

LIST OF FIGURES

Figure 2-1	General control structure of grid tied PV system	14
Figure 2-2	Classification of the grid tied PV system topology	15
Figure 2-3	General structure of two –stage grid tied PV system	17
Figure 2-4	General structure of Single –Stage grid tied PV system	18
Figure 2-5	General structure of single-stage PV system with Galvanic Isolation	19
Figure 2-6	Power-voltage PV characteristic	20
Figure 2-7	Flowchart of perturb and observe maximum power point algorithm	21
Figure 2-8	Flowchart of incremental conductance (INC) MPPT algorithm	22
Figure 2-9	Flowchart of modified incremental conductance (INC) MPPT algorithm	24
Figure 2-10	Flowchart of ripple correlation MPPT algorithm	25
Figure 2-11	One-line diagram of a STATCOM	27
Figure 2-12	Per-phase fundamental equivalent circuit	31
Figure 2-13	Phasor diagram for leading and lagging mode	32
Figure 2-14	Vector representation of instantaneous three-phase variables	32
Figure 2-15	Definition of orthogonal coordinates	33
Figure 2-16	Definition of rotating reference frame	34
Figure 2-17	Control structure of grid tied PV system in synchronous reference frame	35
Figure 2-18	Current Control loop of grid tied PV system for stationary reference frame(PR controller)	36
Figure 2-19	Current Control loop of grid tied PV system for dead-beat controller	37
Figure 2-20	Control structure of grid tied PV system using hysteresis current controller	38
Figure 2-21	Control structure of grid tied PV system using sinusoidal pulse width modulation	39

Figure 3- 1	Phase lock loop block diagram	46
Figure 3-2	Phase lock loop Linearized block diagram in the complex frequency domain	46
Figure 3- 3	Step response of Phase lock loop	48
Figure 3- 4	Block diagram of PLL with quadrature signal generator and two phase detector	48
Figure 3- 5	Block diagram of SRF- PLL	49
Figure 3- 6	Simulation results of SRF-PLL during Phase Jump of 90° at t=0.1 second	50
Figure 3- 7	Simulation results of SRF-PLL during voltage Imbalance of 10% on phase-B	51
Figure 3-8	Simulation results of SRF-PLL during 5th Harmonic content in grid voltages (5%)	52
Figure 3- 9	Simulation results of SRF-PLL during balanced voltage change (Voltage Sags and Dips)	53
Figure 3- 10	Voltage vectors of unbalanced three phase system	55
Figure 3- 11	Voltage vector on stationary and synchronous reference frame	56
Figure 3- 12	Voltage vector representation	57
Figure 3- 13	Dynamic performance of DDSRF-PLL during balanced grid voltages, unbalanced in phase B of grid voltages, and distorted grid voltages	61
Figure 3- 14	Dynamic performance of DDSRF-PLL during balanced grid voltages, and unbalanced in phase B of distorted grid voltages	63
Figure 3- 15	(a) Basic structure of Second-order generalized integrator, (b) Bode diagram of transfer function $(Y(s) / V_{in}(s))$ and $(Y'(s) / V_{in}(s))$ of SOGI , and (c) Step response of SOGI	65
Figure 3-16	(a) Block diagram of SOGI-OSG, (b) Bode Diagram of $D_v(s)$, and (c) Bode Diagram of $Q_v(s)$ with different value of k	66
Figure 3-17	(a) Block diagram of SOGI-FLL, and (b) the Bode diagram of transfer functions, $E_v(s)$ and $Q_v(s)$ (dotted line shows the SOGI resonance frequency (ω'))	67

