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# Contents

<b>Abstract</b>	v
<b>Acknowledgment</b>	viii
<b>List of Figures</b>	x
<b>List of Tables</b>	xiv
<b>List of Acronyms</b>	xv
<b>Symbols Used</b>	xvii
<b>Chapter 1. Introduction</b> .....	1
<b>1.1</b> Background and Motivation.....	1
<b>1.2</b> Literature Review.....	5
<b>1.2.1</b> Control Strategy of Harmonic Compensation for Grid Current.....	7
<b>1.2.2</b> Control Strategy for Reduction of Active and Reactive Power Oscillations.....	10
<b>1.2.3</b> Control Strategy for Enhancement of LVRT.....	12
<b>1.3</b> Challenges in the Grid-Tied PV System .....	15
<b>1.4</b> Thesis Objectives.....	17
<b>1.5</b> Thesis Organizations.....	21
<b>Chapter 2. Methodology for Reactive Power Management in Grid-Tied PV System with Coordinated Control Strategy</b> .....	25
<b>2.1.</b> Introduction.....	25
<b>2.2</b> System Architecture and Control Strategy of the Grid-Tied PV System....	26
<b>2.2.1</b> Phase Locked Loop.....	27
<b>2.2.2</b> Maximum Power Point Tracking Controller .....	29
<b>2.2.3</b> DC-link Voltage Controller Design.....	30
<b>2.2.4</b> Current Controller Design.....	32
<b>2.3</b> Approximate Model For the P-Q Capability Curve of the Grid-Tied PV System .....	34
<b>2.4</b> Improved Methodology for the P-Q Capability Curve.....	35
<b>2.5</b> Simulation and Experimental Analysis .....	40

2.5.1 Simulation Results.....	40
2.5.1.1 Grid-Tied PV System at Non MPP Condition Under Different Environmental Conditions.....	40
2.5.1.2 Grid-Tied PV System at MPP Condition Under Different Environmental Conditions.....	42
2.5.1.3 Dynamic Performance of the Grid-tied PV System under Different Environmental conditions.....	47
2.5.2 Experimental Verification.....	48
2.6 Conclusion.....	51
<b>Chapter 3. PLL Based Control Strategy of a Grid-Tied PV System Under Distorted Grid Voltage Conditions.....</b>	<b>53</b>
3.1 Introduction.....	53
3.2 System Architecture of the Grid-Tied PV System.....	53
3.2.1 DC-link Voltage Controller Design.....	54
3.2.2 Adaptive step size MPPT Controller Design.....	56
3.3 Proposed Control Strategy.....	57
3.3.1 The Conventional Proportional Multi Resonant Controller.....	57
3.3.2 The Proposed Advanced Proportional Multi Resonant Controller....	60
3.3.2.1 Frequency Response Analysis of the Proposed APMR Controller.....	63
3.3.3 Compensator for Grid Voltage Sag with APMR Controller.....	67
3.4 Experimental Verification .....	70
3.4.1 Performance Evaluation of Proposed APMR Controller Under Harmonic Disturbances .....	70
3.4.2 Performance Evaluation of Proposed APMR Controller During Grid Frequency Variation .....	74
3.4.3 Performance Evaluation of Proposed APMR Controller with CGVS Under Grid Voltage Sag.....	77
3.4.4 Tracking Performance Evaluation with Adaptive step-size MPPT...	83
3.4.5 Comparison Between the Proposed Control Strategy with the Existing Control Strategy.....	84
3.5 Conclusion .....	85

