Electric Power Systems Research 150 (2017) 177–187

Contents lists available at ScienceDirect

Electric Power Systems Research

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

Modelling and control of an interface power converter for the operation of small diesel gen-sets in grid-connected and stand-alone modes

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ARTICLE INFO

Article history:
Received 11 October 2016
Received in revised form 20 March 2017
Accepted 11 May 2017

Keywords:
Dispersed generation system
Grid-forming
Grid-feeding
Grid-conditioning
Diesel generator
Voltage-sourced converter

ABSTRACT

This paper presents the modelling and control design steps of a two-stage static conversion structure used as interface to integrate a diesel generator set into a secondary distribution network. In order to guarantee that the inverter works within the PWM linear range, a boost converter is used to increase the DC voltage level. The proposed structure allows two operation modes, connected to the AC mains or isolated. In the isolated mode the interface converter may be controlled as grid-forming or grid-conditioning (active power filter). The inverter current controllers are designed in the synchronous reference frame together with multiple integrators in order to effectively track non-sinusoidal currents. The stability analysis is performed through the Nyquist plot. Experimental results obtained with a 5.5 kW diesel generator set are presented to validate the proposed system operation and control strategies.

1. Introduction

Diesel generator (DG) driven by internal combustion engine (ICE) is an alternative to provide electricity to customers [1]. In addition to wide power range units, these DGs have a low purchase and installation costs when they are compared to other alternative generation systems. They also present an additional advantage when biodiesel fuel is used, becoming a renewable energy source [2,3].

Traditionally DG are used to supply isolated loads, however a suitable control strategy allows its integration into the grid. In this case, the energy offer is increased and the load peak can be controlled or reduced [3–5]. Nevertheless, in applications connected to the grid, it is not possible to freely change the diesel generator speed [5].

Regardless of the operation mode, isolated or grid-connected, the DG performance is strongly affected by the load characteristics. Singh and Solanki [6] use a distribution static synchronous compensator (DSTATCOM) to compensate reactive power, load imbalance and distorted currents in an isolated system supplied by a DG. Since these sources have low values of inertia and high values of output equivalent impedance, their output voltages can become very distorted and torque ripples can arise on the prime mover shaft when imbalance and harmonic currents are drained on their terminals. These factors increase fuel consumption of the DG set [6].

Low capacity DG works within a wide frequency variation range due to its ICE speed regulator poor response. Therefore, the integration of these diesel gen-sets into AC grid can be facilitated using an interface circuit based on static power electronic converters. Besides the advantage of decoupling the diesel generator speed from the grid frequency, maximizing the efficiency of the prime mover, the interface converter is capable of providing the following additional tasks: frequency regulation, voltage support, active power injection and power quality improvement [4,7].

Depending on their operation in an AC microgrid, power converters can be classified into: (i) grid–forming, (ii) grid-feeding and (iii) grid-supporting. The grid-forming converters work as voltage sources with a low-output impedance, setting the voltage amplitude and frequency of the local loads. The grid-feeding are mainly designed to deliver power to an energized grid. The grid-supporting converters are between a grid-feeding and a grid-forming, being its main objective to regulate active and reactive power flux to contribute grid operation [8]. It is also possible to envisage a fourth operation mode, the grid-conditioning, where the goal is the power quality improvement. Active power filters belong to this category.

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http://dx.doi.org/10.1016/j.epsr.2017.05.016

Microgrids require a set of structured controllers to ensure a proper system operation under general operating conditions. Depending on the application, a suitable control strategy must be applied to regulate voltage or current at the point of common coupling (PCC). These controllers should have fast response with satisfactory filtering characteristic. Besides, this controllers take care of the microgrid stability.

Nowadays, growing attention is paid to control of grid connected VSCs. Typical control methods implemented in AC microgrid systems are: linear control [9,4,10–12], adaptive control [13,14], hysteresis control [6,15,16], sliding mode control [17,18] and repetitive control [19,20]. In general, the classic VSC control strategies can be divided in Voltage Oriented Control (VOC) and Virtual Flux Oriented Control (VFOC). A combination of methods and strategies results in diverse control concepts, such as: synchronous VOC with linear controllers, stationary VOC with proportional resonant controllers, synchronous VFOC with linear controllers, Direct Power Control (DPC), virtual flux DPC [17].

Because of the large number of possible control configurations, some papers have investigated and compared some current controllers applied to grid-connected systems [21–24]. In [24] a comparison of different types of current controllers for Active Power Filter (APF) is analysed. Transient response, THD of compensated current and execution time are the evaluation criteria for some types of controllers. Among the options, PI controller in a synchronous reference frame with multiple rotating integrators (PI-MRI) presents good results in all of the tests. For comparison purpose, Repetitive control presents high harmonic compensation capability, but has the slowest response among controllers tested. According to [24], PI-MRI appears to be more attractive in terms of implementation code in Digital Signal Processing (DSP).

