

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

**NOR HANISAH BINTI BAHARUDIN**

**UNIVERSITI MALAYSIA PERLIS**  
2018



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

by

**NOR HANISAH BINTI BAHARUDIN  
1440911321**

A thesis submitted in fulfillment of the requirements for the degree of  
Doctor of Philosophy

**School of Electrical System Engineering  
UNIVERSITI MALAYSIA PERLIS**

**2018**

## ACKNOWLEDGEMENTS

I am most grateful to Almighty ALLAH, the Most Knowledgeable, the Most Expert and the Most Wise. Peace and blessings of ALLAH upon His Last Messenger Muhammad SAW and his family who guided us to the right path. First and foremost, I do express my deepest gratitude and indebtedness to Ir. Dr. Muhammad Irwanto Misrun and Prof. Madya Ir. Dr. Rosnazri Ali for providing me a life-time opportunity to do the PhD work under their supervision. Their deep insights with ample research ideas, continuous monitoring and valuable guidance have immensely helped me in carrying out my research. My heartfelt thanks to Prof. Dr. Syed Idris Syed Hassan and Prof. Dr. Puteh Saad, my previous supervisors who have equally given valuable guidance, advices and inspiration to improve the quality of my research work. I must thank Kementerian Pengajian Tinggi and Universiti Malaysia Perlis (UniMAP) for providing me a valuable opportunity to further my PhD study. I am grateful to all my colleagues and staffs at UniMAP for their kind co-operation who deserves heartfelt thanks. I am extremely grateful particularly the research members and technicians of Center of Renewable Energy (CERE), UniMAP for providing me immense facilities and assistance to carry out my research work. I am also grateful to those who have directly or indirectly helped me to complete my thesis work. If I get any success today for my research work, the entire credit and honor should go to my husband, Ir. Hj. Tunku Muhammad Nizar bin Tunku Mansur, who was supporting me through thick and thin. I will cherish his valuable contribution to motivate me in completing this research. Last but not least, my deepest love and indebtedness goes to my beloved parents, in-laws, my sisters, my little daughter and son, Tunku Intan Maryam and Tunku Muhammad Imran as well as the rest of family members for their support, encouragement and continuous prayers for my success in this world and hereafter.

## TABLE OF CONTENTS

<b>THESIS DECLARATIONS</b>	<b>i</b>
<b>ACKNOWLEDGEMENTS</b>	<b>ii</b>
<b>TABLE OF CONTENTS</b>	<b>iii</b>
<b>LIST OF TABLES</b>	<b>vi</b>
<b>LIST OF FIGURES</b>	<b>vii</b>
<b>LIST OF ABBREVIATIONS</b>	<b>xii</b>
<b>LIST OF SYMBOLS</b>	<b>xv</b>
<b>ABSTRAK</b>	<b>xix</b>
<b>ABSTRACT</b>	<b>xx</b>
<b>CHAPTER 1 INTRODUCTION</b>	<b>1</b>
1.1 Introduction	1
1.2 Problem statement	3
1.3 Objectives	9
1.4 Scope of Research	10
1.5 List of contributions	11
1.6 Thesis organization	12
<b>CHAPTER 2 LITERATURE REVIEW</b>	<b>14</b>
2.1 Introduction	14
2.2 Photovoltaic (PV) based DSTATCOM System	15
2.3 Power Quality Issues	18
2.4 Custom Power Devices	21
2.5 Distribution Static Compensator (DSTATCOM)	24
2.5.1 Topologies of DSTATCOM	25
2.5.2 Control Algorithms of DSTATCOM	30