<b>Chapter 4. PLL-less Control Strategy of a Grid-Tied PV System Under Distorted Grid Voltage Conditions.....</b>	<b>87</b>
4.1 Introduction.....	87
4.2 System Architecture of the PLL-Less Grid-Tied PV System.....	87
4.2.1 Adaptive step size MPPT Controller Design.....	88
4.2.2 DC-link Voltage Controller Modelling.....	89
4.3 PLL-Based Control Strategy.....	90
4.4 Proposed PLL-Less Control Strategy.....	91
4.4.1 The Proposed APMR Controller.....	92
4.4.1.1 Frequency Response Analysis of the Proposed APMR Controller.....	93
4.4.1.2 Selection and Influence of Control Parameters of the Proposed APMR Controller.....	94
4.4.2 Active and Reactive Power Oscillations Under Unbalanced Grid Voltages.....	98
4.4.3 Phase Compensated Reference Current Generator.....	101
4.5 Experimental Validation.....	103
4.5.1 Performance Assessment with Grid Voltage Harmonics Distortions.....	105
4.5.2 Performance Assessment with Grid Voltage Sag and Swell Under Varying Solar Irradiance.....	107
4.5.3 Performance Assessment with Grid Frequency Variations.....	111
4.5.4 Tracking Performance Assessment with Adaptive Step-Size INC MPPT.....	112
4.5.5 Comparative Assessment of the Proposed Control Strategy with the Existing Control Strategies.....	113
4.6 Conclusion.....	115
<b>Chapter 5. PLL-Less Control Strategy of a Grid-Tied PV System Under Distorted Grid, Weak Grid and Grid Fault Conditions.....</b>	<b>117</b>
5.1 Introduction.....	117
5.2 System Architecture of the PLL-Less Grid-Tied PV System.....	117
5.2.1 DC-link Voltage Controller Modelling.....	118



5.3 Proposed PLL-Less Control Strategy.....	119
5.3.1 Active Power Regulator with Dynamic Reactive Power Support Controller.....	120
5.3.2. The Proposed APCMR Controller.....	122
5.3.2.1 Frequency Response Analysis of the Proposed APCMR Controller.....	123
5.3.3 Phase Compensated Reference Current Generator.....	128
5.4 Experimental Verification.....	132
5.4.1 Performance Evaluations under Harmonically Distorted Grid Voltages.....	134
5.4.2 Performance Evaluations Under Grid Impedance Variations (Weak Grid) .....	135
5.4.3 Performance Evaluations with LVRT During Various Grid Faults.....	136
5.4.4 Performance Evaluations with Grid Frequency Variations.....	140
5.4.5 Comparative Analysis of the Proposed Control Strategy with the Existing Control strategies.....	141
5.5 Conclusion.....	143
<b>Chapter 6. Conclusions and Scope of Future Research.....</b>	<b>145</b>
6.1 Introduction.....	145
6.2 Conclusion.....	145
6.3 Scope for Future Research.....	148
<b>Bibliography.....</b>	<b>151</b>
<b>List of Publications .....</b>	<b>167</b>

# Abstract

Renewable energy sources (RESs) are the sustainable solution to the present energy crisis and environmental pollution issues, which produces energy from natural sources like sunlight, wind, tides and geothermal. Among the RESs, solar photovoltaic (PV) technology is more popular and widely accepted due to lack of moving mechanical parts, and lower maintenance. According to the recent PV technology developments, solar PV-based renewable power generation has experienced swift growth among the commercial and residential sectors. Therefore, more and more PV systems are being installed and integrated into the distribution grid in the form of grid-tied PV system. However, there are some challenges in the power quality in the grid-tied PV systems due to various issues such as grid voltage harmonics, voltage sags, voltage swells and frequency deviation. The increased use of nonlinear loads such as compact fluorescent lamps, variable speed drives and power electronics interfaced converters increases the harmonic pollution and consequently deteriorates the power quality of the grid-tied PV systems. The increased harmonics in the injected current of the grid-tied PV system minimizes the life span and raises the malfunction of the equipment connected to the distribution network. The other issues of power qualities are active and reactive power oscillations during grid voltage sags/faults the grid-tied PV system. These power oscillations lead to ripples in DC-link voltage, which degrades the performance of the grid-tied PV system by increasing losses in the system and reducing the life span of PV sources. Further, during the grid fault conditions, the PV sources must achieve low voltage ride-through (LVRT) capability for keeping it connected with the grid for better reliability. Another issue in the grid-tied PV system is the weak grid (large grid impedance). The problem of power quality increases under weak grid conditions. Also, under this condition, the wide variation of the grid impedance leads to voltage fluctuations at the point of common coupling. As a consequence, the system cannot achieve the desired control performance. These issues are the driving force for the researchers to orient their research work to suppress grid current harmonics, eliminate power oscillations and enhance the LVRT capability of the grid-tied PV system.

