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Dedicated to My Parents for Their Exceptional Love and Caring

Contents

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)

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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	Peturb 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
ω_0	Grid fundamental frequency
T_0	Grid fundamental period
h	Harmonic order
L_{if} andR_{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
θ and ω	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

$k_p^{v_{dc}}$ and $k_i^{v_{dc}}$	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*
ω_g	Resonant frequency of the proposed APMR controller
ξ	Damping factor of the proposed APMR controller
θ_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
δ_p and δ_n	Positive and negative sequence phase angles
$v_{g\propto}^+$ and $v_{g\propto}^-$	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^+_{gq},	Positive and negative sequence of i_{gd}.
i^-_{gd} and i^-_{gq}	Positive and negative sequence of i_{gq}.
$i_{g\propto ref(p)}$ and $i_{g\beta ref(p)}$	Reference active power current $i_{g\propto}$ and $i_{g\beta}$.
$i_{g\propto ref(q)}$ and $i_{g\beta ref(q)}$	Reference reactive power current $i_{g\propto}$ and $i_{g\beta}$.
G_{brf}(s)	Transfer function of a band reject filter.
ω_n and $\alpha\omega_n$	Band-reject and cut-off frequencies of the band reject filter.