ISSN : 2248-9622, Vol. 4, Issue 9(Version 5), September 2014, pp.46-50

RESEARCH ARTICLE OPEN ACCESS

Design and Simulation of a Three Phase Power Converter Connected To a Distribution System

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ABSTRACT
The distributed generation systems based on renewable energy sources (photovoltaic, fuel cells, and storage systems such as ultra capacitors and batteries) are of great interest due to their low environmental impact and technical advantages such as improvements in voltage levels and reduced power losses when a distributed generation system is installed in radial lines. Two control algorithms were proposed to improve the grid-connected and intentional-islanding operations methods, in which the distributed generation system must detect the situation and switch from power or current to voltage as a control variable to provide constant rms voltage to the local loads.

The power flow between the grid and the distributed generation is controlled by applying a power/voltage method that regulates the amplitude and the displacement of the grid voltage synthesized by the distributed generation, while a phase-locked loop algorithm is used to synchronize the grid and distributed generation.
Index Terms— Distributed generation (DG), islanding modes, power converters.

I. INTRODUCTION

THE use of distributed generation (DG) sources is currently being considered as a solution to the growing problems of energy demand. Apart from the consequent reduction in the size of the generating plants and the possibility of modular implementation, DG systems based on renewable energy sources (photovoltaic, fuel cells, and storage systems such as ultra capacitors and batteries) are of great interest due to their low environmental impact and technical advantages such as improvements in voltage levels and reduced power losses when a DG system is installed in radial lines. DG systems also promote cogeneration and improve overall system efficiency. A DG system operating at high performance requires a detailed evaluation of the feeder where the DG will be installed, plus an assessment of the load type the DG must supply locally and its working regime. Without these requirements, the effects of DG may be more harmful than beneficial: the insertion of new generation sources in the distribution system may cause transient effects due to switching operations, changing short-circuit levels, lower margin of stability, and inversion of the power flow through the distribution system, causing erroneous operations of the protection devices and islanding in part of the system. In addition, the DG operation should not exceed the limits established by international standards for the following parameters: harmonic distortion, voltage imbalance, voltage fluctuations, and fast transients, whether the local load is unbalanced, nonlinear, or a dynamic load, such as a motor. Recently, the use of power or current in the d-q synchronous reference frame as control variables to command the voltage source inverter (VSI) connected to the grid has generated considerable interest from the scientific community. With either method, before or after the contingency takes place, the control variable remains the same, making the DG operate with limited capability to supply the load. On the other hand, two control algorithms were proposed to improve the grid-connected and intentional-islanding operations methods in which the DG system must detect the situation and switch from power or current to voltage as a control variable to provide constant rms voltage to the local loads.

In the power flow is determined by controlling the amplitude and angle of displacement between the voltage produced by the DG and the grid voltage, i.e., the control variable is the same before and after the islanding mode occurs. The voltage control provides the capability to supply different kinds of loads to the DG system, such as linear, nonlinear, motor, balanced, or unbalanced, even if the DG operates in the islanding mode. These kinds of controls are suitable for DGs operating in parallel as each of the DGs are connected to the grid through a distribution transformer (DT). Conversely, the other approaches introduced in are more effective. This paper analyzes the effects caused by 50 to 5000-kVA DG sources inserted into the distribution system, whether the local load is linear or nonlinear, or if the grid is operating under abnormal conditions. Section II details the method used to drive both converters. Section III discusses the technique to control the power flow through the grid. Sections IV and V show the simulations and experimental setup to confirm the previous analysis, while the main points presented in this paper appear in the conclusion.

II. CHARACTERISTICS OF THE DG SYSTEM

Fig. 1 shows a diagram of the system used to analyze a typical connection of a DG system to a specific feeder, although studies to determine the best site for DG insertion should be performed before the operation analysis.

A power plant represents a secondary source (DG systems), while in this study the standard grid is a basic configuration system found in 1547 standard (simulated system) or a California Instruments LX 4500 source (experimental setup).

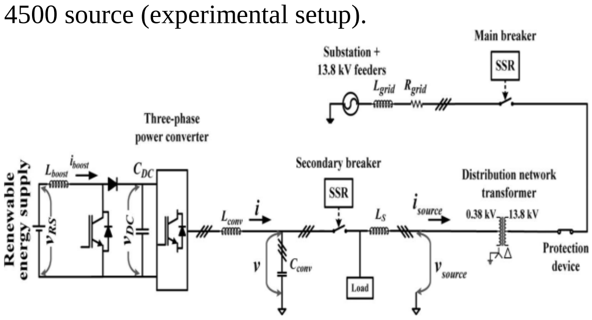

Fig.1. General diagram of the distributed generation system

Furthermore, the primary energy used in the proposed DG system is the same as the previously mentioned renewable energy sources. A dc-dc converter is employed to equalize the dc link voltage and deliver energy for fast transients when required by the local load, while a dc-ac converter is used to guarantee the power quality delivered to customers (local load) and the specific feeder. To avoid disturbances between the dc-ac converter and the feeder, a phase-locked loop (PLL) algorithm associated with the zero voltage crossing detectors was used. Appendix I shows the design procedure for key passive components.

