DESIGN, CONTROL AND IMPLEMENTATION OF SOLAR PHOTOVOLTAIC ARRAY AND BATTERY INTEGRATED UNIFIED POWER QUALITY CONDITIONER

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DESIGN, CONTROL AND IMPLEMENTATION OF SOLAR PHOTOVOLTAIC ARRAY AND BATTERY INTEGRATED UNIFIED POWER QUALITY CONDITIONER

by

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CERTIFICATE

This is to certify that the thesis entitled, **"Design, Control and Implementation of Solar Photovoltaic Array and Battery Integrated Unified Power Quality Conditioner"** being submitted by **Mr. Sachin Devassy** for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work carried out by him in the Department of Electrical Engineering of Indian Institute of Technology Delhi.

Mr. Sachin Devassy has worked under my guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to my knowledge has reached the requisite standard. The results obtained here in have not been submitted to any other University or Institute for the award of any degree.

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ABSTRACT

With the advancement in semiconductor electronics, there has been increasing use of sophisticated power electronic systems such as switched mode power supplies (SMPS), adjustable speed drives (ASDs), etc. The main advantage of these systems are that they are energy efficient. However, as they contain switching devices, they draw nonlinear currents which can cause distortion in the voltage at the point of common coupling. Moreover, these loads are highly sensitive to fluctuations in voltage at point of common coupling (PCC). Another major trend in recent years is the increasing focus on use of renewable energy system particularly solar photovoltaic systems. Hence, the major requirement of modern distribution systems is deployment of multi-functional devices which can integrate distribution generation along with power quality improvement.

This research work focuses on the design, control and implementation of solar PV array and battery integrated UPQC for use in modern distribution systems. Detailed design, simulation analysis and experimental validation are done for various configuration of PV-UPQC and PV-B-UPQC. Various topologies of PV-UPQC and PV-B-UPQC are designed and its performances analyzed in detail.

Single phase PV-UPQC systems are designed and its performances are analyzed in detail. These systems are an ideal solution for small household rooftop systems where it can protect senstive loads from PCC voltage sags/swells as well as inject power from PV array into grid and also compensate for load current quality issues. Three phase three wire and Three phase four wire PV-UPQC systems are designed and its performance under various dynamic conditions such as PCC voltage sags/swells, irradiation variation and load unbalancing etc are analyzed. For both single phase and three phase PV-UPQC systems, both single stage and double stage PV-UPQC systems are designed and analyzed in detail.

Different configurations of PV-B-UPQC systems for both single phase and three phase distribution systems are designed and analyzed. The presence of battery energy storage enables these systems to operate in standalone mode when the grid is not available and can operate in grid connected mode when there is grid available. Improved control logics were developed for automated transition from grid connected to standalone mode and vice versa.

Novel control techniques have been developed for improved control of PV-UPQC and

PV-B-UPQC. Extensive analysis has been done on the performance of the system through Matlab-Simulink software. The simulated performance of PV-UPQC systems and PV-B-UPQC systems were validated experimentally on laboratory prototype. The major focus of this research work has been on designing and developing PV-UPQC systems and PV-B-UPQC systems for compensating power quality issues and integrate solar energy under application scenarios such as for small household rooftops systems as well as for rooftop systems of large commercial buildings etc.

