Energy 96 (2016) 325–334

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

A control strategy for the stable operation of shunt active power filters in power grids

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ARTICLE INFO

Article history:
Received 15 June 2015
Received in revised form
15 December 2015
Accepted 17 December 2015
Available online 4 February 2016

Keywords:
Shunt active power filters (SAPF)
Voltage source converter (VSC)
Harmonic current components
Reactive power compensation

ABSTRACT

This paper introduces a control strategy for the assessment of SAPF (shunt active power filters) role in the electrical power networks. The proposed control scheme is based on the Lyapunov control theory and defines a stable operating region for the interfaced converter during the integration time with the utility grid. The compensation of instantaneous variations of reference current components in the control loop of SAPF in ac-side, and dc-link voltage oscillations in dc-side of the proposed model, is thoroughly considered in the stable operation of interfaced converter, which is the main contribution of this proposal in comparison with other potential control approaches. The proposed control scheme can guarantee the injection of all harmonic components of current and reactive power of grid-connected loads, with a fast dynamic response that results in a unity power factor between the grid currents and voltages during the integration of SAPF into the power grid. An extensive simulation study is performed, assessing the effectiveness of the proposed control strategy in the utilization of SAPF in power networks.

1. Introduction

Nonlinear loads connection to the power grid causes harmonic pollution through drawing nonlinear currents from the utility grid. Circulation of these harmonic components of currents throughout the feeders and the protection elements of the network generates Joule losses and electromagnetic disseminations which can interfere with other components connected to the grid, and adversely affect the performance of control loop and protection network in the whole system [1–5]. This concept has been widely investigated as a major prohibition to achieve a pure source of energy with a high power quality meeting the standard level of harmonic distortion, and unity power factor in the main grid. To reach these goals, several structures of power filters i.e., passive [6], shunt [7,8], series [9], and combination of shunt and series active filters with passive components [10,11] have been presented as solutions in a polluted electric network. Among active filter topologies, SAPF (shunt active power filter) with its naive implementation is paid more attentions in both time and frequency domains to facilitate the compensation of harmonic currents and reactive power of non-linear loads [12]. In Ref. [13], a digital implementation of fuzzy control algorithm has been presented for the SAPF in power system. A control method is presented in Ref. [14] for the control of a three-level neutral-point-clamped converter and the injection of harmonic current components of nonlinear loads. The proposed control method can also guarantee a unity power factor for the utility grid. A control plan also presented in Ref. [15] to reject the uncertainties from the power grid. The proposed scheme is based on the fuzzy logic control theory and guarantees a stable voltage across the dc-link of interfaced converter beside its fast dynamic response in tracking the reference current. A model reference adaptive control technique is presented in Ref. [16] for the single-phase SAPF to enhance the power factor of utility grid and drop the harmonic contaminations from the line currents. A nonlinear control technique based on feedback linearization theory is employed in Ref. [17] for the control of multilevel converter topologies utilized as interfacing systems between the renewable energy resources and the distribution grid. By utilization

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http://dx.doi.org/10.1016/j.energy.2015.12.075
0360-5442/

Nomenclature

Indices

s	a, b, c
j	d, q

Variables

i_{SFs}	Current components of SAPF
v_{dc}	dc-link voltage
v_{gs}	Grid voltages
i_{gs}	Grid currents
i_{ls}	Load current
u_{eqj}	Switching state function of SAPF
i_{SFs}	Current of SAPF in dq frame
v_m	Maximum voltage amplitude at the PCC
$\widetilde{I}_{av_j}$	Average values of reference currents
I_{SFj1}	Currents of SAPF in main frequency
i_{jhx}	Load harmonic components not supplied by SAPF
$\sum_{n=2}^{\infty} i_{ljhx}$	Harmonic current components of load

Abbreviation

R_T	Resistance of transformer
PI	Proportional-Integral
CCF	Capability Curve of Filter
SAPF	Shunt Active Power Filter
HCF	Harmonic Curve of Filter
THD	Total Harmonic Distortion
DLC	Direct Lyapunov Control
$\sum_{n=2}^{\infty} P_{SFhn}$	SAPF active power in harmonic frequencies
P_{SF}	Active power of SAPF
Q_{SF}	Reactive power of SAPF
$V(x)$	Lyapunov Function
r	Radius of HCF
c	Centre of HCF
u_{eqj}^*	Reference of switching state function
i_{SFj}^*	Reference current of SAPF in dq frame
$\sum_{n=2}^{\infty} i_{SFjhn}^*$	harmonic currents injected by SAPF
v_s	Voltage at the PCC
i_{dc}	dc-link current