A. DC-DC Converter

A dc-dc step-up converter was used as an interface between the dc source and dc link of the three-phase dc-ac converter. The step-up converter boosts the dc voltage and supplies the fast transients of energy required for the local load, thereby minimizing disturbances in the feeder current. The behavior of the step-up converter is similar to a voltage source, and the power it delivers to the grid depends on the point of maximum power (PMP) defined by the dc source. The PMP is obtained using a tracking algorithm, based on the primary energy source.

B. DC-AC Converter

Closed-loop controls of the output current and voltage were implemented to guarantee inverter voltage quality. PIs controllers were also used as the control technique, while the design method of these PIs is the same as that used in the dc-dc step-up converter. Since the closed-loop cutoff frequency of the PI current controller was chosen one decade below the switching frequency, the PI of the current retains a good compensation capability in the frequency range of interest. To improve this capability, a feed forward of the reference voltage could be used to compensate the residual error in the closed-loop gain at low frequencies. Due to its high power and the need for a reduced switching frequency, the voltage controller exhibits a low regulation bandwidth (a few hundred Hertz).

C. Grid Characteristics

In the simulations, the complete distribution system found in 1547 standard is composed of 13.8-kV feeders connected to a 69-kV radial line through 69/13.8-kV substation transformers, as shown in Fig. 1. To insert the DG at the distribution system, a 13.8/0.38 kV distribution network transformer is required to equalize the voltage levels. The line model employed in the simulations took into account the Bergeron’s traveling wave method used by the Electromagnetic Transients Program, which utilized wave propagation phenomena and line end reflections. Additionally, a set of switches was inserted between the DGs and distribution system, isolating them from each other to avoid the DG system supplies loads (loads placed in neighboring feeders where the DG was installed) connected to the high voltage side of the distribution transform. Due to the high level of power and voltage, 12 kHz was used as the PWM switching frequency for both converters.

III. SIMULATION ANALYSIS

Simulations were performed using MatLab/Simulink software, as shown in Fig. 2.

A. Connection and Power Transfer

Two procedures are required to connect the DG system to the feeder. First, an algorithm must be used to synchronize v_{source} with the voltage produced by the converter v. After synchronization, the algorithm to detect zero crossing of v_{source} must be initiated. When this is done, the switch connecting both systems is closed, minimizing the transient effects to the feeder. Subsequently, a soft transfer (40 kVA/s) of power starts at 0.25 s of the simulation range, followed by a base load operation. Due to the method used—synchronization and soft transfer of power—

minimal disturbances are observed in the grid. However, when the soft transfer of power is completed, two groups of resistive loads are connected within a short time interval

Due to load capability, the current flowing through the grid inverts its direction, making additional power come from the grid. At the moment of the load connection, most of the electric variables are submitted to fast transients. However, this is not observed in the grid voltages because the short-circuit power of the grid is higher than the short-circuit power of the DG. To verify the power quality delivered to customers, total harmonic distortion (THD) of the DG voltage is well below 5%, whereas the PF is close to unity.

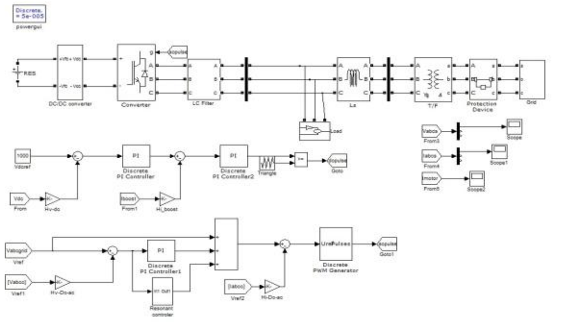

Fig.2. Simulation Diagram of Converter connected to distributed generation system

