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Grid-tie three-phase inverter with active power injection and reactive power compensation

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A B S T R A C T

This paper proposes a methodology for the active and reactive power flow control, applied to a grid-tie three-phase power inverter, considering local and/or regionalized power flow control necessity in the forthcoming distributed generation scenario. The controllers are designed by means of robust pole placement technique, which is determined using the Linear Matrix Inequalities with D-stability criteria. The linearized models used in the control design are obtained by means of feedback linearization, aiming to reduce system nonlinearities, improve the controller's performance and mitigate potential disturbances. Through multi-loop control, the power loop uses active and reactive power transfer adapted expressions to obtain the magnitude of the voltage and power transfer angle to control the power flow between the distributed generation and the utility grid. The methodology main idea is to obtain the best controllers with the lowest gains as possible placing the poles in the left-half s-plane region, resulting in fast responses with reduced oscillations. In order to demonstrate the feasibility of the proposal a 3 kVA three-phase prototype was implemented and a comparison with conventional controller is performed to demonstrate the proposed methodology performance. In addition, anti-islanding detection and protection against over/under voltage and frequency deviations are demonstrated through experimental results.

1. Introduction

The old-fashioned electricity generation scenario has been changing considering that most part of its conventional generation results in pollutant processes, and consequently it causes risks and impacts to the environment and humans. The new generation scenario is been modified as it uses alternative and renewable electrical energy sources with the distributed generation (DG) concept next to the consumption centers, integrating sources such as photovoltaic, wind, fuel cell, and other with the conventional distribution utility grid [1–4]. In 2035, considering the population increasing and the industrial sector expanding, mainly in the development country, the global electrical energy consumption is estimated to be increased more than 50% compared to 2008 [5].

In this context, the distributed generation is becoming increasingly highlighted in the world with the purpose to integrate the renewable electrical energy sources into the traditional electrical power distribution grid [3,4,6].

Conventionally, the energy sources used in the DG are connected to a DC-bus, while utility grids work with alternated current (AC). In this context, to connect this kind of energies into the grid it is necessary to use power electronic converters, which are, usually, applied to step-up the alternative energies voltage, to perform the DC to AC conversion and for synchronization to the utility grid. Therefore, the voltage source inverter (VSI) is the most used topology to perform the DC–AC conversion. Basically, to achieve connection to the grid it is necessary to filter the harmonic contents to feed a sinusoidal current to the grid; thus, the most common used filters are the L and the LCL filters [6].

Therefore, some related papers propose the VSI current control to perform the active power injection into the utility grid [8,9]. Several works propose different control techniques in order to

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operate with uncertain quantities related to the grid parameters and to reduce possible perturbations in the control loops [7–9]. Other papers suggest the VSI voltage control; mainly, when autonomous operation is required and/or a parallelism of the DG is performed. Thus, this operation is usually implemented by means of the droop control technique, in which the frequency control is performed by the active power droop curve and the voltage control is performed using the reactive power droop curve [6,10,11]. For optimizing the droop control performance it is possible to use an evolutionary algorithm to determine the best gains used in the active and reactive power curves [12–14]. As the conventional droop control is implemented through a simple droop gain an error is inherent in this control. Therefore, to minimize the error and to improve the transient response it is possible to apply adaptive and improved droop control methodologies to have the accurate voltage and frequency for the DG control [15–17]. In addition, the droop control concept can be used as an auxiliary control to impose the reference values of active and reactive power to the DG, in order to achieve active power injection and reactive power compensation, where these references can also be generated by a supervisory control (remote and/or local) [18].

Consequently, it is common the usage of control techniques applied at power electronics to track a desirable reference, e.g., the VSI output filter voltage needs to follow a sinusoidal reference. With this purpose, the PI and PID controllers are widely employed to control the power electronics converters [19,20], which are designed from the linearized model of the converters obtained by means of small-signal analysis for the operational quiescent point. Sometimes, the converter can operate out of the specified boundary, which can produce undesirable effects and at worst, the system can operate out of the stable region [21,22].