Various control techniques have been used to handle the power quality issues in the grid-tied PV system. However, the existing control techniques face several challenges such as 1) unable to identify the active and reactive power limits of a PV system at MPP conditions;

2) lesser stability of the controllers at grid frequency; 3) complexity in the controller for design and implementation; 4) the simultaneous mitigation of grid currents harmonic and power oscillations; 5) simultaneous mitigations of current harmonics and enhancement of LVRT of the grid-tied PV systems and 6) the performance of the existing control strategies are not satisfactory under distorted and weak grid conditions.

To take care of the above issues, an improved mathematical methodology for deriving the active and reactive power limit for MPP operation and three advanced control strategies for mitigating power quality issues are proposed in this thesis. The improved mathematical methodology is used to obtain the  $P$ - $Q$  capability curve of the grid-tied PV system under MPP conditions defining the active and reactive power limits. The first advanced phase-locked loop (PLL)-based control strategy proposed in this work simultaneously reduces the grid current harmonics and power oscillations under distorted grid voltage conditions. The second control strategy reduces the grid current harmonics and eliminates the active and reactive power oscillations without PLL under distorted grid voltage conditions. The third control strategy is the PLL-less strategy that enhances the LVRT capability with reduced grid current harmonics in grid-tied PV system under distorted and weak grid conditions.

The improved methodology is presented to derive the  $P$ - $Q$  capability curve of the grid-tied PV system to find real and reactive power limits at MPP under various environmental conditions. The reactive power is managed by selecting all the possible sets of working points within the stable region of operation. The reactive power reference for the current controller of a grid-tied PV system is obtained by utilizing the capability curve. The first advanced PLL-based control strategy proposed in this thesis is used to simultaneously reduce grid current harmonics and eliminate power oscillations under distorted grid voltages. The proposed control strategy comprises an advanced proportional multi-resonant (APMR) controller integrated with a compensator for grid voltage sag (CGVS). The proposed APMR controller achieves wider bandwidth than the conventional PMR (CPMR) controller and finite gain at the resonant frequency. The CGVS and APMR controllers operate co-ordinately to eliminate the active and reactive power oscillations under unbalanced grid voltage conditions. Further, an adaptive step size incremental conductance (ASINC) maximum power point tracking (MPPT) controller in integration with the proposed control strategy is used for faster tracking of MPP under different environmental conditions. The effectiveness of the proposed control strategy is verified on a laboratory prototype of 3.8 kW PV power using a real-time digital simulator OPAL-RT OP4510. The

experimental results show that the proposed control strategy achieves reduced current harmonics, low total harmonic distortion (THD), negligible power oscillations and faster frequency adaptability as compared to the CPMR control strategy.

The proposed APMR control strategy reduces the grid current harmonics effectively. However it requires a PLL block to synchronize the PV inverter to the grid. The PLL-based control strategy has poor frequency adaptability under grid frequency variations. To address these issues, the second, advanced control strategy based on PLL-less scheme is proposed for the simultaneous reduction of grid current harmonics and power oscillations under distorted grid voltage conditions. The proposed PLL-less APMR controller is integrated with a phase compensated reference current generator (PCRCG) to simultaneously reduce the grid current harmonics and power oscillations. The proposed PLL-less control strategy is implemented in the  $\alpha\beta$  stationary reference frame, thus reducing the associated computational requirement and complexity. The experiments are carried out on a 3.65 kW PV power module. The experimental results show satisfactory performance of the proposed PLL-less control strategy with reduced grid current harmonics and power oscillations than the conventional PLL-based control strategy.

