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A Comparison between Line-Start Synchronous Machines and Induction Machines in Distributed Generation

***Abstract**. The phenomenon of the self-synchronisation in line-start synchronous machines can be suitably used in distributed generation plants. With a simple control equipment based on contactors, it is possible to overcome the restrictions imposed to the synchronous generators in some countries. The paper shows that synchronous machines can be suitable also when both stand-alone and grid-connected operations are involved. The paper reports finally a comparison with an equivalent system based on induction machines by means of experimental tests on sample test benches with the target to put in evidence the different characteristics of the two plant typologies.*

***Streszczenie.** W artykule wykazano że generator synchroniczny może być z powodzeniem użyty jako jednostka samodzielna i w lokalnej sieci. Porównano dwie sieci – z generatorami synchronicznymi i indukcyjnymi. (**Porównanie pracy generatora synchronicznego i indukcyjnego w sieci rozdzielczej**)*

Keywords: distributed generation, synchronous generator, stand-alone generation systems.
Słowa kluczowe: generator synchroniczny, sieć dystrybucyjna.

Introduction

The European directive 2003/54/CE was established to improve the participation of small producers to the market of electricity. The wide spread of distributed generation is in charge of the company that manages the distribution system which is responsible of the correct operation of the distribution network by guaranteeing safety and reliability. The introduction of new producers has to be done assuring an auxiliary support of energy to the grid without reducing the quality [1-4]. The new scenario of the open market requires to take carefully into account problems related to the electrical interface of the generation plants in case of distributed generation [5,6]. The electrical interface, that is the connection device necessary to assure the communication between two electrical systems otherwise not compatible, is usually realized by connecting the electric machines to the distribution grid. Nowadays the plants for distributed generation have an induction machine with a power factor correction (PFC) and equipped with a soft-starter [7,8]. The use of induction machines allows electrical energy generation on the distribution grid in a limited speed range that corresponds to the slip of the machine. This solution can be adopted in case of plants that utilize adjustable prime movers like gas turbines, hydraulic turbines and internal combustion engines [9], but it is not so good for plants having a generation not constant but dependent on the instantaneous availability of energy source like wind turbines [10,11]. The possibility of speed control at constant generation frequency is very important to assure the continuity of production in such typology of plants. It is well known that turbines with a fixed speed makes possible to obtain high efficiency only in proximity of a rated wind speed having slip of 1-2 %. There are systems that utilize wound rotors doubly-fed induction machines that allow a speed control in a range approximately equal to 30% of the rated speed. The speed control is done by feeding the rotor with proper phase voltages at slip frequency by means of a converter with a power up to 25% of the systems rated power [12]. The speed variation is instead possible in a wide range only by connecting the generator to the grid by means of an intermediate dc stage. In this case it is, however, necessary the use of full power converter with high efficiency to avoid efficiency reduction of the whole system.

The constant speed and frequency generators (CSCF – constant speed constant frequency) have to be capable of generating in parallel to the network, but they are also frequently asked to operate stand-alone to feed privileged loads in case of failures or network interruptions. If induction generators are used, it is not possible to regulate the reactive power exchanged with the grid when they are connected in parallel to the network; moreover, stand-alone operations does not guarantee rated voltage and frequency in every load configurations, if power electronics systems are not utilized.

These inconveniences could be usefully overcame for CSCF by using synchronous machines that are capable of generating in stand-alone grids. It is then possible to feed, in stand-alone systems, privileged loads at rated voltage and frequency by controlling respectively the field current and the rotating speed. It is moreover possible to supply the grid (if interconnected) with an ancillary service of reactive power exchange by varying the field current. The operation during interconnection is possible only in case of synchronism with the grid voltage. Therefore, the problem of synchronization with the grid occurs every time the machine is disconnected for stand-alone operation on a passive network.

In this case, the local generation system could lose the synchronism with the grid voltage, or generate a voltage out of phase respect that of the grid. This situation implies, at the reconnection to the network, an heavy operating condition both for the self-producer and for the grid. For this reason, the standards don't allow to connect to the network self-production systems that make use of synchronous generators or switching power converters with internal voltage references.

