6TH INTERNATIONAL CONFERENCE ON ELECTROMECHANICAL AND POWER SYSTEMS
October 4-6, 2007 - Chişinău, Rep.Moldova

IG CONTROLLED BY A PWM-VSI SUPPLYING STATIC AND DYNAMIC LOADS

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Abstract **– The paper analyses the operation of an induction generator (IG) controlled by a voltage source inverter (VSI) circuit. The VSI circuit performs both voltage and frequency regulation. The IG frequency is controlled by keeping constant the VSI synchronous frequency. For the IG voltage regulation two cascaded regulators are used, which have as reference the line voltage and the VSI DC voltage, respectively. Simulations and experiments are carried out in order to investigate the reliability of such configuration when supplying static and dynamic loads.**

Keywords*: *renewable energy, induction generator, voltage source inverter, cascaded regulators.

1. INTRODUCTION

The actual tendencies on energy markets – due to the rapid depletion and enhanced costs of conventional fuels –, combined with growing concerns about the environment, have led to an important technical progress in the field of renewable energy systems. Green energy can be obtained using renewable energy sources such as wind, solar, biomass, and micro-hydro.

For stand-alone low power systems based on micro-hydro and wind, the IG is the most suitable, due to the following advantages over the synchronous one: price, robustness, simpler starting and control. Nevertheless, two main problems should be solved, respectively voltage and frequency regulation.

Two aspects arise concerning frequency regulation. First, the mechanical power delivered by the turbines can vary, especially in wind farms. Second, and most important, the loads supplied by such systems are variable by nature, so an active power balance should be achieved rapidly.

The two main solutions regarding frequency regulations rely either on a turbine governor, either on an electronic load controller [1]. The second solution seems more appropriate in terms of efficiency and costs.

For voltage control, the regulating devices have evolved from switched capacitors and saturable core reactor to linearly varying current elements (emulating capacitor) like in [2].

Properly controlled inverters are used to perform both voltage and frequency regulation [3]. There are two main controlling techniques, according to the desired behavior of the inverter. If only reactive power control, or harmonic compensation is required the inverter and its control system forms a static compensator (STATCOM) [4]. The configuration, used also in this paper, ensures the control of both, active and reactive powers of the IG and loads, and has a different control technique than a STATCOM [5, 6].

Nevertheless, the process of frequency regulation must be – for such stand-alone systems – in accordance with voltage regulation. Thus, common control circuits have been developed, in order to ensure the most efficient regulation procedure possible.

2. SYSTEM CONFIGURATION

The circuit diagram of the proposed IG control scheme is presented in fig. 1. It consists in a three-phase IG, excitation capacitors, a VSI with adaptation transformer and inductive filter, and consumers (variable loads). It also contains the IG voltage-frequency control system.

The circuit diagram from Fig.1 follows an experimental scheme. The need for the adaptation transformer arises from the voltage limitations imposed by the VSI semiconductor devices and DC capacitor.

The hydraulic turbine (replaced in the experiments by a DC motor, properly controlled), which drives the IG, has no regulation. In these circumstances, any variation in load may accelerate/decelerate the machine, thus bringing the voltage and frequency levels outside the allowable range [7]. Thereby, the exceeding power delivered by the IG has to be consumed by a dumping resistance, in order to achieve constant voltage and frequency.

The excitation capacitors supply almost the entire reactive power necessary for the IG self-excitation process; they also sustain the rated voltage in steady-state regime. The IG control is accomplished by a VSI, which acts as an impedance controller. The interconnection between the VSI and the IG is made through an adaptation transformer and an inductive filter, L_f. On the DC side of the VSI there is a capacitor -C_{dc} - and a dissipative circuit for the exceeding power, also known as dump load (DL). The dissipative circuit consists in a DC chopper and a dumping resistance. The amount of power delivered

to the dump load is controlled by modifying the PWM duty cycle that drives the T_D transistor.
An additional low-voltage source (V_{st-up}) in series with a series diode on the inverter DC side is used for the IG start-up. This source supplies the initial current required by the IG to start the self-excitation process. The start-up process is detailed in [8].

