INVESTIGATIONS ON HIGH POWER CONVERTERS BASED GRID INTERFACED SOLAR PV POWER GENERATING SYSTEMS

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by

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CERTIFICATE

It is certified that the thesis entitled "**Investigations on High Power Converters Based Grid Interfaced Solar PV Power Generating Systems**," being submitted by **Mr. Ikhlaq Hussain** 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.

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ABSTRACT

During last decade, solar photovoltaic (PV) power generation has become a focus area of research and development as it is ecofriendly, renewable and available in large quantity. Because of availability of the PV energy everywhere, it is possible to use it in both isolated and grid connected systems. In this thesis work, the various system configurations for single stage high power grid tied PV power generating systems based on two level, multilevel (diode clamped, flying capacitor, binary and ternary cascaded) and multipulse converters, are investigated in detail. The design, control and implementation of various system configurations of PV power generating systems are carried out and their performance are evaluated under varying solar insolation levels.

This research work focuses on investigations of grid tied PV power generating systems such as two level VSC (Voltage Source Converter) based PV-DSTATCOM (Distribution Static Compensator), multilevel VSC based PV-STATCOM (Static Compensator) and other multilevel converters. In PV-DSTATCOM system, two level converter is utilized to do multiple functions in three modes. In mode 1, it transfers active power to the grid and connected loads while mitigating the power quality issues in the distribution network. In mode 2, it transfers only active power to the grid at unity power factor while in mode 3, it does only power quality mitigations. In PV-STATCOM system, it transfers large power at high voltage to the three phase AC grid with STATCOM capabilities thereby increasing the transmission transferring capability. For PV-STATCOM system working in three modes, five and seven level converters are utilized to integrate the PV arrays with the grid at low switching frequency with STATCOM capabilities. In both systems, the VSCs are fully utilized to their full capacity in the proposed system for 24 hours. To improve the efficiency of the system, a single stage topology is adopted over double stage topology in the PV grid tied systems.

However, to transfer large power from a PV array to the three phase grid at high voltage, multilevel and multipulse VSCs are viable solution as losses in the VSC, are decreased due to low switching frequency. The various configurations (binary cascaded 31 level converter, ternary cascaded 9 and 27 level converters, 12 and 18 pulse converter) of the PV system operating at FFS (Fundamental Frequency Switching) are investigated. Due to FFS, the switching losses of the converters are reduced, thereby, increasing overall efficacy of the system, which results in reduction of unit cost of electricity. The binary and ternary cascaded converters operating at FFS and single stage topology, offers advantages viz. high number of voltage levels, less number of switching devices, low THD, low switching losses, ease of operation at high voltages that leads to the improvement in power quality of the system. All these converter based grid tied power generating systems are simulated in MATLAB and the responses are verified through experimental results achieved on the developed prototype in the laboratory, to demonstrate the system performance under varying conditions. The major focus of this research work, is investigations of high power converter based PV grid tied system, for active power transfer to the grid as well as mitigating power quality (PQ) issues, while satisfying the IEEE standards.

अब्स्ट्रक्ट

दूरिंग लास्ट डिकेड ,सोलर फोटोवोल्टाइक (पीवी) पावर जनरेशन हैस बिकम ऐ फोकस एरिया ऑफ़ रिसर्च एंड डेवलपमेंट एस इट इस इकोफ्रेंडली,रिन्यूएबल एंड अवेलेबल इन लार्ज क्वांटिट .बिकॉज़ ऑफ़ अवेलेबिलिटी ऑफ़ दा पीवी एनर्जी एवरीव्हेर,इट इस पॉसिबल तू यूज आईटी इन बोथ आइसोलेटेड एंड ग्रिड कनेक्टेड सिस्टम्स. इन थिस थीसिस वर्क,दा वेरियस सिस्टम कॉन्फ़िगरेशंस फॉर सिंगल स्टेज हाई पावर ग्रिड टाईड पीवी पावर जनरेटिंग सिस्टम्स बेस्ड आन तू लेवल, मल्टीलेवल (डायोड क्लाम्पेद , फ्लाइंग कपैसिटर, बाइनरी एंड टेरनरी कास्केडेड) एंड मल्टीपल्स कन्वर्टर्स, आर इंवेस्टीगेटेड इन डिटेल. दा डिज़ाइन, कण्ट्रोल एंड इम्प्लीमेंटेशन ऑफ़ वेरियस सिस्टम कॉन्फ़िगरेशंस ऑफ़ पीवी पावर जनरेटिंग सिस्टम्स आर कर्रिएद आउट एंड थेइर परफॉरमेंस आर एवलुएटेड अंडर वैरीइंग सोलर इन्सुलेशन लेवल्स.