This paper describes a comparison between synchronous machines and induction machines in distributed generation systems for both stand-alone and grid connected operations. Making use of the self-synchronization phenomenon of synchronous machines with a cage for asynchronous starting, it is proposed a simple system to realize the reconnection to the distribution grid avoiding short circuits. The generator with a synchronous machine is compared to a system with an induction machine, to evaluate the performances by experimental investigations. The most significant results are discussed evidencing the potentialities and the limits of the two different generation systems.

Stand-alone operations

The generation system operating stand-alone has to be capable of generating electrical energy autonomously on passive networks. Therefore the electrical machines have to be equipped by suitable self-excitation systems. The suitable generators can be synchronous machines, induction machines and dc sources equipped with static converters, e.g. photovoltaic and fuel cell systems. Synchronous generators are intrinsically capable of self-excitation. On the basis of the excitation type there are two main categories of synchronous machines, namely brushless with permanent magnets and brushed with traditional dc current winding. Both permanent magnets and the traditional dc excitation circuit allow the machine the possibility to supply independent ac networks.

More complex is the use of induction generators, because these require auxiliary circuits for the self excitation. There are two basic configurations: the former is traditional and is characterised by capacitors connected in parallel with the armature windings and the latter is characterised by the use of inverters (fig. 1). In both configurations, the self-excitation of the machine can be achieved by suitable auxiliary circuits for the charge of capacitors. The configuration with parallel capacitors on the ac side presents the inconvenient that the generation frequency is dependent on the load conditions. If constant generation frequency is required, capacitor banks shall be used and the equivalent capacitance has to be selected according to load conditions. Power electronics converters make the generation system autonomous and independent on load conditions, because the generation frequency is set up by the controller of converter itself.

In the case of dc sources, the inverters for the realisation of independent ac networks must be switch-mode dc-ac, as fig. 2 shows. At present, only for very high powers thyristors are still used. In this case, the inverter are equipped with suitable turn-off circuits. As an example, fig. 2 shows the inverter with McMurray turn-off circuits [13].

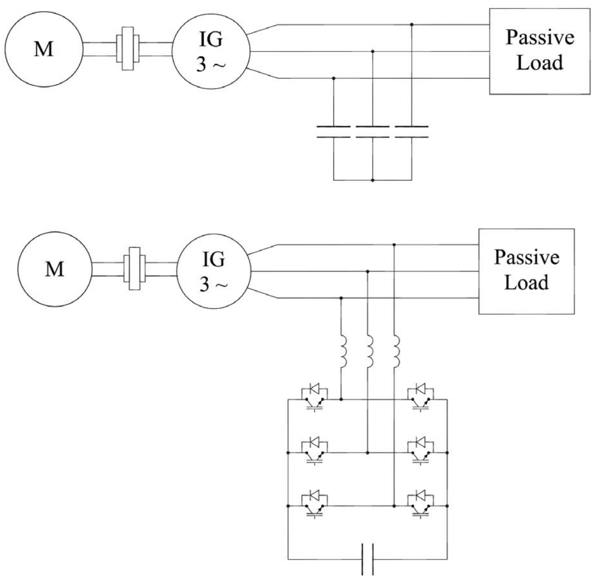

Fig.1. Induction generators for stand-alone networks: traditional and inverter-based configurations

Switch mode inverters are commonly realised with controllable switches, e.g. IGBTs, MosFETs and GTOs, as represented in fig. 2.

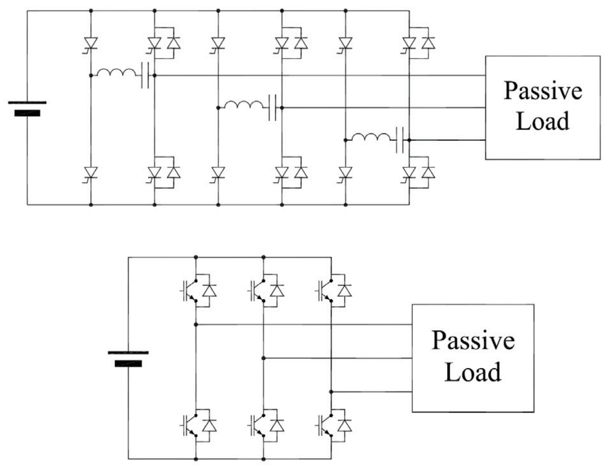

Fig.2. Inverters for stand-alone networks: with thyristors and McMurray turn off circuits, and with IGBTs

Grid-connected operations

The generation unit connected to the mains is subject to the following conditions [14]:

- the self producer must not perturb the service of the public network. Conversely, the generator has to be provided by an appropriate system that breaks immediately and automatically the connection;
- in case of voltage sags of the public network, the generation plants have not to supply the network itself;
- any unexpected event must yield the automatic disconnection of the self producer from the public network.