In the case of grid fault, the PV system must remain connected with the grid for reliable operation. For that purpose, the PV system should have LVRT capability. The performance of the proposed PLL-less APMR strategy integrated with PCRCG deteriorates under fault and weak grid conditions. The third proposed control strategy is a modified form of the PLL-less APMR control strategy, which successfully achieves enhanced LVRT operation, reduced grid current harmonics and negligible power oscillations simultaneously under weak and distorted grid voltages. This proposed modified PLL-less control strategy consists of an active power regulator (APR) with dynamic reactive power support (DRPS) controller, which enhances the LVRT capability of the grid-tied PV system during unbalanced grid faults. Further, an advanced phase compensated multi resonant (APCMR) controller integrated with APR and DRPS controller reduces grid the current harmonics under distorted and weak grid conditions. The proposed PLL-less control strategy is validated by conducting detailed experimental studies on a 4.3 kW laboratory prototype. A comparison among the proposed and different existing control strategies are also discussed to bring out the effectiveness of the proposed PLL-less control strategy in terms of various features such as LVRT capability enhancement, harmonic current mitigation, power oscillations reduction and frequency adaptability improvement.

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(Manash Kumar Mishra)

# List of Figures

Figure	Caption	Page No.
1.1	Schematic diagram for the grid-tied PV system	2
1.2	System configuration of grid-tied PV system	3
1.3	A general structure for $dq$ frame control using cross-coupling and voltage feedforward terms	6
1.4	Block diagram of the MBCC strategy	7
1.5	Control structure representation block diagram of RPC	10
1.6	Control structure block diagram of RC	10
1.7	Control structure block diagram of double synchronous frame current controller	12
1.8	LVRT requirement	14
1.9	Block diagram of control strategy for enhancement of LVRT capability	14
1.10	Block diagram representation of the proposed control strategies for the grid-tied PV system	20
2.1	System configuration of the grid-tied PV system	26
2.2	Linearized Model of the SRF-PLL	28
2.3	Control Structure of the SRF-PLL	29
2.4	Flow chart of the ASINC MPPT controller	30
2.5	Block diagram of the DC-link voltage controller	32
2.6	Control structure block diagram of the current controller	32
2.7	Three-phase voltage source inverter connected with the grid	33
2.8	Approximate simplified model of a grid -tied PV system	35
2.9	Real-time simulated responses for: PV voltage( $v_{pv}$ ), Active power ( $P_g$ ), Reactive power ( $Q_g$ ) at $m_a = 0.8$ and $\delta = 0.1$	41
2.10	PV voltage (DC) as a function of phase angle $\delta$ for $m_a = 0.8$	41
2.11	Active power $P_g$ and reactive power $Q_g$ as a function of $\delta$ for $m_a=0.8$	41
2.12	Total capability curve of the PV system for different environmental conditions (Non MPP condition)	43
2.13	Plot between $m$ and $\delta$ at maximum power point condition (with MPP condition)	43
2.14	Active power $P_g$ and reactive power $Q_g$ as a function of $\delta$ (with MPP condition)	43

2.15	Real-time simulated responses for: PV voltage ( $v_{pv}$ ), Active power ( $P_g$ ), Reactive power ( $Q_g$ )	44
2.16	Real-time Simulated responses of modulation waveforms	45
2.17	Reactive power limit for different temperature and Irradiance level	45
2.18	P versus V characteristics of PV module for different temperature and Irradiance level	46
2.19	Dynamic performance of ASINC MPPT under variable atmospheric condition	47
2.20	Photograph of the experimental setup for the grid-tied PV system	49
2.21	Experimental waveforms for: PV voltage ( $v_{pv}$ ), active power ( $P_g$ ), reactive power ( $Q_g$ ) at $m = 0.85$ and $\delta = 0.12$	50
2.22	Dynamic experimental responses of grid-tied PV system at MPP	50
2.23	Experimental waveforms of modulation waveforms	51
3.1	Schematic diagram of the three-phase grid-tied PV system with the proposed control strategy of APMR with CGVS	54
3.2	Block diagram of the DC-link voltage controller	55
3.3	Control structure block diagram of the CPMR current controller	58
3.4	A simplified model of the grid-tied PV system	58
3.5	Bode diagrams of $G_{ac}(s)$ , $G_{bc}(s)$ and $g_r(s)$ with conventional PMR controller	60
3.6	Detailed representative block diagram and control structure block diagram of the proposed APMR current controller	62
3.7	Bode diagrams of $G_a(s)$ , $G_b(s)$ and $g_r(s)$ with different $K_p$	64
3.8	Bode diagrams of $G_a(s)$ , $G_b(s)$ and $g_r(s)$ with different $K_r$	65
3.9	Bode diagrams of $G_a(s)$ , $G_b(s)$ and $g_r(s)$ with different $\zeta$	66
3.10	Bode diagrams of $G_a(s)$ , $G_b(s)$ and $g_r(s)$ with $K_p = 30$ , $K_r = 250$ and $\zeta = 0.02$ .	67
3.11	Block diagram of PLL with CGVS	70
3.12	Photograph of laboratory setup	71
3.13	Real-time experimental waveforms under harmonically distorted grid voltage conditions	73
3.14	FFT spectra the grid current with different control strategies	73
3.15	Experimental waveforms when grid frequency changes from 50 Hz to 52 Hz	75
3.16	Experimental waveforms when grid frequency changes from 52 Hz to 50 Hz	77
3.17	Experimental waveforms with 40% voltage sag in phase $a$	79