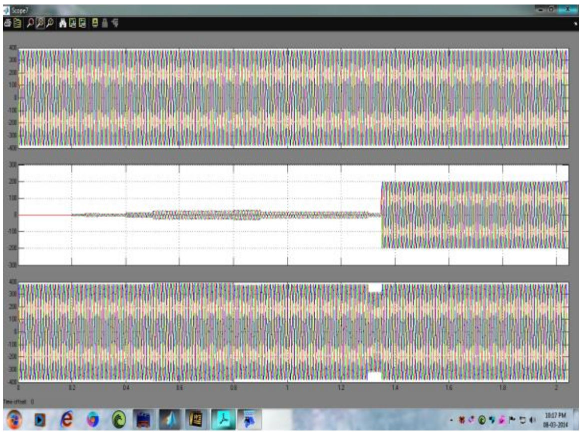

Fig. DG absorbing active power from the grid

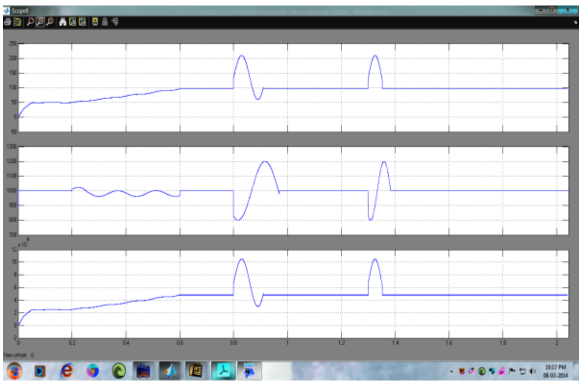

Fig. Operation of the boost converter

B. Nonlinear Load

Another issue to be analyzed is the influence of a nonlinear load connected to the DG terminals. In this case, the control technique used to synthesize the ac voltage by the inverter plays an important role. In fact, it reduces the impedance of the inverter, making the DG system compensate the local load harmonics. In this test, the load is inserted at 0.4 s and the DG is connected to the grid at 2 s, remaining so for 6 s. To observe the system's capability, the minimal value of active and reactive power flows through the grid, with the nonlinear load represented by a non controlled three-phase power rectifier plus *RC* load that demands around 50 kVA from the DG.

In this operation mode, the THD of the voltage imposed by the VSI rises to 3%, even with the resonant controller compensating the 1st, 3rd, and 5th to 15th harmonics, however, the THD of the load current achieves more than 115%. To observe what happens with the DG system, a short time interval (1.96 to 2.04 s) before and after the connection with the grid is presented, which demonstrates the DG capability to supply nonlinear loads in the connected or isolated modes.

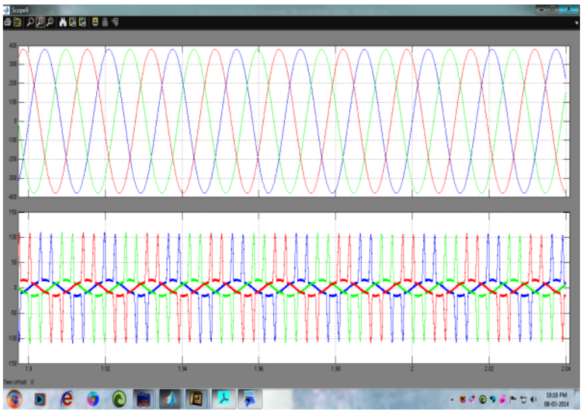

Fig. Zoom of the load currents and voltages produced by the DG with nonlinear load

C. Islanding Mode Consideration

When a short-circuit occurs on the high voltage side of the DT, the protection devices closest to the event disconnect the grid from the distribution system in order to avoid stability problems. However, the DG remains connected, forming a local area whose mode of operation may be dangerous if the local load demand is greater than the power produced by the DG. To avoid this, the DG must identify the contingency as soon as possible and disconnect it from the local area.

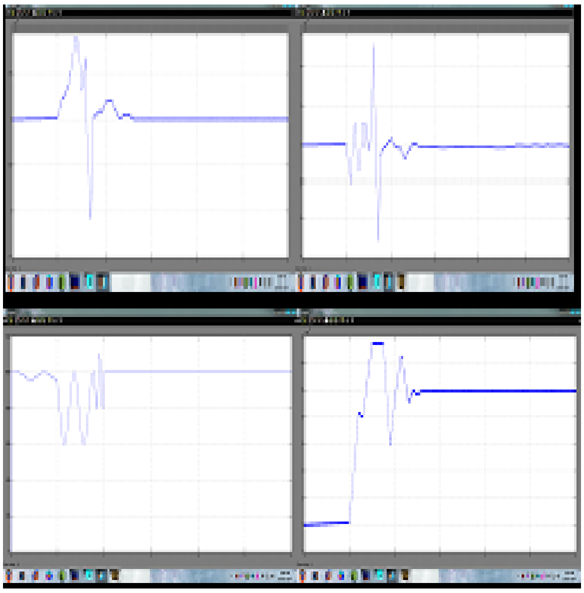

Fig. Islanding with zero power flow

To understand the effects on the grid and power converters, the following series of events was performed. First, a balanced three-phase linear load demanding almost 25 kW was connected to the DG terminals at the beginning of the simulation. At 1.8 s, the power produced by the DG system was reduced, and a 75-kW three phase linear load was connected to the DG terminals to obtain a minimal power level exchanged with the grid, which, as reported in literature, is the most difficult situation to identify the islanding mode. The effect of the islanding mode compared with the load connection or power transfer to the grid. In each case, the islanding mode did not affect the dc link voltage and power, or the ac power flow through the grid, which was not the case for the load connection or power transfer.