सार

सेमीकंडक्टर इलेक्ट्रॉनिक्स में उन्नति के साथ, परिष्कृत पावर इलेक्ट्रॉनिक सिस्टम जैसे स्विच्ड मोड पावर सप्लाई (एसएमपीएस), एडजस्टेबल स्पीड ड्राइव (एएसडी), आदि का उपयोग बढ़ रहा है। इन प्रणालियों का मुख्य लाभ यह है कि वे ऊर्जा कुशल हैं। हालांकि, चूंकि उनमें स्विचिंग डिवाइस होते हैं, वे नॉनलाइनर धाराओं को खींचते हैं जो सामान्य युग्मन के बिंदु पर वोल्टेज में विकृति पैदा कर सकते हैं। इसके अलावा, ये भार सामान्य युग्मन (पीसीसी) के बिंदु पर वोल्टेज में उतार-चढ़ाव के प्रति अत्यधिक संवेदनशील होते हैं। हाल के वर्षों में एक और प्रमुख प्रवृत्ति नवीकरणीय ऊर्जा प्रणाली विशेष रूप से सौर फोटोवोल्टिक प्रणालियों के उपयोग पर ध्यान केंद्रित करना है। इसलिए, आधुनिक वितरण प्रणालियों की प्रमुख आवश्यकता बहु-कार्यात्मक उपकरणों की तैनाती है जो बिजली की गुणवत्ता में सुधार के साथ वितरण पीढ़ी को एकीकृत कर सकते हैं।

यह शोध कार्य आधुनिक वितरण प्रणालियों में उपयोग के लिए सौर पीवी सरणी और बैटरी एकीकृत यूपीक्यूसी के डिजाइन, नियंत्रण और कार्यान्वयन पर केंद्रित है। पीवी-यूपीक्यूसी और पीवी-बी-यूपीक्यूसी के विभिन्न विन्यास के लिए विस्तृत डिजाइन, सिमुलेशन विश्लेषण और प्रयोगात्मक सत्यापन किया जाता है। पीवी-यूपीक्यूसी और पीवी-बी-यूपीक्यूसी के विभिन्न टोपोलॉजी डिज़ाइन किए गए हैं और इसके प्रदर्शन का विस्तार से विश्लेषण किया गया है।

एकल चरण पीवी-यूपीक्यूसी सिस्टम तैयार किए गए हैं और इसके प्रदर्शन का विस्तार से विश्लेषण किया गया है। ये सिस्टम छोटे घरेलू रूफटॉप सिस्टम के लिए एक आदर्श समाधान हैं जहाँ यह पीसीसी वोल्टेज सैग्स / स्वैलस से सीनेस्टिव लोड की रक्षा कर सकता है और साथ ही पीवी सरणी से ग्रिड में बिजली इंजेक्ट करता है और लोड करंट क्वालिटी के मुद्दों की भरपाई भी करता है। तीन चरण तीन तार और तीन चरण चार तार पीवी - यूपीक्यूसी सिस्टम डिज़ाइन किए गए हैं और इसके प्रदर्शन को विभिन्न गतिशील परिस्थितियों जैसे पीसीसी वोल्टेज

कमी /वृद्धि, विकिरण भिन्नता और भार असंतुलित करना आदि का विश्लेषण किया जाता है। सिंगल फेज और थ्री फेज पीवी-यूपीक्यूसी सिस्टम के लिए, सिंगल स्टेज और डबल स्टेज पीवी-यूपीक्यूसी सिस्टम को डिजाइन और एनालिसिस किया जाता है।

एकल चरण और तीन चरण वितरण प्रणाली दोनों के लिए पीवी-बी-यूपीक्यूसी सिस्टम के विभिन्न कॉन्फ़िगरेशन डिज़ाइन और विश्लेषण किए गए हैं। बैटरी ऊर्जा भंडारण की उपस्थिति इन प्रणालियों को

स्टैंडअलोन मोड में संचालित करने में सक्षम बनाती है जब ग्रिड उपलब्ध नहीं होता है और ग्रिड उपलब्ध होने पर ग्रिड कनेक्टेड मोड में काम कर सकता है। स्टैंडअलोन मोड से जुड़े ग्रिड से स्वचालित संक्रमण के लिए बेहतर नियंत्रण लॉजिक्स विकसित किए गए थे और इसके विपरीत।