2.5.3	Switching Schemes of DSTATCOM	37
2.5.4	Motivation for an FPGA as PV based DSTATCOM Controller	38
2.6	Summary	40
<b>CHAPTER 3 RESEARCH METHODOLOGY</b>		<b>43</b>
3.1	Introduction	43
3.2	Design and Configuration of DSTATCOM System	45
3.2.1	Selection of DC bus voltage	46
3.2.2	Selection of DC bus capacitor	47
3.2.3	Selection of an interfacing AC inductor	48
3.2.4	Voltage and Current Ratings of the Solid-State Switches	48
3.3	Design of Photovoltaic (PV) based DSTATCOM	49
3.3.1	Site Selection	49
3.3.2	Load Profile	51
3.3.3	Photovoltaic (PV) system	52
3.3.4	Modelling of Photovoltaic (PV) array and DC-DC boost converter.	54
3.4	Design Control Algorithms of DSTATCOM	60
3.4.1	Design of Voltage Reference Configuration (VRC) Control Algorithm	60
3.4.2	Design of Radial Basis Function Neural Network (RBFNN) Control Algorithm	63
3.4.3	Design of Back Propagation Neural Network (BPNN) Control Algorithm	67
3.5	MATLAB integrated FPGA-in-the-loop (FIL)	69
3.6	Prototype construction on FPGA platform	73
3.7	Summary	79
<b>CHAPTER 4 RESULTS &amp; DISCUSSION</b>		<b>80</b>
4.1	Introduction	80

4.2	Design of PV System based DSTATCOM for Power Quality Improvement	81
4.3	Modeling of photovoltaic (PV) system and DC-DC boost converter.	84
4.4	Performance of DSTATCOM with Different Control Algorithms	89
4.4.1	Voltage Reference Configuration (VRC) Control Algorithm	90
4.4.2	Radial Basis Function Neural Network Control Algorithm (RBFNN)	99
4.4.3	Back Propagation Neural Network Control Algorithm (BPNN)	102
4.5	Hardware Implementation of Three-Phase DSTATCOM	111
4.5.1	Performance of MATLAB integrated FPGA-in-the-loop (FIL) DSTATCOM System	112
4.5.2	Laboratory Prototype Test	114
4.6	Summary	127
	<b>CHAPTER 5 CONCLUSIONS</b>	<b>133</b>
5.1	Conclusions	133
5.2	Impact of the Undertaken Research Work to the Society	139
5.3	Future Work	140
	<b>REFERENCES</b>	<b>142</b>
	<b>APPENDIX A</b>	<b>162</b>
	<b>APPENDIX B</b>	<b>163</b>
	<b>APPENDIX C</b>	<b>165</b>
	<b>LIST OF PUBLICATIONS</b>	<b>166</b>
	<b>LIST OF AWARDS</b>	<b>172</b>

## LIST OF TABLES

NO.		PAGE
2.1	Summary Review of PV based DSTATCOM Control Algorithms.	17
2.2	IEEE-519 Harmonic Voltage Distortion Limits (in %) ( <i>IEEE Std 519<sup>TM</sup>-2014 (Revision of IEEE Std 519-1992)</i> , 2014).	20
2.3	Summary of neural network control algorithm in various applications.	36
2.4	Summary Review of Control Algorithms with FPGA Controller.	40
3.1	Electrical parameters at Standard Test Conditions (STC)	53
3.2	Parameters of DC-DC boost converter.	59
3.3	Data Type Conversion Parameters	70
3.4	FGH40T120SMD IGBT absolute maximum ratings at $T_C = 25^\circ\text{C}$ .	75
3.5	Resources for the Altera FPGA Cyclone IV EP4CE115F29C7N	77
4.1	Cost Summary of PV System Sizing	82
4.2	Parameters comparison of DC-DC boost converter.	87
4.3	Performance of DSTATCOM with VRC control algorithm under nonlinear load.	96
4.4	Comparison result between different training algorithms of BPNN with RBFNN.	106
4.5	Comparison of THD between simulation and FPGA-in-the-Loop (FIL) results.	114
4.6	Performance parameters of DSTATCOM with VRC control algorithm under nonlinear load.	123
4.7	Line-to-line performance of DSTATCOM.	127
4.8	Performance of Voltage Reference Configuration (VRC) control algorithm in (% THD).	128
4.9	Performance of RBFNN and BPNN for THD improvement in (% THD).	132
5.1	Summary performance of proposed DSTATCOM control algorithms in (% THD).	138
5.2	Data Type Conversion Parameters	163