थिस रिसर्च वर्क फॉक्सेस आन इंवेस्टीगेशंस ऑफ़ ग्रिड टाईड पीवी पावर जनरेटिंग सिस्टम्स सच एस ट्व लेवल वीएससी (वोल्टेज सोर्स कनवर्टर) बेस्ड पीवी-डिस्टॉटकॉम (डिस्ट्रीब्यूशन स्थैतिक कम्पेन्सेटर), मल्टीलेवल वीएससी बेस्ड पीवी-डिस्टॉटकॉम एंड अदर मल्टीलेवल कन्वर्टर्स. इन पीवी-डिस्टॉटकॉम सिस्टम, ट्व लेवल कनवर्टर इस युटीलीज़ेड तू डॉ मल्टीप्ल फंक्शन्स इन थ्री मोड्स. इन मोड 1, इट ट्रान्सफर एक्टिव पावर तू दा ग्रिड एंड कनेक्टेड लोड्स व्हाइल मिटिगेटिंग दा पावर क्वालिटी इश्यूज इन दा डिस्ट्रीब्यूशन नेटवर्क. इन मोड 2, इट ट्रांसफर्स ओनली एक्टिव पावर तू दा ग्रिड येत यूनिटी पावर फैक्टर व्हाइल इन मोड 3, इट डस ओनली पावर क्वालिटी मिटिगेशंस. इन पीवी-डिस्टॉटकॉम सिस्टम, इट ट्रांसफर्स लार्ज पावर अत हाई वोल्टेज तू दा थ्री फेज ऐसी ग्रिड विथ स्टॉटकॉम कैपेबिलिटीज देयेरबाई इन्क्रेअसिंग दा ट्रांसमिशन ट्रांसफरिंग कपाबिलिटी. फॉर पीवी-डिस्टॉटकॉम सिस्टम वर्किंग इन थ्री मोड्स, फाइव एंड सेवन लेवल कन्वर्टर्स आर युटीलीज़ेड तू इंटेग्रटे डा पीवी एर्रे विथ दा ग्रिड येत लो स्वीचिंग फेक्वेन्सी विथ स्टॉटकॉम कैपेबिलिटीज. इन बोथ सिस्टम्स, दा वीएससीस आर फुल्ली युटीलीज़ेड तू थेइर फुल कैपेसिटी इन दा प्रोपोसड सिस्टम फॉर 24 हॉर्स. तू इम्प्रोव दा एफिशिएंसी ऑफ़ दा सिस्टम , अ सिंगल स्टेज टोपोलॉजी इस अडॉप्टेड ओवर डबल स्टेज टोपोलॉजी इन दा पीवी ग्रिड टाईड सिस्टम्स.

हाउएवर, तू ट्रान्सफर लार्ज पावर फ्रॉम अ पीवी ऐरे तू दा थ्री फेज ग्रिड येत हाई वोल्टेज, मल्टीलेवल एंड मल्टीपल्स वीएसीस आर वाइएबल सलूशन एस लॉसेस इन दा वीएसी, आर डिक्रीज़ड दू तू लो स्वीचिंग फ्रीक्वेंसी. दा वेरियस कॉन्फ़िगरेशंस (बाइनरी कास्केडेड 31 लेवल कनवर्टर, टेरनरी कास्केडेड 9 एंड 27 लेवल कन्वर्टर्स, 12 एंड 18 पल्स कनवर्टर) ऑफ़ दा पीवी सिस्टम

ऑपरेटिंग अत फफस (फंडामेंटल फ्रीक्केंसी स्विचन) आर इंवेस्टीगेटेड. डुए तू फफस, दा स्वीचिंग लॉसेस ऑफ़ दा कन्वर्टर्स आर रेडूसेड , देयेरबाई , इन्क्रेअसिंग ओवरआल एफ्फिकेसी ऑफ़ दा सिस्टम, व्हिच रिजल्ट्स इन रिडक्शन ऑफ़ यूनिट कॉस्ट ऑफ़ इलेक्ट्रिसिटी. दा बाइनरी एंड टेरनरी कास्केडेड कन्वर्टर्स ऑपरेटिंग येत फफस एंड सिंगल स्टेज टोपोलॉजी, ऑफर्स अडवांटागेस विज. हाई नंबर ऑफ़ वोल्टेज लेवल्स, लेस्स नंबर ऑफ़ स्वीचिंग डिवाइसेस, लो टीयाचडी, लो स्वीचिंग लॉसेस, ईज ऑफ़ ऑपरेशन अत हाई वोलटागेस तहत लीडस् तू दा इम्प्रूवमेंट इन पावर क्वालिटी ऑफ़ दा सिस्टम. आल दीज कनवर्टर बेस्ड ग्रिड टाईड पावर जनरेटिंग सिस्टम्स आर सिमुलेटेड इन मैटलैब एंड दा रेस्पॉन्सेस आर वेरिफ़िएड थ्रू एक्सपेरिमेंटल रिजल्ट्स अचीवेद ओन दा डेवलप्ड प्रोटोटाइप इन दा लेबोरेटरी, तू डेमोंस्ट्रेटे दा सिस्टम परफॉरमेंस अंडर वारयिंग कंडीशंस. दा मेजर फोकस ऑफ़ थिस रिसर्च वर्क, इस इंवेस्टीगेशंस ऑफ़ हाई पावर कनवर्टर बेस्ड पीवी ग्रिड टाईड सिस्टम, फॉर एक्टिव पावर ट्रान्सफर तू दा ग्रिड एस वेल एस मिटिगेटिंग पावर क्वालिटी (पिक्वी) इश्यूज, व्हाइल सटिस्फीइंग दा आई ट्रिप्पल इ स्टैंडर्ड्स.