3.18	Experimental waveforms with 40 % voltage sag in phase <i>a</i> and phase <i>b</i>	81
3.19	Experimental waveforms under unbalanced grid voltage conditions	82
3.20	Real-time dynamic experimental waveforms of the ASINC MPPT and FSINC MPPT controller under fast environmental changes	84
4.1	The proposed PLL-less control strategy architecture for grid-tied PV system	88
4.2	Pictorial representation of MPP tracking with ASINC MPPT controller	89
4.3	Block diagram of the DC link voltage control	90
4.4	Block diagram of PLL-based CPMR control strategy	91
4.5	Block diagram of the proposed PLL-less APMR control strategy	92
4.6	Flowchart of the proposed PLL-less APMR control strategy	93
4.7	Equivalent circuit of the VSI integrated to the grid in the $\alpha\beta$ reference frame	93
4.8	The Bode diagram of $G_{i-cl}(s)$ with different $K_p$ , $K_{rA}$ , $K_{rB}$ and $\zeta$	96
4.9	The Bode diagram of $G_{iA}(s)$ and $G_{iB}(s)$ of the APMR controller with $K_p=60$ , $K_{rA}=360$ , $K_{rB}=360$ , and $\zeta=0.02$	97
4.10	The Bode diagram of $G_{i-cl}(s)$ with $K_p=60$ , $K_{rA}=360$ , $K_{rB}=360$ , and $\zeta=0.02$	97
4.11	Block diagram of PCRCG	102
4.12	Photograph of the laboratory prototype	104
4.13	Dynamic real-time waveforms of grid-tied PV system under harmonically distorted grid voltages	106
4.14	The spectrum of experimental grid current under different compensation methods	107
4.15	Experimental waveforms when applying a 40 % voltage sag in phase <i>a</i> and irradiance $S_{ir}$ increases from $1000 \text{ W/m}^2$ to $1400 \text{ W/m}^2$	109
4.16	Experimental waveforms when applying a 35% voltage swell in phase <i>a</i> and irradiance $S_{ir}$ decrease from $1000 \text{ W/m}^2$ to $600 \text{ W/m}^2$	111
4.17	Dynamic experimental waveforms during a grid frequency deviation from 49 Hz to 51 Hz	112
4.18	Dynamic performance evaluation of the grid-tied PV system with the ASINC MPPT	113
5.1	Architecture of the proposed PLL-less control strategy with APCMR controller for grid-tied PV system	118
5.2	Block diagram of the DC-link voltage controller	119
5.3	Block diagram of the APR with DRPS controller	121
5.4	PV characteristics when the grid-tied PV system switches between MPPT and LVRT mode	122