## LIST OF FIGURES

NO.		PAGE
1.1	Placement of DSTATCOM in distribution system for harmonic current elimination.	5
2.1	The equivalent circuit diagram Dynamic Voltage Restorer (DVR).	22
2.2	The equivalent circuit diagram Distribution Static Compensator (DSTATCOM).	22
2.3	The equivalent circuit diagram Unified Power Quality Conditioner (UPQC).	23
2.4	Basic operation of DSTATCOM.	24
2.5	Topology classification of DSTATCOM (Bhim Singh et al., 2015)(Mahela & Shaik, 2015)(Bhim Singh, Jayaprakash, Kothari, Chandra, & Haddad, 2014).	26
2.6	Classification of control algorithms in generating reference current for shunt compensation (Bhattacharya, A., Chakraborty, C., Bhattacharya, 2009; Massoud et al., 2004).	31
3.1	Flow chart of design of DSTATCOM system simulation and prototype design.	44
3.2	Schematic diagram of the proposed PV-based DSTATCOM.	45
3.3	Location of PV based DSTATCOM.	50
3.4	Average monthly solar insolation and clearness index in Perlis (NASA, 2016).	51
3.5	Daily load profile of scaled annual average residential load of 10 kWh/day.	52
3.6	Design of PV based DSTATCOM.	53
3.7	MATLAB Simulink model of 3×2 PV array.	54
3.8	(a) Voltage input PV module (b) Current input PV module	55
3.9	Parameters of PV module based on Yingli YL250P29b datasheet.	56
3.10	Topology of DC-DC boost converter for PV array.	57
3.11	DC-DC boost converter in mode 1.	57
3.12	DC-DC boost converter in mode 2.	57
3.13	Matlab model of PV strings and DC-DC boost converter for DSTATCOM.	59
3.14	The proposed DSTATCOM Simulink Model with Voltage Reference Configuration (VRC) Control Algorithm.	61
3.15	Block diagram of Voltage Reference Configuration (VRC) control algorithm.	62

3.16	DSTATCOM system MATLAB based model using Voltage Reference Configuration (VRC) control algorithm for PWM generation.	62
3.17	Typical architecture of RBFNN.	63
3.18	Proposed Radial Basis Function Neural Network (RBFNN) control algorithm for DSTATCOM system.	65
3.19	Summary of the proposed BPNN learning algorithms (Beale, Hagan, & Demuth, 2010).	68
3.20	PWM Generation FIL block in DSTATCOM system integration with Altera FPGA board through JTAG connection.	72
3.21	Overall block diagram of the experimental setup for the DSTATCOM system.	74
3.22	Overall construction of three-phase DSTATCOM system.	76
3.23	Design flow from MATLAB Simulink to Altera FPGA board.	78
4.1	Daily PV output based on hours of availability.	82
4.2	Monthly average electric production from the PV system.	83
4.3	I-V characteristic of Yingli YL250P29b PV module.	84
4.4	Power output of Yingli YL250P29b PV module.	85
4.5	I-V characteristic of $3 \times 2$ Yingli YL250P29b PV array.	86
4.6	Power output of $3 \times 2$ Yingli YL250P29b PV array.	86
4.7	DC-DC boost converter input voltage ( $V_{in}$ ).	87
4.8	DC-DC boost converter output voltage ( $V_{out}$ ).	88
4.9	Duty cycle waveform for controlling output DC-DC boost converter.	88
4.10	Inductor current waveform of the DC-DC boost converter.	88
4.11	Three-phase nonlinear load currents waveform ( $i_{La}$ , $i_{Lb}$ , $i_{Lc}$ ).	90
4.12	Three-phase compensating currents ( $i_{Ca}$ , $i_{Cb}$ , $i_{Cc}$ ).	90
4.13	Three-phase line currents ( $i_{Sa}$ , $i_{Sb}$ , $i_{Sc}$ ).	91
4.14	Three-phase line voltage ( $v_{Sa}$ , $v_{Sb}$ , $v_{Sc}$ ).	91
4.15	Phase A load current ( $i_{La}$ ), line current ( $i_{Sa}$ ) and compensating current ( $i_{Ca}$ ).	92
4.16	Phase B load current ( $i_{Lb}$ ), line current ( $i_{Sb}$ ) and compensating current ( $i_{Cb}$ ).	92
4.17	Phase C load current ( $i_{Lc}$ ), line current ( $i_{Sc}$ ) and compensating current ( $i_{Cc}$ ).	92
4.18	Total harmonic distortion (THD) for phase A load current under steady state condition.	93
4.19	Total harmonic distortion (THD) for phase A line current after compensation under steady state condition.	93