Figure 3-18	Schematic diagrams of the Decouple SOGI and phase-angle computation	69
Figure 3-19	Phasor diagram of direct/quadrature components of \mathbf{v}_α and \mathbf{v}_β grid voltage	70
Figure 3-20	Bode plot of transfer functions $\frac{ v_{\alpha\beta}^+ }{ v_{\alpha\beta}^+ }$ and $\frac{ v_{\alpha\beta}^+ }{ v_{\alpha\beta}^- }$ in the Decouple- SOGI	71
Figure 3-21	Step response of Frequency Estimation (a) different value of k ,constant value $\gamma=5000$, (b) different value of k ,constant value $\gamma=10000$, (c) different value of γ ,constant value $k=1$, and (d) different value of γ ,constant value $k=0.5$	72
Figure 3-22	Simulation result of grid connected PV inverter using decouple-SOGI-FLL :(a)PCC voltages with grid abnormalities,(b)positive component of stationary frame voltages, (c)comparative results of phase-angle and PCC voltages, and (d)frequency extraction	74
Figure 3-23	Time responses of frequency extraction in different grid synchronization techniques	75
Figure 3-24	DC offset elimination IIR high-pass Filter	79
Figure 3-25	Bode plot of IIR high pass filter by taking different value of k	80
Figure 3-26	Functional diagram of MSOGI-FLLL	81
Figure 3-27	Bode diagram of MSOGI-FLL by choosing the value of k and k'	83
Figure 4- 1	A power circuit diagram of single stage grid tied PV system	88
Figure 4- 2	Conceptual Power theory for grid tied PV system	89
Figure 4- 3	Control mechanism of single stage grid tied PV system in Synchronous reference frame	91
Figure 4- 4	Flow-chart of Increment-conductance MPPT algorithm,(b) PV characteristic of PV panel with different temperature, and (c) PV characteristic of PV panel with different solar irradiance	96
Figure 4- 5	Block diagram for a Power factor correction	100
Figure 4- 6	Control for mode of operation	102
Figure 4- 7	Dynamic performance of multipurpose single-stage PV system during full-PV mode (reverse power flow)	104

Figure 4- 8	Dynamic performance of multipurpose single-stage PV system during full-PV mode (forward power flow)	106
Figure 4- 9	Dynamic performance of multipurpose single-stage PV system during Partial PV & Partial-STATCOM mode	108
Figure 4- 10	Dynamic performance of multipurpose single-stage PV system during Full-STATCOM mode	110
Figure 4- 11	Dynamic performance of multipurpose single-stage PV system (PV-STATCOM) during power factor correction	112
Figure 4- 12	Simulation results of MODE A and MODE B (a) P_{pv} (W) and Irradiance $\left(I_{rr}, \frac{w}{m^2}\right)$, (b) V_{dc} and $V_{dc(ref)}$ (c) PV current (I_{dc}), (d) d-q axis PCC voltage, (e) d-q axis inverter current, (f) grid current, inverter current, load current and theta	117
Figure 4- 13	Simulation results of MODE A and MODE B (a) Active Power of P_g (W), P_{inv} (W), P_{load} (W), P_{pv} (W) and Irradiance $\left(I_{rr}, \frac{w}{m^2}\right)$, (b) Reactive Power of Q_g (W), Q_{inv} (W), Q_{load} (W) (c) PCC voltage (Phase a) and, (d) grid current, inverter current, load current	118
Figure 4- 14	Simulation result of Multipurpose PV system connected to capacitive load at PCC (a) Phase a of PCC voltage, and (b) phase a of grid current, inverter current, and load current	119
Figure 4- 15	Simulation result of Multipurpose PV system connected to inductive load at PCC (a) Phase A of PCC voltage, and (b) phase A of grid current, inverter current, and load current	120
Figure 4- 16	Functional diagram of Hysteresis current controller	121
Figure 4- 17	Hysteresis current control mechanisms	122
Figure 4- 18	Functional diagram of grid tied system	123
Figure 4- 19	Basic block schematic of LCL type filter	125
Figure 4-20	Bode Plots for general filter variants	127
Figure 4- 21	Bode plot for LCL type filter considering different conditions	127
Figure 4- 22	Control mechanism of single stage grid tied PV system in	128