5.5	Control schematic of the proposed advanced phase compensated multi resonant controllers	123
5.6	Implementation steps of the proposed PLL-less control strategy	124
5.7	Simplified equivalent circuit of the grid-tied VSI	124
5.8	Bode diagram of the $G_{ol}(s)$ of the APCMR controller with grid inductance variation	126
5.9	Bode diagram of the $G_{ig-cl}(s)$ for different values of $\zeta$ and $\theta_h$	127
5.10	Bode diagram of $G_{rf}(s)$ and $G_{rh}(s)$ of the APCMR controller	128
5.11	Block diagram of the phase-compensated reference current generator	132
5.12	Photograph of the laboratory prototype	133
5.13	Dynamic experimental waveforms under harmonically distorted grid voltages	135
5.14	Experimental waveforms obtained using conventional PBCS with CPMR controller and proposed PLCS with APCMR controller	136
5.15	Experimental waveforms under L-G fault in phase $a$ with grid voltage magnitude 55 % of rated grid voltage	138
5.16	Experimental waveforms under asymmetrical fault (L-L-G fault)	140
5.17	Dynamic experimental waveforms during a grid frequency deviation from 50 Hz to 52 Hz	141

# List of Tables

<b>Table</b>	<b>Caption</b>	<b>Page no.</b>
2.1	System and control parameters	39
3.1	Real-time system and control parameters	72
3.2	Comparative study of the proposed APMR control strategy with the existing control strategies	85
4.1	Real-time system and control parameters	104
4.2	Comparative analysis of the proposed PLL-less control strategy with existing control strategy	114
5.1	Grid-tied PV system operation under different grid condition's	122
5.2	Real-time system and control parameter	133
5.3	Comparative analysis of the proposed PLL-less control strategy with existing control strategy	142

# List of Acronyms

RES	Renewable energy source
PV	Photovoltaic
VSI	Voltage source inverter
SPWM	Sinusoidal pulse width modulation
DG	Distributed generation
DC	Direct current
AC	Alternating current
MPPT	Maximum power point tracking
INC	Incremental conductance
PO	Perturb and observe
ASINC	adaptive step size INC
LVRT	Low voltage ride through
FRT	Fault ride through
THD	Total harmonic distortion
PLL	Phase-locked loop
PLL-less	Phase-locked loop-less
MBCC	Model-based current control
DPC	Direct power control
PR	Proportional resonant
PRC	Proportional resonant compensator
RHC	Resonant harmonic compensators
MRHC	multi resonant harmonic controller
QPR	Quasi proportional resonant
AQPR	Adaptive quasi proportional resonant
RC	Repetitive controller
RSC	Resonant controller
CPMR	Conventional PMR
APMR	Advanced proportional multi-resonant
APCMR	Advanced phase compensated multi-resonant
CGVS	Compensator for grid voltage sag

PLL	Phase-locked loop
SRF-PLL	Synchronous reference frame phase-locked loop
PCRCG	phase compensated reference current generator
GCPPP	Grid connected PV power plant
APR	active power regulator
DRPS	Dynamic reactive power support
FBL	Feedback linearization
LTI	Linear time-invariant
DSP	Digital signal processor
SIL	Software in the loop
HIL	Hardware in the loop
IGBT	Insulated gate bipolar transistor
FFT	Fast Fourier Transform
MBC	Model based control strategy
RCC	Resonant current control
VCC-DPC	Vector current control direct power control
RCG	reference current generator
PCRCG	phase compensated reference current generator
PLCS	PLL-less control strategy
PBCS	PLL-based control strategy