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PV	Solar photovoltaic
VSC	Voltage source converter
IEEE	Institute of Electrical and Electronics Engineers
IEC	International Electrotechnical Commission
MPPT	Maximum power point tracking
PLL	Phase locked loop
DSTATCOM	Distribution static compensator
STATCOM	STATic COMpensator
THD	Total harmonic distortion
MATLAB	Matrix laboratory
HIL	Hardware in-loop
PWM	Pulse width modulation
PCC	Point of common coupling
IC	Incremental conductance
P&O	Perturb and observe
MPP	Maximum power point
DVR	Dynamic voltage restorers
UPQC	Unified power quality conditioners
LMF	Least mean fourth
EPLL	Enhanced phase locked loop
CTF	Current triangle function
NPC	Neutral-point-clamped
RZA	Adaptive reweighted zero-attracting
IGBT	Insulated gate bipolar transistor
DSP	Digital signal processor
DAC	Digital to analog converter
ADC	Analog to digital converter
PI	Proportional integral
RMS	Root mean square
LPF	Low pass filter
SRF	Synchronous reference frame
DDSRF	Decoupled double synchronous reference frame

kVAR	Kilo volt amperes reactive
KVA	Kilo volt amperes
kW	Kilo watts
PD	Phase deposition
SHE	Selective harmonic elimination
FFS	Fundamental switching frequency
SSI-PLL	Sinusoidal signal integrator-phase locked loop

LIST OF SYMBOLS

v_{sab}, v_{sbc}, v_{sca}	Grid Line voltages
v_{sa}, v_{sb}, v_{sc}	Phase voltages
i_{sa}, i_{sb}, i_{sc}	Grid line currents
N_s	Number of PV modules connected in series
N_p	Number of PV modules connected in parallel
V_{dc}	DC link voltage
m	Modulation index
V_{mp}	Voltage of one module at maximum power point
I_{mp}	Current of one module at maximum power point
P_{pv}	PV array power
V_{pv}	PV array voltage
I_{pv}	PV array current
V_{ripple}	Ripple in DC link voltage
L_i	Interfacing inductor
Δi	Current ripple
f_{sw}	Switching frequency of VSC
R_f, C_f	Ripple filter
V_t	Amplitude of terminal voltage
u_{pa}, u_{pb} and u_{pc}	In-phase unit templates
u_{qa}, u_{qb} and u_{qc}	Quadrature unit templates
w_{cq}	Reactive loss component
K_{pt} and K_{it}	Proportional and integral gain constants of AC voltage controller
V_{de}	DC voltage error
V_{dcref}	Reference DC bus voltage
V_{dc}	Sensed DC voltage
C_{dc}	DC link capacitor voltage
K_{pd} and K_{pd}	Proportional and integral constant of DC link voltage controller
I_{ff}	PV feed-forward term
I_{loss}	AC loss component
i_{La}, i_{Lb}, i_{Lc}	Three phase load currents
e_{pa}	Error in the active load current component
e_{qa}	Error in the reactive load current component

w_{sp}	Total weight of active component of reference grid currents
i_{sa}^*, i_{sb}^*, i_{sc}^*	Three phase reference grid currents
Ts	Sampling time
i_{cnva}, i_{cnvb}, i_{cnvc}	VSC currents
G	Insolations level
P	Grid active power
Q	Grid reactive power
f	Grid frequency
I_d^*	Reference direct axis current component
I_d	Direct axis current component
I_q^*	Reference quadrature axis current component
I_q	Quadrature axis current component
V_d^*	Reference direct axis voltage component
V_d	Direct axis voltage component
V_q^*	Reference quadrature axis voltage component
V_q	Quadrature axis voltage component
v_{sa}^*, v_{sb}^* and v_{sc}^*	Reference phase voltages
V_{thd}	THD in the grid voltages
I_{thd}	Grid current THD