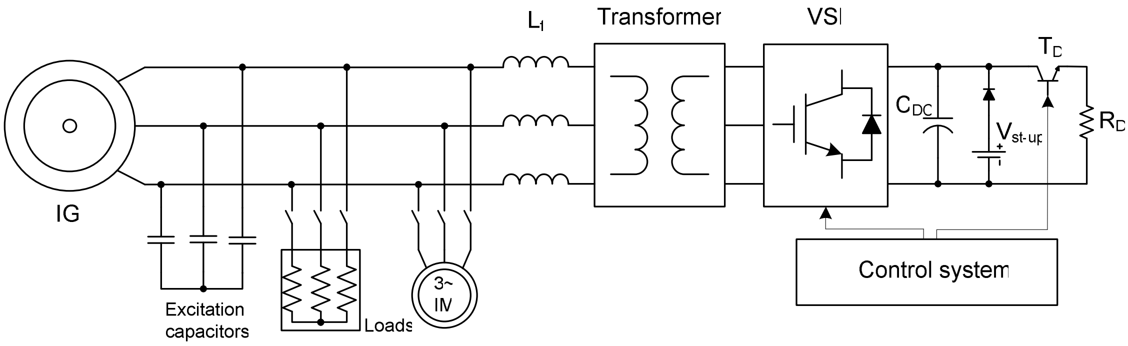

Figure1: Circuit diagram of the proposed control system

3. THE VSI MODELLING

The VSI is a three-phase PWM inverter with six transistors. Its control requires the generation of six PWM pulses, which drive the transistor bridge. The VSI operates at constant synchronous frequency (f_n=50Hz), maintaining the IG frequency constant, excepting the start-up, previous presented. Thus, the system's power balance is reduced to the DC capacitor voltage control.

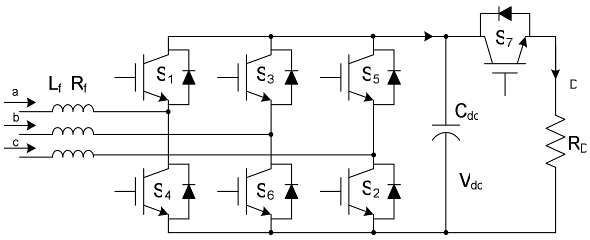

Figure 2: The VSI and DL configuration

The DC capacitor voltage V_{dc} can be written in terms related with the difference between the inverter current II and the dumping resistance current Ip:

$$CpV_{dc} = I_I - I_P \quad (1)$$

where $p = \frac{d}{dt}$

The inverter current II depends on the switching functions of the inverter three arms (S_A, S_B, and S_C):

$$I_I = S_A \cdot I_a + S_B \cdot I_b + S_C \cdot I_c \quad (2)$$

In the mean time, the dumping resistance current is:

$$I_D = S_D \cdot \frac{v_{DC}}{R_d} \quad (3)$$

So the relation becomes:

$$CpV_{dc} = S_A \cdot I_a + S_B \cdot I_b + S_C \cdot I_c - S_D \cdot \frac{v_{DC}}{R_d} \quad (4)$$

The VSI voltage equations can be written as in [9]:

$$V_{as} = r_f \cdot I_a + L_f \cdot p \cdot I_a + \frac{1}{3}(2 \cdot S_A - S_B - S_C) \quad (5)$$

$$V_{bs} = r_f \cdot I_b + L_f \cdot p \cdot I_b + \frac{1}{3}(2 \cdot S_B - S_A - S_C) \quad (6)$$

$$V_{cs} = r_f \cdot I_c + L_f \cdot p \cdot I_c + \frac{1}{3}(2 \cdot S_C - S_A - S_B) \quad (7)$$

where r_f, L_f are the parameters of the filtering inductances.