Parameters

R_g	Resistance of grid
L_g	Inductance of grid
R_{SF}	Resistance of SAPF
L_{SF}	Inductance of SAPF
L_T	Inductance of transformer
R'_{SF}	Sum of R_{SF} and R_T
L'_{SF}	Sum of L_{SF} and L_T
C	Capacitor of dc link
(α_i, β_i)	Constant coefficients for the dynamic state switching functions
ω	Grid angular frequency

of this method, harmonic current components and reactive power of grid-connected loads are supplied through the integration of renewable energy resources to the grid. In Ref. [18], an adaptive linear neuron technique has been proposed as a harmonic extraction strategy for the control of SAPF in power network. The performance of this control technique in compensation of harmonic current components of nonlinear loads has been compared with the instantaneous reactive power theory. Proposed control strategy in Ref. [19] is able to generate the reference current of SAPF in a-b-c reference frame in which this reference generation process works in both the three-phase and single-phase electric systems. Two integrated predictive and adaptive controllers based on ANNs (artificial neural networks) are employed in Ref. [20] for SAPF, to perform a fast estimation of reference current components and reach the first estimate through the convergence of the adaptive ANN based network algorithm. Dynamic state behaviour of dc-link voltage is used in a predictive controller for the decline of THD (total harmonic distortion). An approach of active filter allocation in DC traction networks is proposed in Ref. [21]. The filter allocation is accomplished based on the most sensitive zones of power system in order to perform the allocation determination according to the characteristics of dynamic performance in traction load. In Ref. [22], a control algorithm based on equivalent fundamental positive-sequence voltage is proposed. The reference currents of the proposed filter is achieved through a simplified adaptive linear combiner neural network by the detection of voltage magnitude of source and phase angle at the fundamental frequency, during the presence of distorted and unbalanced voltage sources and load currents. Adaptive hysteresis bands in bipolar/unipolar forms are introduced in Refs. [23–26] for the development of a current control method for APFs in order to achieve a higher quality of reference waveform tracing, less switching losses and a lower cost of construction. A sliding-mode-based control technique is presented in Ref. [27] to enhance the ability of tracing action, and power quality, and to minimize the consumption of reactive power in both transient and steady state operating conditions. In Refs. [28] and [29] a Lyapunov function, based on the state variables of a single phase SAPF is used to decrease the harmonic level and to improve the power quality of system during the connection of various nonlinear loads to the grid. Furthermore, a modified technique has been proposed to achieve a global stability for the interfacing system and to reject the ripple of dc-side voltage components [29]. A Direct Lyapunov control method proposed in Ref. [30] for the control of SAPF combined with series-passive filter. The proposed control technique improves the power quality of utility grid by the injection of harmonic current components during the connection of nonlinear loads to the grid. Several other potential control algorithms have been presented in previous papers and reports to enhance the power quality of the grid. In this paper, the authors are proposing a control scheme for the stable operation of SAPF during the integration into the power grid. The compensation of instantaneous variations of reference currents caused by the harmonic current components of nonlinear loads and, dc-link voltage oscillations in dc-side voltage, on the operation of interfaced converter are considered properly which is the main contribution of this work.

The rest of the paper is organized into five sections. Following the introduction, general schematic diagram of the proposed SAPF will be introduced in Section 2 and elaborated properly in the steady state operating mode. Application of Lyapunov control theory for the control and stable operation of interfacing system during transient and steady-state operating conditions will be presented in Section 3. Moreover, simulations are performed to demonstrate the efficiency and applicability of the developed control plan in Section 4. Eventually, some conclusions are drawn in Section 5.

2. Proposed model analysis

Schematic diagram of the proposed SAPF model is illustrated in Fig. 1. The proposed model is composed of a three phase voltage-source converter with a dc-link voltage. By using a three phase