DSTATCOM CONTROL ALGORITHMS IN INTEGRATED PHOTOVOLTAIC (PV) POWER GENERATION SYSTEM

NOR HANISAH BINTI BAHARUDIN

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by

NOR HANISAH BINTI BAHARUDIN
1440911321

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LIST OF ABBREVIATIONS

ADC	Analog-to-digital converter
AM	Air mass ratio
APF	Active Power Filter
APLC	Active power line conditioners
ASD	Adjustable-speed drives
BESS	Battery energy storage system
BOS	Balance of system
BPNN	Back Propagation Neural Network
CCP	Common Coupling Point
COE	Cost of electricity
CPD	Custom power devices
CSFSHPWM	Constant switching frequency sub-harmonic pulse width modulation
CSI	Current Source Inverter
DC	Direct Current
DG	Distributed generation
DSP	Digital Signal Processing
DSTATCOM	Distribution Static Synchronous Compensator
DVR	Dynamic Voltage Restorer
FFT	Fast Fourier Transform
FiA	Feed-in Approval
FIL	FPGA-in-the-loop
FiT	Feed-in Tariff
FPGA	Field-programmable gate array
GD	Gradient descent

GTP	Government's Transformation Program
HIL	Hardware-in-the-loop
HVDC	High Voltage Direct Current
IGBT	Insulated gate bipolar transistor
ILST	Improved linear sinusoidal tracer
JTAG	Joint Test Action Group
LLMF	Leaky Least Mean Fourth
LME	Least mean eight adaptive algorithm
LR	Learning rate
MSE	Mean Squared Error
NKEA	National Key Economic Areas
NPC	Net present cost
MLMF	Adaptive modified least mean fourth
PAR	Place-and-route
PCB	Printed circuit board
PCC	Point of Common Coupling
P-DPC	Predictive direct power control
PQ	Power quality
PV	Photovoltaic
RBFNN	Radial Basis Function Neural Network
RDFT	Recursive Discrete Fourier Transform
RES	Renewable energy sources
SEDA	Sustainable Energy Development Authority Malaysia
SHEPWM	Selected Harmonic Elimination Pulse Width Modulation
SMPS	Switch mode power supplies

SPS	SimPowerSystem blocks
SPWM	Sinusoidal Pulse Width Modulation
SRF	Synchronous reference frame theory
STATCOM	Static Synchronous Compensator
STC	Standard Test Condition
STFT	Short Time Fourier Transform
SVC	Static VAR Compensator
SVPWM	Space Vector Pulse Width Modulation
THD	Total Harmonic Distortion
TNB	Tenaga Nasional Berhad
UPQC	Power Quality Conditioner Unified
UPS	Uninterruptible power supplies
VRC	Voltage Reference Configuration
VSI	Voltage Source Inverter
3P3W	Three-phase three-wire

LIST OF SYMBOLS

a	Overloading factor
f_s	Switching frequency
i_{crpp}	Ripple current
i_{ab}	Line-to-line current phase AB
i_{bc}	Line-to-line current phase BC
i_{ca}	Line-to-line current phase CA
i_{Ca}	Compensating current phase A
i_{Cab}	Compensating current phase AB
i_{Cb}	Compensating current phase B
i_{Cbc}	Compensating current phase BC
i_{Cca}	Compensating current phase CA
i_{Cc}	Compensating current phase C
i_L	Average current in the inductor
i_{La}	Load current phase A
i_{Lab}	Load current phase AB
i_{Lb}	Load current phase B
i_{Lbc}	Load current phase BC
i_{Lc}	Load current phase C
i_{Lca}	Load current phase CA
i_{Lmax}	Maximum inductor current
i_{Lmin}	Minimum inductor current
i_{Sa}	Source current phase A
i_{Sb}	Source current phase B
i_{Sc}	Source current phase C