4. THE VSI OPERATION

The dump load connected to the VSI DC side will be controlled so that the voltage across the C_{DC} capacitor remains at a constant level, maintaining the system voltage in a standard variation range.
Thus, the difference between the power delivered by the IG and the loads demand will circulate through the VSI towards the C_{DC} capacitor, which acts as a short-time energy storage element. This leads to a voltage increase on the DC capacitor.
The DC voltage variation ratio depends on the capacitance value and on the amount of power transferred from the IG towards the capacitor. The capacitor value plays a very important role during transitory regimes, when it has to handle large amounts of energy (in or out). Large capacitors ensure low voltage drops across the IG lines when dynamic loads (as induction motors) are connected to the system [5]. Likewise, for unbalanced loads asymmetrical currents will flow through the inverter

lines, producing voltage variations on the C_{DC} capacitor.
Thereby, the voltage variation on the C_{DC} capacitor has two sources: the first-one is the exceeding active power from the IG, which is dissipated in the dump load, and the second-one is the reactive power flow through the inverter for asymmetrical and harmonics currents flow. For symmetrical three-phase reactive currents, the voltage variation on the C_{DC} capacitor is close to zero.
Two controllers are used to regulate the system voltage: a PI controller and an on/off controller, as shown in fig. 3. The PI controller is the leading voltage regulator. It compensates the voltage drops across the inverter arms and filter, IG leakage impedances, and other circuit elements, which usually led to a decrease of the IG voltage. The IG root-mean-square (RMS) voltage (V_{AB}) is the feedback signal, it is compared with the 230 V reference signal (V_{REF}), and the error feeds the PI controller, giving the reference signal (V_{DCref}) for the second controller. The on-off controller is used to maintain constant the C_{DC} voltage. The allowed voltage variation (ripple) across C_{DC} capacitor (ΔV_{DC}) will give the frequency and the width of the pulses that drive the T_d transistor from the dump load.

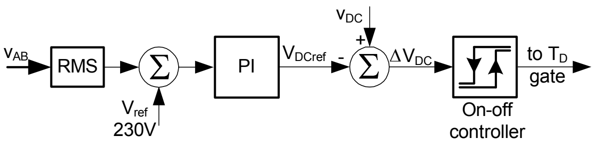

Figure 3: The DC capacitor voltage regulation technique

5. SIMULATIONS AND EXPERIMENTAL RESULTS

The proposed system was modeled and simulated using the Matlab/Simulink environment. The block diagram is shown in Fig. 4. The configuration includes the 4kW IG, a block that models the prime mover (hydraulic turbine), the VSI with an adapter transformer, the two voltage controllers, an adequate capacitor bank, loads and measurement blocks.
The IG parameters are listed below:
P= 4 kW, 400V/50Hz/1500RPM.
Rotor type: squirrel-cage
Stator: Resistance and the leakage inductance (p.u):
$R_s = 0.035$ $L_{ls} = 0.045$
Magnetizing (mutual) inductance (p.u.): $L_m = 1.352$
Rotor: Resistance and leakage inductance both referred to the stator (p.u.):
$R_r^{'} = 0.034$ $L_{lr}^{'} = 0.045\ mH$
The excitation capacitors are star connected with C=100µF.

The adaptation transformer ratio is 1.46, bringing the 230 V from the IG leads to 157 V on the inverter branches and 220 V on the DC capacitor – this is due to the experimental setup limitations –.

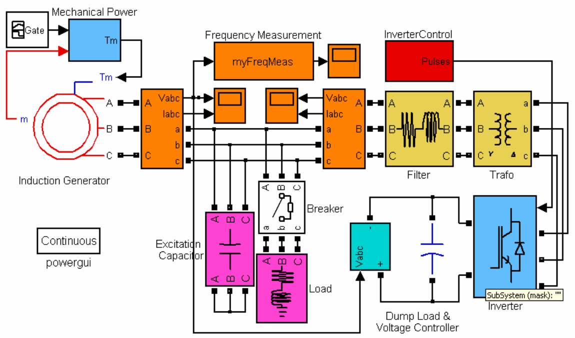

Figure 4: Simulink block diagram of IG-VSI system

The experimental test bench was accomplished on a laboratory-scale prototype, which contains a 3.5 kW/1500 RPM IG and a VSI controlled by a DS1102 dSPACE™ card (TI DSP TMS320C31), used for data acquisition too. As prime mover, a 4 kW/1500 RPM DC motor was employed.

5.1. Steady-state operation

At start-up, the IG works as a motor for a few seconds, being driven by the VSI-PWM. Then the DC motor is coupled and speeded up, and the capacitor bank connected. When the synchronous frequency is attained, the induction machine passes into generating regime.
Due to the limitations imposed by the experimental set-up, the IG and dump load cannot be loaded at their full power, thus in the waveforms that will be presented the experimental voltages and currents are not at their rated values.