पीवी-यूपीक्यूसी और पीवी-बी-यूपीक्यूसी के बेहतर नियंत्रण के लिए नोवेल कंट्रोल तकनीक विकसित की गई है। मैटलैब सिमूलिंक सॉफ्टवेयर के माध्यम से सिस्टम के प्रदर्शन पर व्यापक विश्लेषण किया गया है। पीवी-यूपीक्यूसी सिस्टम और पीवी-बी-यूपीक्यूसी सिस्टम के नकली प्रदर्शन को प्रयोगशाला प्रोटोटाइप पर प्रयोगात्मक रूप से मान्य किया गया था। इस शोध कार्य का प्रमुख फोकस पीवी-यूपीक्यूसी सिस्टम और पीवी-बी-यूपीक्यूसी सिस्टम को डिजाइन करने और विकसित करने और बिजली की गुणवत्ता के मुद्दों की भरपाई के लिए और सौर ऊर्जा को एकीकृत करने के लिए किया गया है, जैसे कि छोटे घरेलू छतों सिस्टम सहित मॉडर्न वितरण प्रणाली के लिए। बड़ी व्यावसायिक इमारतों आदि की छत प्रणालियों के लिए।

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LIST OF ABBREVIATIONS

AC	Alternating Current
ADALINE	Adaptive Linear Element
ANN	Artificial Neural Network
ASD	Adjustable Speed Drives
BPF	Band Pass Filter
BES	Battery Energy Storage
CDSC	Cascaded Delayed Signal Cancellation
CSC	Current Source Converter
CSOGI	Cascaded Second Order Generalized Integrator
DC	Direct Current
DG	Distributed Generation
DSC	Delayed Signal Cancellation
DSP	Digital Signal Processor
DSTATCOM	Distribution Static Compensator
DVR	Dynamic Voltage Restorer
FFPS	Fundamental Frequency Positive Sequence
GCDSC	Generalized Cascaded Delayed Signal Cancellation
HB	Hysteresis Band
HVDC	High Voltage Direct Current
IEC	International Electrotechnical Commision
IEEE	Institute of Electrical and Electronics Engineers
INC	Incremental Conductance
LMF	Least Mean Fourth
LPF	Low Pass Filter
MAF	Moving Average Filter
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
MSSI	Modified Symmetrical Sinusoidal Integrator

PCC	Point of Common Coupling
PES	Power Electronic Switch
PI	Proportional Integral
PLL	Phase Locked Loop
PR	Proportional Resonant
PSO	Particle Swarm Optimization
PV	Solar Photovoltaic
PV-UPQC	Solar Photovoltaic Array Integrated UPQC
PV-B-UPQC	Solar Photovoltaic Array and Battery Integrated UPQC
RLS	Recursive Least Squares
SMPS	Switched Mode Power Supply
SOGI	Second Order Generalized Integrator
SOSF	Second Order Sequence Filter
SRF	Synchronous Reference Frame
S/H	Sample and Hold
THD	Total Harmonic Distortion
UPQC	Unified Power Quality Conditioner
VSC	Voltage Source Converter
VFF	Variable Forgetting Factor
ZCD	Zero Crossing Detection

LIST OF SYMBOLS

a	Over loading factor
C_{dc}	DC-link capacitor (F)
C_f	Shunt ripple filter capacitor (F)
C_r	Series ripple filter capacitor (F)
d_{se}^*	Single phase series compensator control signal
D	Duty cycle of boost converter
$DSC_N()$	Delayed signal cancellation operator
D_{sync}	Synchronization decision signal
e	instantaneous estimation error
e_{vdc}	DC-link voltage error
E	Average error in one period
f_s	Grid frequency (Hz)
f_s^*	Reference Grid frequency (Hz)
f_b	Boost converter switching frequency (Hz)
f_{sh}	Shunt compensator switching frequency (kHz)
F_s	Sampling frequency (kHz)
f_{se}	Series compensator switching frequency (kHz)
G_{PR}	Transfer function of proportional resonant controller
G_{HC}	Transfer function of harmonic controllers
h_b	Blocked harmonics order
I_{bt}	Battery current (A)
i_L	Single phase load current (A)
I_{L1}	Single phase load current fundamental component magnitude (A)
I_{Lap}	Magnitude of FPSC of three phase load currents (A)
I_{Ld}, I_{Lq}	Load currents in $d-q$ domain (A)
I_{Ldf}	Filtered d-domain component of load currents (A)
I_{Lp}	Magnitude grid current corresponding to FPSC of three phase load currents (A)
i_{La}, i_{Lb}, i_{Lc}	Three phase load currents (A)
i_{Lact}	Single phase load active component (A)
I_{loss}	System loss component (A)
$i_{L\alpha}, i_{L\beta}$	Three phase load currents in $\alpha-\beta$ domain (A)
$i_{L\alpha1}^*, i_{L\beta1}^*$	FPSC of load current in $\alpha-\beta$ domain (A)
i_{Lrh}	Single phase load non active components (A)
i_s	Single phase grid current (A)