i^*_{sa}	Reference source currents phase A
i^*_{sb}	Reference source currents phase B
i^*_{sc}	Reference source currents phase C
k	Variation of energy during extreme transient conditions at load perturbation
kWh/day	Kilo Watt hour per day
kWh/m^2-day	Kilo Watt hour per metre square per day
m	Modulation index
r_1	Scaled factor
t	Time when the DC bus voltage is to be recovered
u_{ap}	In phase unit templates phase A
u_{bp}	In phase unit templates phase B
u_{cp}	In phase unit templates phase C
v_{ab}	Line-to-line voltage phase AB
v_{bc}	Line-to-line voltage for phase BC
v_{ca}	Line-to-line voltage phase CA
v_{dcr}	Reference DC bus voltage
v_{de}	Extracted DC bus voltage error
v_{te}	Extracted AC bus voltage error
v_{Sa}	PCC voltage phase A
v_{Sb}	PCC voltage phase B
v_{Sc}	PCC voltage phase C
w_{cp}	DC bus PI controller output
w_{cq}	AC bus PI controller output
w_p	Fundamental weighted value of load active power component of current

w_q	Fundamental weighted value of load reactive power component of current
w_{pA}	The normalized and filtered value of w_p from low frequency components
w_{LpF}	Fundamental active power components of three-phase load currents
w_{LqF}	Fundamental reactive power current components of three-phase load currents
C_{DC}	DC bus capacitor
D	duty cycle
I	Phase current
I_{Lp}	Initial value of three-phase load active power current components
I_{LpA}	Mean value of three-phase load active power component of current
I_{mpp}	Current at P_{max}
I_{PV}	PV current
$I_{PV,mpp}$	Output current of PV array at maximum power point
I_{sc}	Short Circuit Current
I_{sw}	Current rating of the switch
L_f	Interfacing AC inductor
L_{min}	Minimum inductance
L_s	Source inductor
MW	Mega Watt
P_{max}	Power Output
P_{PV}	PV array output power
R_s	Source resistor
T_c	Case temperature
T_s	Switching period

V_d	Variable voltage
V_{in}	Input voltage
V_{mpp}	Voltage at P_{max}
V_{oc}	Open Circuit Voltage
V_{out}	Output voltage
V_s	Source voltage
V_{sw}	Voltage rating of the switch
V_t	Amplitude of PCC voltage
V_{DC}	DC bus voltage
V_{DC1}	Minimum voltage level of DC bus
V_L	Voltage across the inductance of the coupling transformer and filter
V_{LL}	AC line output voltage of the DSTATCOM
$V_{PV,mpp}$	Output voltage of PV array at maximum power point
V_{PV}	PV voltage
W_{spt}	Amplitude of active power components of reference source currents
W_{sqt}	Amplitude of reactive power components of reference source currents
V_{tr}	Reference ac bus voltage
Z_s	AC source impedance or internal grid impedance
α_p	Output signals of receptive field
σ	Standard deviation of three-phase load active power component of current
Φ	Phase
Ω	Frequency
Δi_L	Change in inductor currents
$\Delta V_o/V_o$	Output ripple voltage

Penyelidikan Sistem Kawalan berasaskan DSTATCOM pada Sistem Penjanaan Kuasa Fotovolta (PV) Bersepadu