When connected to the network, the generation system must supply voltage with the same amplitude, frequency and phase of that supplied by the network. These conditions are always satisfied when the generators are induction machines or dc sources connected to the public network by means of line commutated inverters. The same condition can be also satisfied by synchronous machines, provided that they are equipped with specific synchronization systems.

Also the dc sources equipped with switch mode inverters need such synchronization systems. The synchronization procedure can be guaranteed by automatic systems making use of phase locked loop algorithms, which detect the frequency and the phase of the network voltage.

As indicated before, the generator must be disconnected from the network in case of voltage sags or faults. Therefore specific breaking systems has to be used in order to avoid the supplying of the fault. After the end of the faulty condition, the control system can reconnect the generator to the public network.

Mixed operations

Generation systems for mixed operations are requested to satisfy the opposite requirements of stand-alone and grid connected operations. Therefore, these systems need self excitation systems when operating on passive electric networks and synchronization systems when operating in parallel to the mains. The mixed operations require that privileged loads are supplied continuously. In order to achieve the correct switching from grid connected operations to stand alone operations and vice versa, the generator requires suitable devices for the disconnection and the reconnection. There is a transition procedure from grid connected operations to stand alone operations when there is a voltage sag due to faults or failures in the public network. The excitation systems of the generator has to guarantee the continuity in the supplying of privileged loads.

The transition procedure from stand alone to grid connected operations requires that the voltage of the generator has the same amplitude, the same frequency and the same phase of that of the network. For this reason, control systems dedicated to control the output voltage of the generator should be embedded in the generation system.

Comparison of Control Systems with Synchronous Machines and Induction Machines for mixes operations

Distributed generation systems equipped with synchronous machines or with induction machines and VSI inverters need dedicated control units for achieving mixed operations. These control unit manage the transitions between the two operating conditions: grid connected and stand-alone. Moreover, control systems are also capable of managing the starting of the generator. The control unit can be realized in different ways but this paper suggests a very simple configuration that makes use only on some contactors. Since only some simple information and the drive of contactors are needed, the control system can be implemented on a PLC. The proposed configurations using respectively synchronous and induction machine are reported in figs. 3 and 4.

A state logic control system is realized to read the signals from the field and manage the transitions from one to another working condition. In the following, the two state logic control units for the two generation systems are discussed in details.

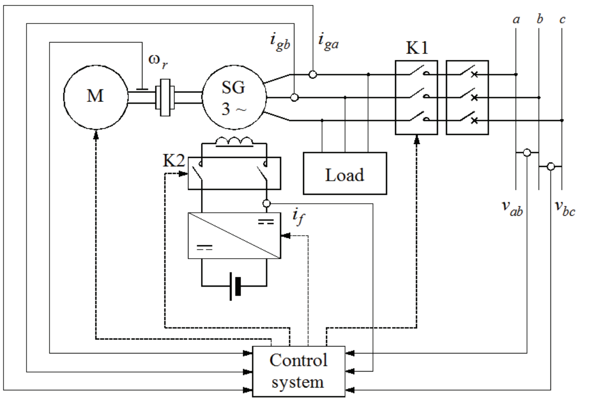

Fig.3. Configuration of the generation system based on synchronous machines

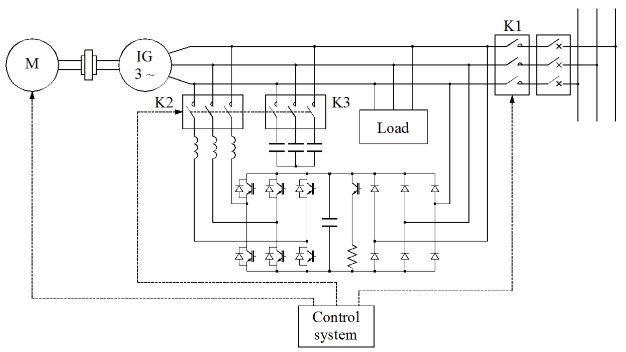

Fig.4. Configuration of the generation system based on induction machines

Systems with line-start synchronous machines

If reference is made to the generation system represented in fig. 3, the control system used for the generation with line start synchronous machines can be summarized by the transition graph shown in fig. 5. At the ignition, the system starts in the State 0 and subsequently manages the transitions among the states using the following logic:

<u>State 0 – Starting</u>. The starting procedure is different depending on the state of the network. The system detects the presence of the mains voltages by means of the measurements of v_{ab} and v_{bc}, given by voltage transducers.