i_{sa}, i_{sb}, i_{sc}	Three phase grid currents (A)
i_{sn}	Grid neutral current (A)
$i_{sa}^*, i_{sb}^*, i_{sc}^*$	Reference three phase grid currents (A)
i_{sn}^*	Reference grid neutral current (A)
$i_{s\alpha}^*, i_{s\beta}^*$	Reference three phase grid currents in $\alpha - \beta$ domain (A)
i_{SH}	Single phase shunt compensator current (A)
$i_{SHa}, i_{SHb}, i_{SHc}$	Shunt compensator currents (A)
i_{Ln}	Load neutral current (A)
i_{SHn}	Shunt compensator neutral current (A)
I_{pv}	PV array current (A)
I_{pvg}	Grid current corresponding to PV array power (A)
I_{sd}^*, I_{sq}^*	Reference grid currents in $d - q$ domain (A)
$I_{cr,pp}$	Compensator ripple current (A)
I_{mpp}	PV array maximum power point current (A)
I_{sc}	PV array short circuit current (A)
k	Kalman gain
K	Sag factor
K_1, K_2	Gains of second order sequence filter
k_1	Variation of Energy in dynamics
K_d	Series compensation decision factor
K_0, K_b	Gains of MSSI filter
Kp_d, Kp_q	Proportional gain of PI controller in $d - q$ control
Ki_d, Ki_q	Integral gain of PI controller in $d - q$ control
K_{se}	Turns Ratio of series injection transformer
K_{FF}	Feedforward gain
K_p,K_i	Gains of DC-link voltage PI controller
Kp_{sync}, Ki_{sync}	Gains of phase generation PI controller
K_{pr}, K_{Ipr}	Gains of Proportional resonant controller
$K_{pr\alpha-\beta}, K_{Ipr\alpha-\beta}$	Gains of Proportional resonant controller in $\alpha - \beta$
Kp_v, Ki_v	Gains of Shunt VSC voltage mode controller
K_{pv}, K_{iv}, K_{ii}	Gains of bidirectional converter controller
L_f	Shunt compensator inductor (H)
L_r	Series compensator inductor (H)
L	Boost converter inductor (H)
M	Delay sample corresponding to delay factor
m	Modulation index of shunt compensator