## Symbols Used

$i_{PV}$ and $v_{PV}$	Output current and voltage from the PV array
$V_{PVoc}$	PV open circuit voltage
$I_{PVsc}$	PV short circuit current
$V_{MPP}$	PV MPP voltage
$I_{MPP}$	PV MPP current
$P_{MPP}$	PV Maximum power
$P_{pv}$	PV power generated
$v_{dc}$	voltage across the DC-link capacitor $c_{dc}$
$v_{dcref}$	Reference DC-link voltage
$v_{gabc}$ and $i_{gabc}$	Grid voltage and grid current
$v_{iabc}$	Output voltage of the VSI
$i_{gd}$ and $v_{gd}$	$d$ -axis grid current and voltage
$i_{gq}$ and $v_{gq}$	$q$ -axis grid current and voltage
$P_g$ and $Q_g$	Active power and reactive power delivered to the grid
$P_{gref}$ and $Q_{gref}$	Active and the reactive power references injected into the grid
$K_{rc}$	Control parameters of the RC harmonic compensator
$\omega_0$	Grid fundamental frequency
$T_0$	Grid fundamental period
$h$	Harmonic order
$L_{if}$ and $R_{if}$	Inductor and resistor of the inverter side filter
$L_{of}$ and $R_{of}$	Inductor and resistor of the grid side filter
$L_g$ and $R_g$	Equivalent inductor and resistor of the grid
$Z_{if}$ , $Z_{og}$ , and $Z_c$	Simplified series impedances of the inverter side, grid side impedance, and shunt impedance of the filter
$m_a$ , $m_b$ and $m_c$	Modulation signals of the VSI
$\theta$ and $\omega$	Grid phase angle and grid voltage's angular frequency
$G_c^{PLL}(s)$	Transfer function of PI controller for PLL
$G_c^{vdc}(s)$	Transfer function of PI controller for DC-link voltage control

$k_p^{vdc}$ and $k_i^{vdc}$	Proportional and integral parameters of DC-link voltage controller
$k_p^{i_d}, k_i^{i_d}, k_p^{i_q}$ and $k_i^{i_q}$	Proportional and integral parameters of $dq$ Current Controller
$k_p^{PLL}$ and $k_i^{PLL}$	Proportional and integral coefficients of PLL
$V_{st}$	Variable step size
$f_g$ and $f_{sw}$	Grid frequency and the switching frequency
$G_{ac}(s)$ and $G_{bc}(s)$	Proportional resonant compensator and resonant harmonic compensator of the conventional PMR controller
$G_a(s)$ and $G_b(s)$	Proportional resonant compensator and resonant harmonic compensator of the proposed APMR controller
$T(s)$	The open-loop gain of the APMR current controller
$g_r(s)$	Closed-loop transfer function between $i_{g\alpha\beta}$ and $i_{g\alpha\beta ref}$
$g_g(s)$	closed-loop transfer function between $i_{g\alpha\beta}$ and $v_{g\alpha\beta}$
$k_p$ and $k_r$	Proportional coefficients and fundamental resonant coefficient of the proposed APMR controller
$k_{rh}$	Resonant controller coefficients of the order $h$
$\omega_g$	Resonant frequency of the proposed APMR controller
$\zeta$	Damping factor of the proposed APMR controller
$\theta_h$	Phase compensation angle at the selected harmonic frequency
	$h\omega_g$
$h$	Harmonic order of the proposed APMR controller
$V_p$ and $V_n$	Positive and negative sequence voltage magnitudes
$\delta_p$ and $\delta_n$	Positive and negative sequence phase angles
$v_{g\alpha^+}$ and $v_{g\alpha^-}$	Positive and negative sequence components of $v_{g\alpha}$
$v_{g\beta^+}$ and $v_{g\beta^-}$	Positive and negative sequence components of $v_{g\beta}$
$v_{gd^+}$ and $v_{gd^-}$	Positive and negative sequence components of $v_{gd}$
$v_{gq^+}$ and $v_{gq^-}$	Positive and negative sequence components of $v_{gq}$
$i_{gd^+}$ and $i_{gd^-}$	Positive and negative sequence of $i_{gd}$ .
$i_{gq^+}$ and $i_{gq^-}$	Positive and negative sequence of $i_{gq}$ .
$i_{g\alpha ref(p)}$ and $i_{g\beta ref(p)}$	Reference active power current $i_{g\alpha}$ and $i_{g\beta}$ .
$i_{g\alpha ref(q)}$ and $i_{g\beta ref(q)}$	Reference reactive power current $i_{g\alpha}$ and $i_{g\beta}$ .
$G_{brf}(s)$	Transfer function of a band reject filter.
$\omega_n$ and $\alpha\omega_n$	Band-reject and cut-off frequencies of the band reject filter.