If the grid is present, the contactor *K1* is closed, *K2* is opened and the synchronous machine starts from the line as an induction machine. When the shaft speed is close to the synchronous speed, as revealed by the speed measurement of the shaft ω_r, the control system switches into the State 1 and *K2* is closed. The trigger is given when the actual speed is greater than an assigned threshold. For traditionally designed machines, this threshold is usually very close to the synchronous speed (98% or more). The field current is supplied to the excitation winding by means of the dc/dc converter with a feedback control on the stator currents, i_{ga} and i_{gb}, measured by the current transducers. When the excitation winding is supplied by the field current, the machine self-synchronize itself with the network [15]. Self-synchronization phenomenon can be analyzed from numerical point of view also from the mathematical model of the machine. Stator currents during this phenomenon are limited by the low value of induced voltage, due to the low value of the field voltage supplied by the rectifier.

If the network is not present, the contactors *K1* and *K2* are both opened and the prime mover starts the synchronous machine. The speed is controlled by the prime mover and the contactor *K2* is closed and the control system switches into State 2 when the shaft speed is greater than the speed threshold.

<u>State 1 – Interconnected operations</u>. After the synchronization, the machine operates as a standard synchronous generator connected in parallel to the mains. The controls of the torque on the prime mover and the field current, if, by means of the dc/dc converter allow respectively the control of the active and reactive power supplied to the network. If during these operations the current supplied to the network falls down to zero or raises more than a given threshold, the system passes to the State 2. The current threshold selected is two times the rated current of the machine for 5 seconds. During the transition *K1* opens and *K2* remains closed.

<u>State 2 – Stand-alone operations</u>. When the system is in the State 2, the machine works as a stand-alone generator onto a passive load. In this case the amplitude and the frequency of the voltage are respectively regulated by means of the field current and the speed. The system keeps working in this state until the mains recover, i.e. the mains voltages are greater than a set threshold, equal to 90% of the rated voltage. During this transition *K2* opens and the control system passes into the State 0. The transition to the State 1 is not direct, because the voltage of the machine and that of the network could be out of phase. In order to avoid the use of a PLL for the synchronization of the two voltages, the field circuit is opened and the synchronous machine is reconnected to the network as an induction machine. Then the supply of the field winding is controlled as explained in the State 0.

Therefore this generator is capable of supplying privileged loads both in grid-connected and standing-alone conditions. When mains fail, the transition from grid-connected to stand-alone operations is necessary, whether or not privileged loads are present, in order to avoid that the generator supplies short circuits on the grid. If there is not stand-alone load and the machine is connected to the network, the active power is supplied directly to the grid. Torque set-point on the prime mover selects the active power supplied by the generator. If there is not stand-alone load and the machine is disconnected to the network, the machine spins in no load conditions: the speed and field current controls guarantee respectively that the frequency and the amplitude of the voltages generated are equal to the rated values.

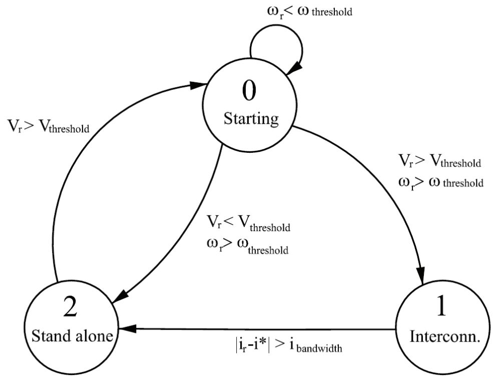

Fig.5. Transition graph of the control system used

Systems with induction machines equipped with shunt inverters

The control system, for this configuration, is represented by the graph reported in fig. 6. In this case only two states are possible because it is not possible the stand alone start of the system when the mains are down. This is due to the need of not null conditions necessary for the self-exciting of the induction generator. In order to start the system, in stand-alone operations, it should be necessary a battery and a contactor system suitable to pre-charge the capacitances. If these are not present, the system can start only when the mains are up, closing *K1* and keeping opened *K2* and *K3* (see fig. 4). The two contactors *K2* and *K3* are mechanically interlocked and are always both open or closed. When *K1* closes the self-exciting phenomenon occurs for the residual induction field present in the machine. The generation unit always starts in state 1 then switches between the two states according with the following rules:

State 1 – Interconnected operations: The system works as a traditional induction generator operating connected to the mains. Controlling the prime torque it is possible to regulate the active power supplied to the network. However, the reactive power cannot be controlled. While in state 1, if the control system detects that the current exchanged between the generation unit and the grid is lower than the minimum threshold or is higher than the maximum threshold, then change the system operation to state 2. The transition is effected opening *K1* and closing *K2* and *K3*. In order to avoid short circuits on the network the contactors *K1* and *K2* are interlocked so that the second can close only after the opening of the former.

State 2 – Stand-alone operations: The system supplies the passive loads. The regulation of amplitude and frequency of the load voltage are controlled by means of the shunt inverter. It is necessary to ensure that the energy supplied by the generator is enough to satisfy the requirements of the loads. This is achieved by controlling the prime mover torque. It is, also, opportune, but not strictly necessary, that the energy supplied by the generator is not greater than the energy absorbed by the loads. If this event occurs the system can work wasting the excess energy on the ballast resistance present in the scheme. The system persist in State 2 until detecting the network restoring. The detection can be achieved measuring the mains *rms* voltage. When the network restores, the control system opens *K2* and *K3* and then closes *K1* passing in the State 1.

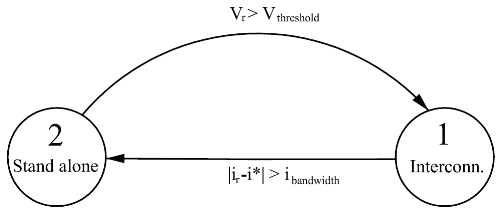

Fig.6. Graph of the states of the induction machine control system

Experimental results

The performances of synchronous and induction machines for distributed generation applications have been tested using two benches in the Department of Electrical Engineering of the University of Naples Federico II. In the tests the starting of the system by means of connection to the mains has been simulated. After about 10 seconds, one voltage sag has been applied having a duration of 10 seconds with subsequent restarting of the mains. The control system, based on the logic described in the previous section, identifies the faulty condition and commands the transition from grid connected to stand alone operations and back. In the following, the results obtained with synchronous and induction machines are reported in details.

Generator equipped with the line-start synchronous machine

The generation system with line start synchronous machine has been equipped with a separately excited motor as a prime mover. The speed control on the prime mover has been performed with the speed feed-back and armature voltage regulation with an inner loop for the control of the armature current. The main data of the two machines are reported in Table I.

Table 1. Nameplate data of the machines used for the tests

	Type	Rated voltage [V]		Rated current [A]		Power [kW]	cosφ
		Armat.	Field	Armat.	Field		
Synchronous machine	Siemens 1FA3 144	380	165	21	4.5	12.5	1.0
Dc machine	Sep.C.S.STAB F 62568	220	160	54.5		11.3	

The layout of the laboratory bench is that of fig. 4. The phase current drawn by the synchronous machine is plotted in fig. 7.

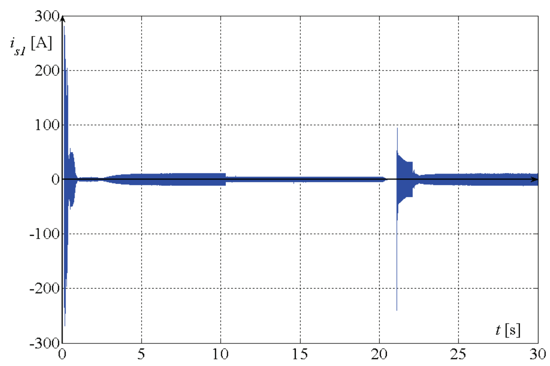

Fig.7. Phase current of the synchronous machine under test

The analysis of fig. 7 points out that the reconnection transient is softer than that of starting, where the machine behaves like an induction motor. This condition is verified only if the voltage induced in the windings by the remnant magnetism is significantly lower than the rated one before the machine is reconnected to the network. For this reason, the contactor *K1* is close 0.8 seconds after the contactor *K2*. Fig. 8 shows the voltage diagrams of the network and the generator. When the network voltage passes from zero to the rated *rms* value of 380 V at the time 20.2 seconds, the voltage of the generator is opposite in phase. Therefore, the instantaneous closing of *K1* would involve an hard condition both for the network and for the machine for the high currents drawn and the long duration of the phenomenon. The delay in closing of *K1* implies the decrease of terminal voltages of the synchronous machine down to the voltage due to the remnant magnetism. Therefore, the behaviour of the machine at the reconnection is similar to that of induction machines and the currents are reduced and have short duration (see fig. 7).