D. Islanding and Reconnection to the Feeder

Another important aspect of the DG operation is the islanding mode followed by a reconnection. As above, the test performed here considers a limited power level exchanged with the grid. At the beginning of the simulations, a balanced three-phase linear load demanding 30 kW was connected to the DG terminals. The power produced by the DG system was reduced from 125 kW to 90 kW, and a 25-kW three-phase linear local load was connected 1.25 s after the simulated range started. The DG voltage amplitude was subsequently adjusted to exchange −10 kVAr with the grid. This was undertaken to obtain a minimal level of active (35 kW) and reactive (−10 kVAr) power through the grid. Unlike what occurred in Section IV-C, the effects of islanding (at 3.0 s) followed by a reconnection (at 5.0 s) were evident on the dc link voltage and power, or on the power flowing through the grid, with the most drastic case being the dc link power, which dropped to zero when the grid was reconnected.

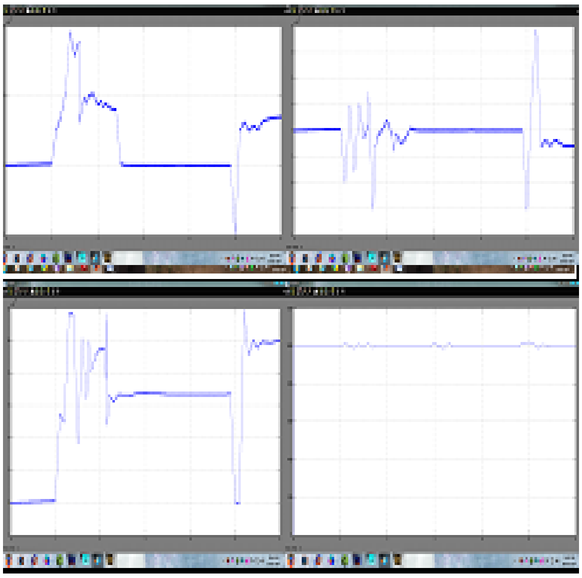

Fig. Islanding and reconnection with nonzero power flow.

Finally, a 0.5 HP 380/220 V induction machine was used as dynamic load. The instant at which the motor is connected, a high current to overcome the mechanical inertia of the motor was absorbed from the grid and the DG. After the system stabilization, the DG voltage THD and the PF were both far from the standards limits (PF was close to one while the DG voltage THD was close to 1%).

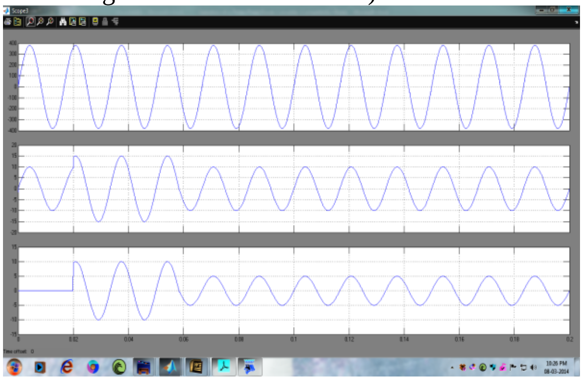

Fig. Motor start-up. Source current (phase A) 10 V/div, source voltage (phase A) 300 V/div, and motor current (phase A) A/div; Horizontal:50 ms/div

IV. CONCLUSION

This paper presents an alternative solution to connecting a DG system to the grid, whereby the amplitude and displacement of the voltage synthesized by the DG is regulated with respect to the grid voltage and the control variable before and after the contingency is always the same.

Additionally, a dc-dc step-up converter and a dc-ac VSI are used in a DG system as an interface with the power grid. The simulation and experimental results demonstrate that the connection of DG sources can have adverse effects, depending on the connection procedures. To improve the DG operation, the dc link voltage must be controlled, in this case by a dc-dc step-up converter.

PI controllers associated with resonant regulators were used as a solution to produce distortion-free DG voltage, even when the local load is nonlinear or when distortion occurs in the grid voltage. Although the PLL algorithm tracks as rapidly as possible, the frequency oscillations are slowly damped due to the limits of amplitude.

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