the problem of the energy crisis, the various PV inverters are proposed in this work which are classified depending on their connection to AC distribution system (single-phase or three-phase) and number of power conversion stages (single-stage or two-stage). In case of two-stage systems, the first stage is a boost converter which serves for MPPT (Maximum Power Point Tracking) and the second stage is a grid tied VSC (Voltage Source Converter). The selection of system configuration depends on the requirements of the end user. The problem of voltage fluctuations is quite common in the weak distribution system. Therefore, simple, intuitive and improved control algorithms for the PV inverters, are developed such that the PV inverter is capable of operating under wide range of voltage variation. These PV inverters feed the sinusoidal current at unity power factor with respect to CPI voltage. In case of two-stage PV inverters an adaptive DC link voltage based control structure has been presented which has shown improvement in performance in terms of reduction of switching losses, high frequency ohmic losses and reduction of ripple content in the output current.

In addition, the SPV energy is not available almost two third period of the day in a typical SPV generating system and its power converter is not utilized when there is no solar PV energy and normally it is switched off in order to reduce its losses. This leads to poor utilization of the power converters involved in the grid interfaced SPV system. Therefore, in order to improve the utilization factor of the SPV generation system multifunctional SECSs are proposed in this work. The multifunctional SECSs are the ones which not only feed the solar PV energy into the grid but also help in power quality improvement at the CPI (Common Point of Interconnection). In these multifunctional SECS, the grid tied VSC not only serves for transferring the generated SPV power into the distribution system but also for additional features such as harmonics mitigation,

reactive power compensation, grid currents balancing and neutral current elimination depending on the circuit configuration. A total of six system configurations for multifunctional SECSs are presented in this work which includes single-stage and two-stage single-phase and three-phase multifunctional SECSs. The three-phase multifunctional SECSs are further classified into three-wire and four-wire grid tied multifunctional SECSs. An adaptive DC link voltage based control approach is proposed for all two-stage single-phase and three-phase multifunctional SECSs. The performance of adaptive DC link based control approach is found satisfactory for all the features of the multifunctional SECS. Moreover, the performance improvement in terms of reduction in losses and ripple current is observed. Simple, intuitive and improved control approaches are proposed for all these SECSs. Moreover, the performance evaluation for all system configurations of SECS has been carried out under non-ideal grid conditions. This work is expected to provide a good exposure to design, development and control approach for shunt grid tied PV inverters and multifunctional SECSs.

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LIST OF ABBREVIATIONS

AC	Alternating Current
ADC	Analog to Digital Converter
CFL	Compact Florescent Lamp
CPI	Common Point of Interconnection
DAC	Digital to Analog Converter
DC	Direct Current
DFSOGI	Double Frequency Second Order Generalized Integrator
DSP	Digital Signal Processor
D-STATCOM	Distribution Static Compensator
FACTS	Flexible Alternating Current Transmission Systems
IGBTs	Insulated Gate Bipolar Transistors
ILST	Improved Linear Sinusoidal Tracer
InC	Incremental Conductance
LPF	Low Pass Filter
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
P&O	Perturb and Observe
PI	Proportional Integral
PLL	Phase Locked Loop
PV	Photo Voltaic
PWM	Pulse Width Modulation
SECS	Solar Energy Conversion System
SHTNF	Second Harmonics Tuned Notch Filter
SPV	Solar Photo Voltaic
SRFT	Synchronous Reference Frame Theory
VSC	Voltage Source Converter

LIST OF SYMBOLS

a	Over loading factor
C_{DC}	DC bus capacitance of the VSC
C_r	Capacitance for ripple filter
D	Duty ratio of boost converter
D_{ref}	Reference duty ratio of boost converter
f_s	Switching frequency
I_{sc}	Short circuit current of single solar cell
I_{mppC}	MPP current of single solar cell
I_{SCA}	Short circuit current of SPV array
ΔI_{in}	Ripple current in the input current of boost converter
I_o	Current in the DC link capacitor
I_{PV}	PV array current
I_{mppA}	MPP current of SPV array
I_{VSC}	VSC current in single-phase system
I_{VSCmax}	Maximum current for VSC
I_{VSCp}	Peak current for VSC
I_{VSCr}	Peak ripple current for VSC
I_{VSCA}	Active power component of VSC current
I_{VSCR}	Reactive power component of VSC current
I_{SW}	Current rating of IGBT switch
I_l	Output of DC link PI controller
I_{PVFF}	PV array feed forward contribution
I_{Lp}	Magnitude of active power component of load current
I_{gp}	Amplitude of reference grid current
i_g	Sensed grid current in single-phase system
$i_{ga}, i_{gb}, i_{gc}, i_{gn}$	Sensed grid currents in three-phase system
i_{gref}	Reference grid current in single-phase system
$i_{garef}, i_{gbref}, i_{gcref}$	Reference grid currents in three-phase system