The main contribution of this paper is the control strategy to a DG grid-connected and stand alone mode. Independently of the grid-forming, supplying, supporting or conditioning operation mode, the control loop is enhanced to mitigate harmonic components. Furthermore, this paper shows through Nyquist plot that harmonic mitigation controller, with dead time compensation included in inner loop, does not effect the system phase margin.

In this context, this paper presents a study on a power electronics based interface structure used to control the power flow from a DG in grid-connected and isolated modes. Loads connected at PCC may be supplied by the grid or the DG according to the operation mode. In the connected mode, named grid-feeding, the static converter is controlled to inject active power into the distribution grid. In the isolated mode, the interface structure may be controlled as grid-forming or grid-conditioning, in specific, working as APF. The modelling and control design are addressed. A PI-MRI is employed in the inner control loop to mitigate current or voltage harmonics, according to operation mode. Experimental results, under different operation modes, are presented in order to validate the proposal.

2. Interface circuit system

Fig. 1 shows the proposed power electronics based interface structure diagram. It is composed of a three-phase uncontrolled rectifier connected to the DG's output terminals, a boost converter and voltage-sourced converter (VSC) with a second order output filter. Depending on the interlocking position, the system can work in three different modes, which will be discussed in the next sections.

Due the fact that the DG's output voltage level is equal to the grid one, it is necessary to include a boost stage to increase the DC voltage level, ensuring that VSC works in the linear modulation region. During load peak demand the interface circuit works as grid-feeding injecting active power from DG into AC grid through the converters.

During a main grid fault, the load bus may be supplied in two different ways. First option is to bypass the converters using the interlocking to connect the DG to the load bus. In this case, DG directly supplies load bus. The VSC may then work as Active Power Filter (APF) compensating reactive power and harmonic currents drained by loads. Second option is to connect the DG to load through the static converter. In this case, the VSC works as grid-forming, regulating the PCC voltage frequency and amplitude.

Despite the benefit of the power injection control, the DG fuel consumption increases due to current harmonics [6] drained by the six-pulse rectifier. On the other hand, the variable speed operation can be used to set the speed of the prime mover in such a way to lead it to operate in a low fuel consumption region [25].

In fact, for medium and high capacity DG sets, the six-pulse rectifier and the boost converter might be replaced by a back-to-back VSI to ensure sinusoidal currents flow through the generator windings. However, the use of only one active switch (boost converter) in the generator-end side circuit will contribute to commutation losses reduction, increasing the overall efficiency in small capacity DG applications. Notwithstanding, all the operation modes and control strategies that is presented here, is valid for the operation of the interface circuit based on the back-to-back connection of VSI.

3. Grid-connected and stand-alone VSC modelling

Neglecting the VSC's output voltage switching harmonics, the currents flowing through the inductors can be written in the synchronous reference frame as follows

$$\begin{cases} L\dfrac{di_d}{dt} = -R_{eq}i_d + \omega L i_q + \left(v_{gd} - v_{sd}\right) \\ L\dfrac{di_q}{dt} = -R_{eq}i_q - \omega L i_d + \left(v_{gq} - v_{sq}\right) \\ L\dfrac{di_0}{dt} = -R_{eq}i_0 + \left(v_{g0} - v_{s0}\right) \end{cases}, \tag{1}$$

where v_{gk} is instantaneous phase voltage at the VSC terminals; i_k is the instantaneous current; v_{sk} is the PCC voltage, such that $k \in \{d, q, 0\}$; L and R_{eq} are the output filter inductance and equivalent resistance, respectively; $\omega = 2\pi f$ is the electric system fundamental angular frequency.

Assuming that a space vector modulation (SVM) strategy is used to generate the switching patterns, the VSC output voltage can be calculated as

$$\begin{cases} v_{gd} = \dfrac{2\sqrt{3}}{3}\left(\dfrac{V_{DC}}{2}\right) m_d \\ v_{gq} = \dfrac{2\sqrt{3}}{3}\left(\dfrac{V_{DC}}{2}\right) m_q \end{cases}, \tag{2}$$

where V_{DC} is the DC voltage and, m_d and m_q are the direct and quadrature axis modulation indexes given by

$$\begin{cases} m_d = \dfrac{\sqrt{3}}{V_{DC}}(u_d - \omega L i_q + v_{sd}) \\ m_q = \dfrac{\sqrt{3}}{V_{DC}}(u_q + \omega L i_d + v_{sq}) \end{cases}, \tag{3}$$

where u_d and u_q are the new control variables.

Substituting (3) into (2) and the result into (1) yields

$$\begin{cases} L\dfrac{di_d}{dt} = -R_{eq}i_d + u_d \\ L\dfrac{di_q}{dt} = -R_{eq}i_q + u_q \end{cases}. \tag{4}$$

Analysing (4) it is clear that the resulting system presents a decoupled first order dynamic.