4.20	Dynamic performance of DSTATCOM under nonlinear load	94
4.21	Three-phase nonlinear load currents waveform ( $i_{La}, i_{Lb}, i_{Lc}$ ).	94
4.22	Three-phase compensating currents ( $i_{Ca}, i_{Cb}, i_{Cc}$ ).	94
4.23	Three-phase line currents ( $i_{Sa}, i_{Sb}, i_{Sc}$ ).	95
4.24	Three-phase line voltage ( $v_{Sa}, v_{Sb}, v_{Sc}$ ).	95
4.25	Total harmonic distortion (THD) for phase A load current under dynamic condition.	95
4.26	Total harmonic distortion (THD) for phase A line current after compensation under dynamic condition.	95
4.27	Dynamic performance of DSTATCOM system under 37.5 kVA star connected linear load at 0.8 p.f for load balancing.	97
4.28	Line currents under linear load in steady-state condition.	97
4.29	Total harmonic distortion (THD) for line currents under linear load.	97
4.30	Load current after removing phase A.	98
4.31	Line current after removing phase A.	98
4.32	Load current after removing phase B.	98
4.33	Line current after removing phase B.	98
4.34	Load current after removing phase C.	99
4.35	Line current after removing phase C.	99
4.36	Modeling of DSTATCOM system using Radial Basis Function Neural Network (RBFNN) control algorithm in Simulink MATLAB under nonlinear load.	100
4.37	Phase A load current ( $i_{La}$ ).	101
4.38	Phase A compensating current ( $i_{Ca}$ ).	101
4.39	Phase A line current ( $i_{Sa}$ ).	101
4.40	Total harmonic distortion (THD) for load currents.	101
4.41	Total harmonic distortion (THD) for line currents after compensation.	101
4.42	Preliminary model of DSTATCOM system using VRC control algorithm as the basis for BPNN offline training.	102
4.43	Phase A load currents waveform ( $i_{La}$ ).	103
4.44	Phase A compensating currents waveform ( $i_{Ca}$ ).	103
4.45	Phase A line currents waveform after compensation ( $i_{Sa}$ ).	103
4.46	Phase A line voltage waveform after compensation ( $v_{Sa}$ ).	103
4.47	Harmonic spectra of the load current.	104
4.48	Harmonic spectra of the line current.	104
4.49	Comparison performance of different learning algorithms of BPNN based on its accuracy, training time and no. of epochs.	105

4.50	Performance of BPNN training algorithm with Jacobian derivatives (a) Levenberg-Marquardt (trainlm) (b) Bayesian Regulation (trainbr).	106
4.51	Performance of BPNN training algorithm with Gradient derivatives using Broyden, Fletcher, Goldfarb and Shanno (BFGS) quasi-Newton method (trainbfg).	107
4.52	Performance of BPNN training algorithm with Gradient derivatives using conjugate gradient (a) Powell-Beale restart (traincgb) (b) Fletcher-Reeves updates (traincgf) (c) Polak-Ribiere updates (traincgp) (d) scaled conjugate gradient (trainscg) (e) RPROP resilient back propagation (trainrp) (f) one step secant (trainoss).	108
4.53	Performance of BPNN training algorithm with Gradient derivatives using (a) gradient descent (GD) (traingd) (b) GD with momentum (traingdm) (c) GD with adaptive learning rate (LR) (d) GD with momentum and adaptive learning rate (LR).	109
4.54	Performance of BPNN training algorithm with supervised weight/bias training functions (a) Batch training with weight and bias learning rules (trainb) (b) Cyclical order (trainc) (c) Random order (trainr) (d) Sequential order (trains).	109
4.55	FPGA-in-the-loop (FIL) validation for the proposed VRC control algorithm (a) Nonlinear load current (b) Compensating current (c) Line current.	113
4.56	Harmonic spectrum of distorted load current.	114
4.57	Harmonic spectrum of line current at PCC.	114
4.58	Experimental setup of DSTATCOM system.	115
4.59	Line current after compensation ( $i_s$ ), load current ( $i_L$ ) and compensating current ( $i_C$ ).	116
4.60	Line current ( $i_s$ ), distorted load current ( $i_L$ ) and compensating current ( $i_C$ ) in phase.	116
4.61	Line current ( $i_s$ ), distorted load current ( $i_L$ ) and compensating current ( $i_C$ ).	117
4.62	Line voltage ( $v_s$ ), load current ( $i_L$ ), compensating current ( $i_c$ ) and line current ( $i_s$ ) before compensation.	118
4.63	Line voltage ( $v_s$ ), load current ( $i_L$ ), compensating current ( $i_c$ ) and line current ( $i_s$ ) after compensation.	118
4.64	Harmonic spectra of nonlinear load current ( $i_L$ ) before compensation.	118
4.65	Harmonic spectra of line current ( $i_s$ ) after compensation.	119
4.66	Line voltage ( $v_s$ ), line current ( $i_s$ ), DC link capacitor voltage ( $V_{DC}$ ), load current ( $i_L$ ) and compensating current ( $i_c$ ) before compensation.	119
4.67	Line voltage ( $v_s$ ), line current ( $i_s$ ), DC link capacitor voltage ( $V_{DC}$ ), load current ( $i_L$ ) and compensating current ( $i_c$ ) after compensation.	120