Providing better control results, new power electronics control schemes can handle with system nonlinearities by applying nonlinear control techniques [23]. One of its possible application is to find a better linear approximation model around one operation quiescent point, attenuating those system nonlinearities, dealing with uncertain models and working in wide operation range [7,24].

The feedback linearization is a control technique used to obtain a linearized model from the nonlinear systems by means of the feedback states [23–25]. This approach seeks to minimize the nonlinearity main effects that is present in the system to be controlled, due to exact state transformation and through feedback, this technique is usually better than the conventional approach used to obtain the linearized converter model. On the other hand, the drawback of this technique is the parameter sensitivity involved in the linearization process, which may prevent the exact compensation of possible nonlinearity presents in the system [23].

Recently, researches have been proposed the linear matrix inequalities (LMI) as a better solution to control several applications. In order to guarantee the system robustness, the LMI techniques can be applied to reject or minimize system perturbations, achieving best controllers in a multi-objective problem working even with polytopic uncertainties [26–28].

The LMI constraints together with the D-Stability criteria are powerful tools to be applied in pole placement designs for feedback systems. These techniques can be used to guarantee the system performance, placing the poles in a complex s-plane defined region for the closed-loop system with the purpose to ensure some desirable system dynamic behavior, e.g., overshoot, settling time, transient response and less oscillations. The pole placement is ensured by means of the minimum decay rate, minimum damping ratio and maximum undamped natural frequency, which is used to delimit a maximum time to the vector norm [18,28].

Consequently, this paper proposes a control methodology that uses the LMI constraints in conjunction with D-stability criteria in order to place the poles of the closed-loop system in the complex left-half s-plane region. The linear model used to determine the PI controller gains is obtained by the feedback linearization technique. A three-phase inverter multi-loop control is performed to manage the active and reactive power flow control between distributed generation and the utility grid. In Section 2 the proposed control methodology is presented for each control loop; in Section 3 it is demonstrated the main experimental results and the comparisons between the proposed control and the conventional technique; finally the conclusions and some considerations are described in Section 4.

2. The proposed control

It is proposed to control the active power injection and reactive power compensation applied in three-phase system in alternating current low voltage (AC-LV) grid. In this section it is presented the three-phase inverter state-space equations; the feedback linearization technique; the controller design, the LMI constraints and D-stability criteria, and the proposed control techniques applied to the power, voltage and current control loops.

2.1. Three-phase inverter

The three-phase inverter control is performed by a multi-loop control based on power, voltage and current control loops, where all compensators are determined using feedback linearization with LMI constraints and based on D-stability criteria. Fig. 1 shows the

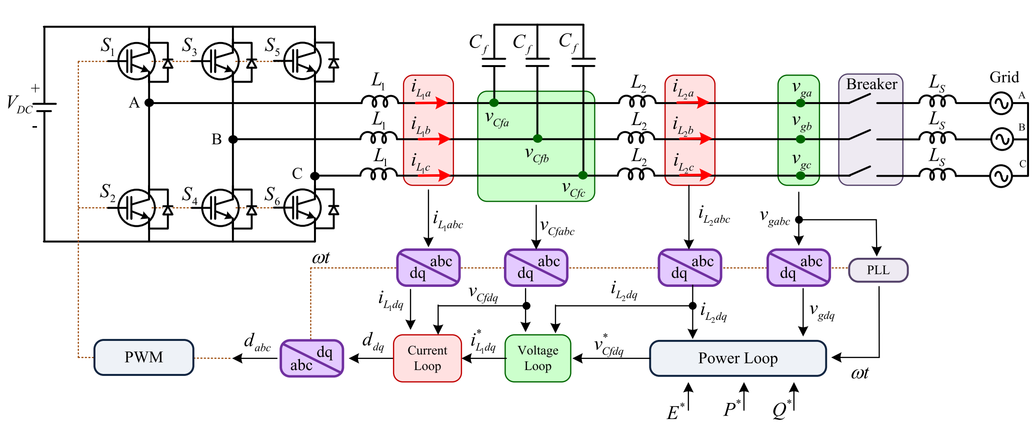

Fig. 1. Proposed control technique applied to grid-tie three-phase inverter with LCL filter.