i_L	Sensed load current in single-phase system
i_h	Harmonics component in sensed load current
$i_{La}, i_{L\beta}$	Estimated fundamental currents by notch filter algorithm
$i_{La}, i_{Lb}, i_{Lc}, i_{Ln}$	Sensed load currents in three-phase system
$i_{VSCa}, i_{VSCb}, i_{VSCc}, i_{VSCn}$	VSC currents in three-phase system
i_d, i_{2fd}, i_{dh}	Internal parameters of DFSOGI algorithm
$i_d, i_{SHd}, i_{dh}, i_{SHq}, P_{10}$	Internal parameters of SHTNF algorithm
$i_{ea}, i_{1a}, i_{2a}, i_{3a}, i_{fa}, i_{fp(a,b,c)}$	Internal parameters of ILST algorithm
$i_{ea}, M_{1a}, I_{oa}, SH_a, i_{pa}$	Internal parameters of adaptive noise detection algorithm
I_{Lg}	Average active power component of load current
I_{LR}	Reactive power component of load current
K_p	Proportional constant for PI controller
K_i	Integral constant for PI controller
L_B	Inductor for boost converter
L_{VSC}	Interfacing inductor for VSC
L_{VSCn}	Interfacing inductor for neutral leg of VSC
m	Modulation index
n_p	Number of parallel solar cells
n_s	Number of series solar cells
P_{maxA}	MPP power of SPV array
P_{maxM}	Maximum power from a PV array under standard ambience condition
P_L	Power consumed by the load
P_{PV}	Power supplied by the PV array
P_{VSC}	Power supplied by the VSC
R_r	Resistance for ripple filter
T_s	Switching time period
v_{DC}	Nominal DC bus voltage
V_{DCref}	Reference DC link voltage
V_{DCmin}	Minimum DC bus voltage
V_{DCmax}	Maximum DC bus voltage

V_{DCr}	Peak to peak current ripple on DC bus voltage
V_{in}	Input voltage of boost converter
V_{mppC}	MPP voltage of single solar cell
V_{mppA}	MPP voltage of SPV array
V_{oc}	Open circuit voltage of single solar cell
V_{OCA}	Open circuit voltage of SPV array
v_{PV}	PV array voltage
V_{PVref}	Reference PV array voltage
V_s	Nominal CPI voltage
V_{smin}	Minimum CPI voltage
V_{smax}	Maximum CPI voltage
V_m	Estimated amplitude of single-phase CPI voltage
V_z	Estimated amplitude of three-phase CPI voltage
V_{SW}	Voltage rating of IGBT switch
v_s	CPI voltage in single-phase system
v_{sa}, v_{sb}, v_{sc}	CPI phase voltages in three-phase system
$v_{sab}, v_{sbc}, v_{sca}$	CPI line voltages in single-phase system
v_{s1}, v_{s2}	Orthogonal voltages in single-phase control approach
$v_{sa}, v_{s\beta}$	Orthogonal voltages estimated by notch filter algorithm
v_e	Error voltage in DC link voltage control loop
u_p, u_q	Unit vectors for single-phase systems
z_a, z_b, z_c	Synchronization vectors for three-phase systems
z_{ap}, z_{bp}, z_{cp}	In-phase unit vectors for three-phase systems
z_{aq}, z_{bq}, z_{cq}	Quadrature unit vectors for three-phase systems
α, β	Internal parameters for ILST algorithm
ω_o	Line frequency in rad/sec
ζ	Internal parameter for notch filter algorithm
σ	Internal parameter for adaptive noise detection algorithm
μ	Scaling factor in an adaptive DC link voltage control