4.68	Phase A waveforms of line voltage ( $v_{Sa}$ ), line current ( $i_{Sa}$ ), compensating current ( $i_{Ca}$ ) and load current ( $i_{La}$ ).	121
4.69	Harmonic spectrum (a) Load current phase A ( $i_{La}$ ) (b) Line current phase A after compensation ( $i_{Sa}$ ).	121
4.70	Phase B waveforms of line voltage ( $v_{Sb}$ ), line current ( $i_{Sb}$ ), compensating current ( $i_{Cb}$ ) and load current ( $i_{Lb}$ ).	121
4.71	Harmonic spectrum (a) Load current phase B ( $i_{Lb}$ ) (b) Line current phase B after compensation ( $i_{Sb}$ ).	122
4.72	Phase C waveforms of line voltage ( $v_{Sc}$ ), line current ( $i_{Sc}$ ), compensating current ( $i_{Cc}$ ) and load current ( $i_{Lc}$ ).	123
4.73	Harmonic spectrum (a) Load current phase C ( $i_{Lc}$ ) (b) Line current phase C after compensation ( $i_{Sc}$ ).	123
4.74	Waveforms of line-to-line voltage ( $v_{bc}$ ), line-to-line current ( $i_{bc}$ ), compensating current ( $i_{Cbc}$ ) and load current ( $i_{Lbc}$ ).	124
4.75	Harmonic spectrum (a) Line to line load current ( $i_{Lbc}$ ) (b) Line current after compensation ( $i_{bc}$ ).	124
4.76	Waveforms of line-to-line voltage ( $v_{ab}$ ), line-to-line current ( $i_{ab}$ ), compensating current ( $i_{Cab}$ ) and load current ( $i_{Lab}$ ).	125
4.77	Harmonic spectrum (a) Line to line load current ( $i_{Lab}$ ) (b) Line current after compensation ( $i_{ab}$ ).	125
4.78	Waveforms of line-to-line voltage ( $v_{ca}$ ), line-to-line current ( $i_{ca}$ ), compensating current ( $i_{Cca}$ ) and load current ( $i_{Lca}$ ).	126
4.79	Harmonic spectrum (a) Line to line load current ( $i_{Lca}$ ) (b) Line current after compensation ( $i_{ca}$ ).	127
4.80	Sources of limitations in term of time delays and quantization noise in a digital control scheme of a power-conversion application (Eric Monmasson, Idkhajine, & Naouar, 2011).	131

## 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 <sup>2</sup> -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
$\alpha_p$	Output signals of receptive field
$\sigma$	Standard deviation of three-phase load active power component of current
$\Phi$	Phase
$\Omega$	Frequency
$\Delta i_L$	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 10<sup>th</sup> 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 mechanism on 1<sup>st</sup> 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