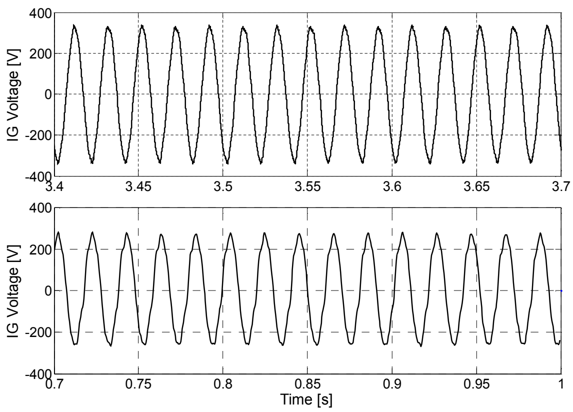

Figure 5: IG Voltage in steady-state regime

The obtained results are presented including the simulated ones (the upper figure) and the experimental ones (the lower figure). The experimental waveforms have some small disturbances, due to the data acquisition errors.

Let's assume that in steady-state regime, the IG supplies a 2 kW load – simulations- and a 800W – experimental-.

The IG voltage is presented in figure 5, while the IG current in figure 6. It can be noticed that in simulations, the current is around 9 A, while in the experiments around 3A. The exceeding energy that is not consumed by the loads passes through the VSI inverter in order to be dissipated on the dumping resistance. Thus, the current through the VSI reaches 4.5A and 1A respectively, as it can be seen in figure 7.

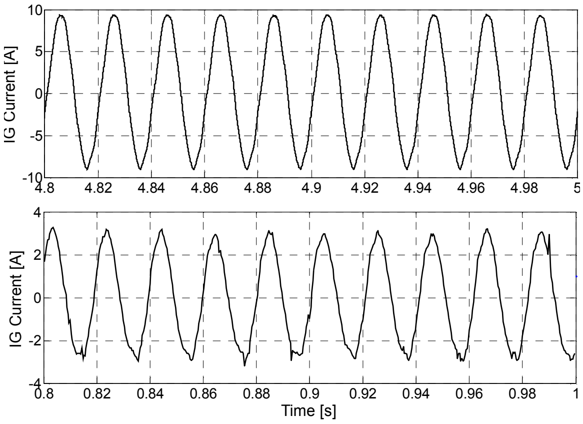

Figure 6: IG Current in steady-state regime

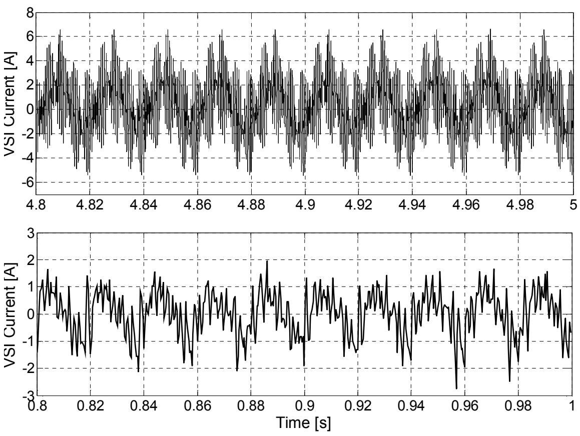

Figure 7: VSI Current in steady-state regime

5.2. Static load connection

As loads supplied by an autonomous IG are variable by nature, their effect on voltage and frequency characteristics are of real interest.

At t=4s, a pure resistive load with P=2kW is connected to the IG leads. Its influence on several parameters is shown in the figures below.

After the R load connection, at t=4s, the IG voltage has a little sag (fig. 8); in consequence, the VSI DC capacitor voltage decreases as well, the regulators command an increase of the DC voltage in order to compensate this phenomena..