ABSTRAK

Pertambahan pesat beban elektronik tak linear telah menyisipkan harmonik ke dalam rangkaian pengagihan dan mencemarkan rangkaian bekalan dengan masalah kualiti kuasa. Peralatan kuasa khusus (CPD) jenis pampasan adalah penyelesaian yang sesuai untuk menyelesaikan isu kualiti kuasa di titik gandingan umum (PCC) seperti penyingkiran harmonik bagi menepati Standard IEEE 519-2014. Pemampas statik agihan (DSTATCOM) merupakan CPD yang bersambung secara selari telah didapati sebagai penyelesaian yang efektif untuk menyelesaikan masalah kualiti kuasa yang berkaitan dengan arus harmonik kerana gerak balas yang cepat dan licin semasa pengusikan beban. Kecekapan DSTATCOM bergantung pada algoritma kawalan untuk menghasilkan isyarat pensuisan bagi Penyongsang Sumber Voltan (VSI) dan mengeluarkan arus pampasan pada PCC. Kajian kerja ini membentangkan topologi baru bagi PV berdasarkan DSTATCOM dengan tiga algoritma-algoritma kawalan baru dengan menggunakan algoritma kawalan Konfigurasi Voltan Rujukan (VRC), rangkaian neural perambatan balik (BPNN) dan rangkaian neural fungsi asas radial (RBFNN) untuk pembaikan kualiti kuasa bagi penyingkiran harmonik ketika beban tidak linear. Algoritma-algoritma kawalan ini diperlukan untuk mengekstrak arus talian rujukan daripada arus beban terherot bagi menghasilkan arus pampasan dengan ralat arus pada titik gandingan umum (PCC) supaya dapat disesuaikan dengan arus talian sehampir mungkin dengan arus talian rujukan. Oleh yang demikian, DSTATCOM yang dicadangkan akan menyebabkan arus talian PCC menjadi bentuk sinus, arus harmonik yang rendah berdasarkan Standard IEEE 519-2014 dan sama fasa dengan voltan talian. Prestasi DSTATCOM diuji dengan menggunakan perisian MATLAB Simulink dan set Blok Sistem Kuasa (PSB). Konfigurasi bersepadu PV bagi DSTATCOM telah direka bentuk untuk memelihara pautan AT bagi pampasan berterusan. Reka bentuk optima bagi tatasusunan PV dengan AT-AT penukar galak telah dinilai melalui aspek teknikal dan ekonomi bagi bekalan tenaga boleh baharu yang berterusan dengan menggunakan perisian Homer Pro. Ujian FPGA-dalam-gelung (FIL) bagi algoritma kawalan yang dicadangkan telah dilaksanakan untuk mengesahkan kecekapannya. Kemudian, sebuah prototaip DSTATCOM telah dibangunkan dengan menggunakan Altera FPGA Cyclone IV EP4CE115F29C7N dan prestasinya telah dikaji dalam keadaan mantap dan dinamik. Prestasi DSTATCOM dengan algoritma kawalan yang dicadangkan telah didapati memuaskan ketika keadaan beban tidak linear bagi penyisihan harmonik di PCC pada sistem pengagihan tiga fasa voltan rendah.

Investigation of Control Systems using DSTATCOM in Integrated Photovoltaic (PV) Power Generation System

ABSTRACT

In recent years, the proliferation of nonlinear electronic loads have injected harmonics into the distribution network and polluted the supply network with power quality problems. Compensating type of custom power devices (CPD) is the possible solution to solve the power quality issues at the Point of Common Coupling (PCC) such as harmonic elimination to comply with the IEEE Standard 519-2014. Distribution Static Compensator (DSTATCOM) is a shunt connected CPD which found to be an effective solution to mitigate the current related power quality problems especially harmonic currents due to its fast and smooth response during load perturbation. The effectiveness of DSTATCOM depends on its control algorithms to generate the switching signals for the Voltage Source Inverter (VSI) and injecting the compensating currents at the PCC. This research work presents new topology of PV based DSTATCOM with three new main control algorithms proposed for it which are Voltage Reference Configuration (VRC) control algorithm, Back Propagation Neural Network (BPNN) and Radial Basis Function Neural Network (RBFNN) for power quality improvement in term of harmonic elimination under nonlinear loads. These control algorithms are required to extract the reference line currents from the distorted load currents in order to inject the compensating currents with current error at the point of common coupling (PCC) to match the line currents as close as possible with the reference line currents. Thus, the proposed DSTATCOM will force the PCC line currents to be sinusoidal, low current harmonic according to IEEE Standard 519-2014 and in-phase with the line voltage. The performance of DSTATCOM is validated using MATLAB software with its Simulink and Power System Block set (PSB) toolboxes. The optimum design of PV array with DC-DC boost converter is evaluated its viability in term of technical and economic aspects for continuous renewable supply and reduce the cost of electricity (COE) with Homer Pro software. Prior to hardware implementation, FPGA-in-the-loop (FIL) test of the proposed control algorithm has been implemented to verify its effectiveness. Then, a prototype of DSTATCOM is developed using an Altera FPGA Cyclone IV EP4CE115F29C7N FPGA board and its performance is studied under steady-state and dynamic conditions. The performance of the DSTATCOM with the proposed control algorithm is found to be satisfactory under nonlinear load condition for harmonic elimination at the PCC in the three-phase three-wire low voltage distribution system.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Renewable energy sources (RES) have been recognized as the fifth fuel for electricity generation apart from conventional fuels which consist of oil, gas, coal and hydro when the Five Fuel Policy was announced in 2001. Accordingly, the road map of the 10th Malaysia Plan has planned necessary actions to further improve the sustainable energy sector through Government's Transformation Program (GTP) and National Key Economic Areas (NKEA) as a proof of Malaysia's commitment towards a greener future and developed nation as envisaged in Vision 2020 (Performance Management & Delivery Unit (PEMANDU), 2017).