	abc reference frame	
Figure 4- 23	Simulation result of Multipurpose PV system connected to non-linear load at PCC (a) PCC voltage, (b) grid currents, (c) inverter currents, (d) load currents, and (e) dc-link voltage	130
Figure 4- 24	Functional and Phasor diagram of grid tied PV system during power injection into a grid	132
Figure 4- 25	Power curve for PV panel using sin angle based dc current sensor-less MPPT	133
Figure 4- 26	Power curve for PV panel using modified dc current sensor-less MPPT	136
Figure 4- 27	Tracking the change in V_{PV} [Upper Trace: Voltage Generated by PV Array (Red): X axis: 1 Div. = 20 mSec, Y axis : 1 Div. = 5 V; Lower Trace: Reference Voltage Generated by MPPT Algorithm (Blue): X axis : 1 Div. = 20 mSec, Y axis : 1 Div. = 5 V]	136
Figure 4- 28	Dynamic performance of Multipurpose PV system using a modified DC current sensor-less MPPT and synchronous frame current control	138
Figure 5-1	Target Simulink/MATLAB diagram for the control system of Multifunction Single-stage grid tied PV System	145
Figure 5-2	Schematic Diagram of (a) voltage Hall sensor circuit, (b) AC voltage sensor circuit using Potential divider and voltage transformer, and(c) current transformer circuit with DC-bias	147
Figure 5-3	Configuration view of A/D converter in the target Simulink	149
Figure 5-4	Configuration view and Pin assignment of A/D converter in the target Simulink	150
Figure 5-5	Configuration schematic of Start/Stop of gating pulses control in the target Simulink	151
Figure 5-6	Configuration schematic of DC signal conditioning in the target Simulink	152
Figure 5-7	Configuration schematic of DQ transformation for (a) three phase inverter currents, and (b) three phase load currents in the target Simulink	153

Figure 5-8	Configuration schematic of modified SOGI-FLL and angle computation block in the target Simulink	154
Figure 5-9	Configuration schematic of DQ transformation for the three phase voltage signal in the target Simulink	155
Figure 5-10	Test bench schematic diagram for Modified SOGI-FLL by designing programmable source in the target Simulink	156
Figure 5-11	Experimental results obtained from test bench of SOGI-FLL and measured during 10% frequency and 45° phase shift in grid voltages: (a) three-phase voltage signals and phase –angle of grid, (b)Zoom view of phase-a voltage signal of three phase and phase(c) dynamic performance of angular frequency, and(d)Zoom view of dynamic performance of angular frequency	157
Figure 5-12	Experimental results obtained from test bench of SOGI-FLL during 50% balanced sag in the grid voltages	158
Figure 5-13	Experimental results for grid synchronization during grid voltages effected by the harmonics, and (b) Experimental results of single-phase grid interfaced voltage source converter (Time scale:10ms//div) : i_g (Pink and blue; Scale 2A/div), v_g (Orange; Scale: 40V/div), and theta(green)	159
Figure 5-14	Configuration View and m-file of modified MPPT algorithm	160
Figure 5-15	Configuration View of synchronous frame inner current control loop	162
Figure 5-16	Experimental results of inner current control loop obtained in grid-tied PV system without outer voltage controller by taking $i_{inverter(ref)d} = -2$ A and $i_{inverter(ref)q} = 0$, Conventional PV system	163
Figure 5-17	Experimental results of inner current control loop obtained in grid-tied PV system without outer voltage controller obtained by taking (a) $i_{inverter(ref)d} = -2$ A and $i_{inverter(ref)q} = +1.5$, and (b) $i_{inverter(ref)d} = -2$ A and $i_{inverter(ref)q} = -1.5$, Partial PV-STATCOM	164
Figure 5-18	Experimental results of inner current control loop obtained in	165