m_a	Modulation index of series compensator
n	Sampling instant
N	Delay factor in DSC
Pm	Inverse of input correlation matrix
P	Power handled by shunt compenstor (W)
p_L	Instantaneous load active power (W)
P_L	Average load active power (W)
P_{loss}	PV-UPQC loss components (W)
P_{pv}	PV array power (W)
P_{ref}	Reference active power (W)
q_L	Instantaneous load reactive power(VAR)
Q_L	Average load reactive power (VAR)
Q_{SH}	Shunt Compensator reactive power (VAR)
Q_{SE}	Series Compensator reactive power (VAR)
R_f	Shunt ripple filter resistor (Ω)
R_r	Series ripple filter resistor (Ω)
$R(\theta)$	Rotation Matrix
s	Laplace operator
$sin(\phi_{v1}), cos(\phi_{v1})$	In-phase and quadrature template of PCC voltage fundamental component
$sin(\phi_{i1}), cos(\phi_{i1})$	In-phase and quadrature template of load current fundamental component
t	Transient recovery time (s)
T_s	Sampling time (s)
T_w	Window length of moving average filter (s)
u_s	Single phase PCC voltage template
u_{sa}, u_{sb}, u_{sc}	Three phase PCC voltage templates
V_{bt}	Battery voltage (V)
V_{dc}	DC-link voltage (V)
V_{dc}^*	Reference DC-link voltage (V)
ΔV_{dc}	DC-link voltage ripple (V)
V_{LL}	RMS line voltage (V)
v_{La}, v_{Lb}, v_{Lc}	Three phase instantaneous load phase voltages (V)
$v_{Lab}, v_{Lbc}, v_{Lca}$	Three phase instantaneous load line voltages(V)
$v_{L\alpha}, v_{L\beta}$	Three phase load voltages in $alpha - beta$ domain (V)
V_{Ld}, V_{Lq}	Three phase load voltages in $d - q$ domain (V)
V_{Ld}^*, V_{Lq}^*	Three phase load reference voltages in $d - q$ domain (V)
V_{mpp}	PV array maximum power point voltage (V)

v_{ma}, v_{mb}, v_{mc}	Three phase instantaneous grid voltages (V)
V_{oc}	PV array open circuit voltage (V)
V_{pv}	PV array voltage (V)
$v_{\alpha-\beta}$	Voltage vector in $\alpha - \beta$ domain (V)
v_s	Single phase instantaneous PCC voltage (V)
V_s	RMS PCC phase voltage (V)
v_{sa}, v_{sb}, v_{sc}	Three phase instantaneous PCC phase voltages (V)
$v_{s\alpha}, v_{s\beta}$	Three phase PCC voltages in $\alpha - \beta$ domain
V_{sd}, V_{sq}	Three phase PCC voltages in $d - q$ domain (V)
$v_{s1\alpha}, v_{s1\beta}$	Three phase GCDSC filtered PCC voltages in $\alpha - \beta$ domain (V)
$v_{sf1\alpha}, v_{sf1\beta}$	Three phase fundamental positive sequence PCC voltages in $\alpha - \beta$ domain (V)
$v_{sab}, v_{sbc}, v_{sca}$	Three phase instantaneous PCC line voltages (V)
v_{SE}	Single phase instantaneous series compensator voltage (V)
V_{SE}	RMS Series compensator line voltage (V)
$v_{sea}, v_{seb}, v_{sec}$	Three phase instantaneous series compensator phase voltages (V)
V^*_{sed}, V^*_{seq}	Series compensator reference voltages in $d - q$ domain (V)
$v^*_{sea}, v^*_{seb}, v^*_{sec}$	Series compensator reference voltages (V)
$v_{seab}, v_{sebc}, v_{seca}$	Three phase instantaneous series compensator line voltages (V)
v'_{s1}, qv'_{s1}	In-phase and quadrature component of SOGI filter output (V)
v_{s1}, qv_{s1}	In-phase and Quadrature component of CSOGI filter output (V)
V_{s1}	Magnitude of PCC fundamental component (V)
V_s	Magnitude of PCC phase voltage (V)
w	Weight factor corresponding to load current active component
z	Z-domain operator
α_c	Convergence Factor
δ	Power Angle (°)
Δe_{vdc}	Change in DC-link voltage error
δP_{pv}	Change in PV array power
ΔD	Duty cycle step size
ϕ	Load power factor angle (°)
θ_L	Load phase angle (°)
θ_s	PCC voltage phase angle (°)
ω	Grid frequency (rad/s)
ω_c	Cut-off frequency of proportional resonant controller (rad/s)
λ	Forgetting factor
μ	is gain factor of ZFLMS