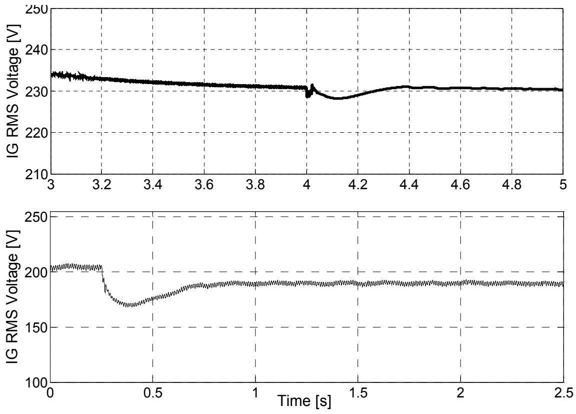

Figure 8: The IG RMS voltage variation

As the 2kW loads is connected at t=4s, the frequency tends to decrease; in order to stabilize it, the dissipated active power must decrease accordingly to the new regime. Thus, the current through VSI decreases from 4.5A to 2A (see figure 10) , stabilizing in approximately 0.1s, and keeping the IG current constant (fig. 9).

The system frequency variation is insignificant due to the constant frequency VSI operation, which imposes the system frequency.

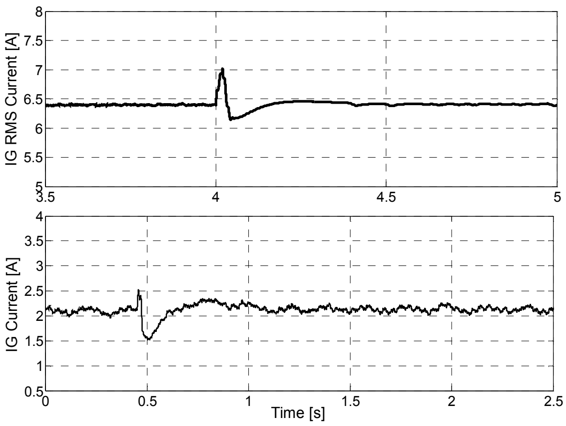

Figure 9: The IG RMS current variation

For the experimental setup, at t=0.3s, a pure resistive load with P=1kW is connected to the IG leads. This leads to a decrease of the IG voltage (fig. 8); the regulators bring it back to the initial value in approximately 0.5s; the VSI current decreases from 1.5 to 0.5A, thus keeping the IG current constant. The IG and VSI current variations for this situation are depicted in figures 9 and 10.

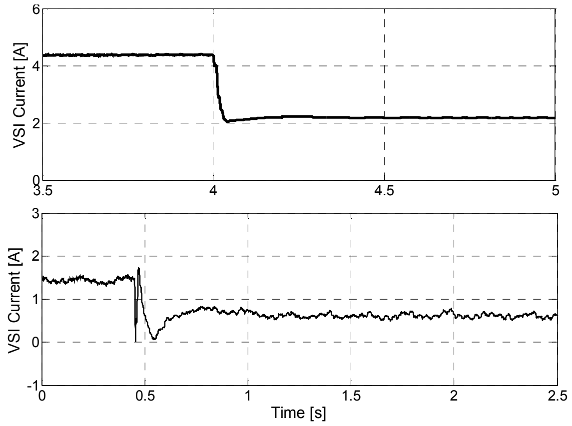

Figure 10: The VSI RMS current variation

5.3. Dynamic load connection

Next, the system's behavior at an inductive load connection is analyzed. For this, an unloaded induction motor is used.

At t=4s, a 2kW induction motor is connected to the IG leads. The IG voltage has a little sag (fig. 11); the regulators response is fast, bringing the voltage value to its rated value in around 0.2s. The IG voltage variation is depicted in the upper region of figure 11. In figure 12 the IG current variation is presented, while in figure 13 the induction motor current at start-up.

In the experiments, a 1kW induction motor is connected at t=0.6. The influence on the IG voltage is presented in figure 11. The length of the voltage sag is bigger then in the simulations – around 0.6s- which is due to the limitations of the experimental set-up previously mentioned. The influence on the IG's current is also more significant, as it can be seen in figure 12. The current drawn by the induction motor is presented in figure 13.