	grid-tied PV system without outer voltage controller obtained by $i_{inverter(ref)d} = 0A$ (a) $i_{inverter(ref)q} = +1.5$, and (b) $i_{inverter(ref)q} = -1.5$, Full -STATCOM	
Figure 5-19	Configuration view of PWM generation block in target Simulink file	166
Figure 5-20	Configuration view of Display unit and DSO unit in target Simulink file	167
Figure 5-21	Configuration View and m-file Protection algorithm of system	168
Figure 5-22	Schematic of experimental set-up of Single Stage grid tied PV system	171
Figure 5-23	Experimental set-up of Single Stage grid tied PV system	172
Figure 5-24	Dynamic performance of single stage grid tied PV system during variable solar irradiance (Time scale:60ms//div) : v_{PCC} (Red; Scale 75V/div), i_{source} (Pink; Scale: 4A/div), P_{PV} (Blue; Scale: 500W/div), and i_d (green Scale: 4A/div)	176
Figure 5-25	Dynamic performance of single stage grid tied PV system during variable solar irradiance (Time scale:60ms//div) : v_{PCC} (Red; Scale 75V/div), i_{source} (Pink; Scale: 4A/div), P_{PV} (Blue; Scale: 500W/div), and i_d (green Scale: 4A/div)	176
Figure 5-26	(a)Dynamic Performance of DC-bus reference voltage and DC-bus voltage and d-axis current synchronous reference frame. (Time scale:2ms//div) : V_{DC} (purple)and V_{DCref} (orange) : Scale: 110V/div, and i_d (cyan)Scale: 1A/div, and (b) the PV curve characteristics	177
Figure 5-27	Waveform of sensed Phase-A PCC voltage and sensed three phase inductive load currents, (b)Experimental Results of PV inverter without reactive power support at grid side, and (c) Experimental Results of PV inverter with reactive power support at grid side(Time scale:10ms//div) : v_{PCC} (Red; Scale 75V/div), i_{source} (Pink; Scale: 0.4A/div), $i_{inverter}$ (Blue; Scale: 1.6A/div), and i_{load} (green Scale: 0.5A/div)	180
Figure 5-28	Experimental results(Time scale:10ms//div) (a) PCC voltage of	181

	Phase-A(Orange; Scale 75V/div), Source current of Phase-A((Cyan; Scale 1A/div), load current of Phase-A(Purple:Scale-2A/div), and grid angle(green), and (b) PCC voltage of Phase-A, Source current of Phase-A, load current of Phase-A, and inverter current of Phase-A(green: scale :2A/div	
Figure 5- 29	Dynamic results of PCC voltage of Phase-A, Source current of Phase-A, inverter current Phase-A, and load current of Phase-A (Time scale:10ms//div) : PCC voltage of Phase-A(Red: Scale 50V/div), Source current of Phase-A((Pink), load current of Phase-A(Blue), and load current of Phase-A, (green), from no load to inductive load of 1 A	182
Figure 5-30	Zoom view of Figure 5-29 and experimental results of PCC voltage of Phase-A, Source current of Phase-A, inverter current Phase-A, and load current of Phase-A.	183
Figure 5-31	Experimental results during PCC voltage control(Source current phase-A, q-axis inverter current , and line to line grid voltage): (a) without PCC voltage control, and(b) with voltage control	184
Figure 5-32	Experimental results during PCC voltage control(inverter current phase-A, solar power , and line to line grid voltage): (a) without PCC voltage control, and(b) with voltage control	184

LIST OF TABLES

Table 3-1	Impact Analysis of SOGI-FLL	73
Table 3-2	Time response of frequency extraction and performance assessment of different grid synchronization techniques.	75
Table 3-3	Highlights of Comparative Performance Assessment	84
Table 4-1	Summary of performance evaluation for multipurpose single stage PV system in Full-PV mode	103
Table 4-2	Summary of performance assessment for multipurpose single stage PV system in Full-PV mode (Forward power flow)	105
Table 4-3	Summary of performance assessment for multipurpose single stage PV system in PV-STATCOM mode	107
Table:4-4	Summary of performance assessment for multipurpose single stage PV system during Night time	111
Table 5-1	PV PANEL AND CONVERTER SPECIFICATIONS	173
Table-5-2	Possible Variations in Modified DC current Sensor-less MPPT	178

LIST OF ABBREVIATION

DG	Distributed Generations
SCs	Shunt Capacitor Banks
OLTCs	On Load Tap Changer
SVR	Step Type Regulator
SVC	Static VAR Compensator
STATCOM	Static Synchronous Compensator
VSI	Voltage Source Inverter
VSC	Voltage Source Converter
PV	Photovoltaic
SOG	Second Ordered Generalized Integrator
SRF	Synchronous Reference Frame
DSRF	Double Synchronous Reference Frame
DDSRF	Decouple Double Synchronous Reference Frame
DSOGI	Dual Second Ordered Generalized Integrator
FLL	Frequency Lock Loop
PLL	Phase Lock Loop
TOV	Transient Over Voltage
PCC	Point Of Common Coupling