Sustainable Energy Development Authority (SEDA Malaysia) is a statutory body that has been authorized under the Sustainable Energy Development Authority Act 2011 to administer and manage the execution of the feed-in tariff mechanism (FiT) as announced under the Renewable Energy Act 2011 (Sustainable Energy Development Authority Malaysia (SEDA), 2011). Before FiT mechanism is introduced, there were only 63.45 MW grid-connected renewable energy resources. Since the implementation of FiT mechanicm on 1st December 2011, there were abrupt increases of 450.85 MW total applications capacity that have been approved by SEDA in 2012 (SEDA, 2012). Moreover, 1,800 applications of Feed-in Approval (FiA) have been approved in 2013 which represents a year over-year increment of 188% and the largest contributors comes from individuals installations of photovoltaic (PV) system (SEDA, 2013).

The lucrative incentive that has been given by Malaysian government has further accelerated the renewable energy development growth amongst small producers especially for PV for the individuals. However, there are current issues that can affect the power quality at the point of common coupling (PCC) when high penetration of small renewable energy systems connected to the utility grid which will also inject harmonic components (M. Singh, Khadkikar, Chandra, & Varma, 2011). Available international standards such as IEEE 929-2000 and IEC 61727 (1995-06) on guidance of utility interface for photovoltaic (PV) systems had shown that renewable energy resources interfacing inverter parallel with the utility grid will be expected to introduce problem in the future including power quality problems (*IEEE Recommended Practice for Utility Interface of Photovoltaic (PV) Systems*, 2000)(Enslin & Heskes, 2004). This is due to high penetration level of intermittent renewable energy sources into the grid that may affect its stability, power quality and voltage regulation. The utility will assess strictly the system performance to ensure its technical performance in term of the system reliability, safety and overall efficiency as well as to facilitate the interfacing between RES and the utility through strict regulatory framework. Besides, power quality problems in term of increasing harmonics, low power factor, voltage dip and over voltage are also generated from the connected nonlinear loads by consumers through fluorescent lights, computers, laser printers, fax machines, uninterruptible power supplies (UPS), adjustable-speed drives (ASD) and power electronic equipment.

Active power line conditioners which are based on leading-edge power electronics technology, have already been recognized as the best solution to provide harmonics elimination, voltage-flicker reduction, power factor correction, voltage regulation and load balancing(Akagi, Watanabe, & Aredes, 2007)(Mariun, Alam, Mahmod, & Hizam, 2004). Furthermore, improved active power line conditioners that are located in the distribution networks are called as custom power devices (CPDs). The CPDs are consisted of Distribution Static Synchronous Compensator (DSTATCOM), Unified Power Quality Conditioner (UPQC) and Dynamic Voltage Restorer (DVR). DSTATCOM is found to be the most viable, cost effective solution, effective device with faster response (Paserba, Reed, Takeda, & Aritsuka, 2000)(Masand, Jain, & Agnihotri, 2006).

1.2 Problem statement

Due to modernization and economic developments, numerous power electronic devices have been produced for different applications in households, industries and commercial sectors such as fluorescent lights, computers, laser printers, fax machines, uninterruptible power supplies (UPS) and adjustable-speed drives (ASD). These power electronic devices have caused major power quality problems in the distribution system such as harmonics, unbalanced loads, poor power factor, voltage flickers and distortion due to resonance. Furthermore, harmonics are amongst the prime causes that deteriorate the power quality, which can be considered as pollutions in the power system. Various problems may incurred due to harmonics such as overheating of transformer and electrical motors, overheating of capacitors for power factor correction, voltage form distortion at the point of common coupling (PCC), resonance with source impedance, excessive power losses in the supply line, voltage flickers and interference with communication system (Akagi et al., 2007; Arya & Singh, 2014b; Padiyar, 2007; Rechka, Ngandui, Xu, & Sicard, 2003). The injection of harmonic current source or