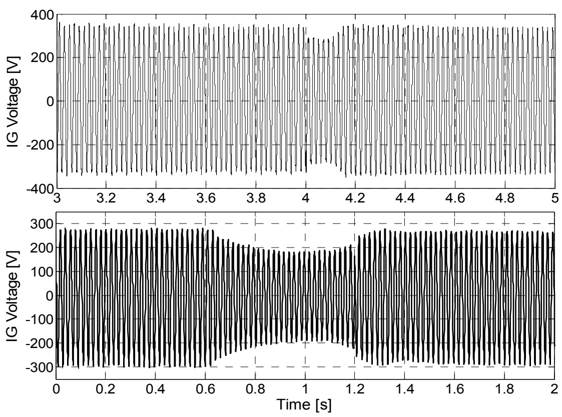

Figure 11: The IG Voltage variation

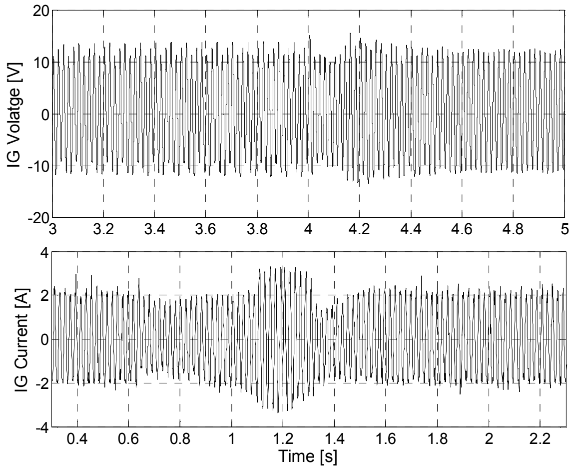

Figure 12: The IG Current variation

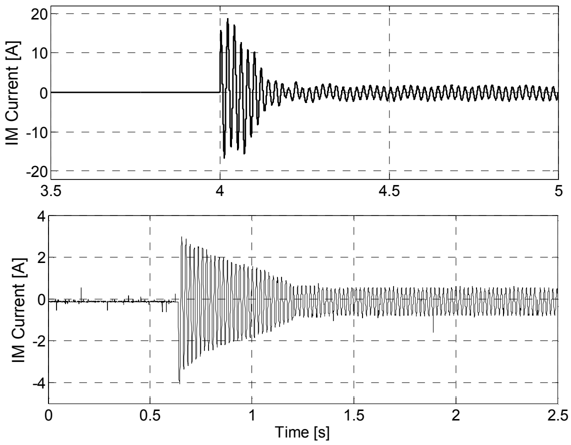

Figure 13: The IM Current variation

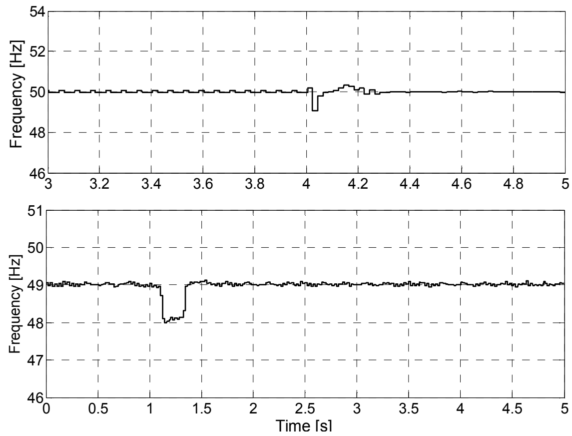

Figure 14: Frequency variation

In figure 14 the influence on frequency is presented. In both cases, it has a drop of around 1 Hz, but it is rapidly brought back to its rated value.

It can be clearly seen that the experimental results are in concordance with the simulated ones. Conclusively, the studied configuration ensures a high degree of stability for a small-power stand-alone power system, when supplying different types of loads.

6. CONCLUSIONS

This paper investigates the operation of an IG controlled by a VSI circuit. The control circuit performs both frequency and voltage regulation when supplying static and dynamic loads.

The proposed system configuration was modeled and simulated using Matlab/Simulink environment. In addition, experiments were carried out using a laboratory-scale prototype.

Both simulation and experimental results were satisfactory and they have shown the effectiveness of the proposed control method.

Acknowledgments

The Romanian Ministry of Education and Research supports this research theme under project CNCSIS-TD no. 131/2006.

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