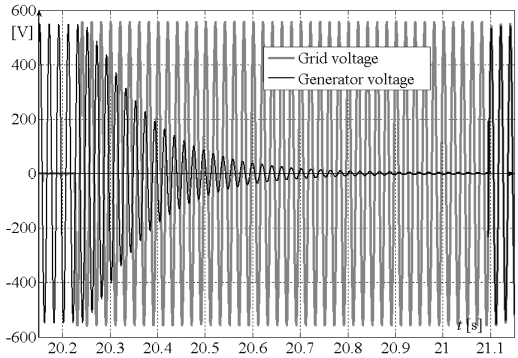

Fig.8. Mains voltage and synchronous machine voltage at the reconnection of the network

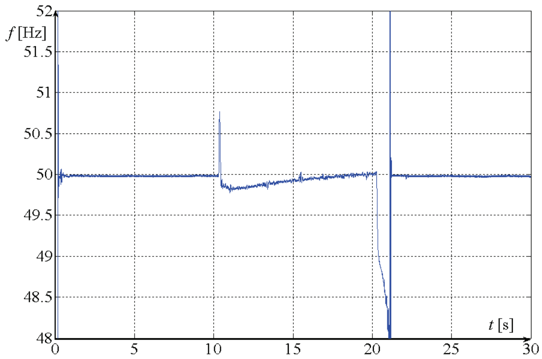

Fig.9. Frequency of load voltage

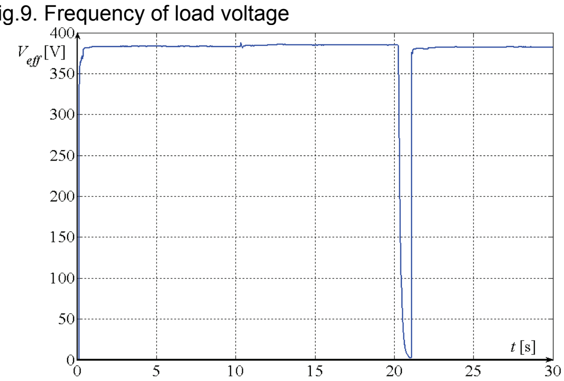

Fig.10. Rms value of the load voltage

For the whole duration of the test the amplitude and frequency of the voltage are set to their rated value. This condition is satisfied by the control of synchronous generator and of the prime mover when the network is not present. Figs. 9 and 10 show respectively the diagrams of the frequency and of the *rms* of the network voltage at load terminal. The frequency has been evaluated according to reference [16], whereas the voltage *rms* has been evaluated in each period taking into account the value of the frequency given by frequency estimation. The analysis of these figures highlight clearly that the transition from grid connected to stand alone operations is in practice very soft for the load. There is a short voltage sag during the inverse transition, whose duration is 0.8 seconds. This sag is due to the aforementioned closing delay of contactor K2.

Generator equipped with the induction machine and shunt inverter

Also in the tests made with the induction machine the prime mover has been a separately excited dc motor. The speed control has been realized in the same way of that of synchronous generation system. The main data of the machines are reported in Table 2.

Table 2. Nameplate data of the machines used for the tests

	Type	Rated voltage [V]		Rated current [A]		Power [kW]
		Armat.	Field	Armat.	Field	
Induction machine	Siemens 1LA5163	380		22.5		11.0
Dc machine	Tecnomasio GCNa104	220	220	100	2	20.0

The layout of the generation system realised in the laboratory is that of fig. 5. The current supplied by the induction generator during the test has been plotted in fig. 11. The analysis of fig. 11 highlights that the current of the machine falls down to zero two times. When there is the transition from grid connected to stand alone operations, the contactor *K1* must be opened and *K2* and *K3* have to be closed. However, the commutation can't be done immediately because the voltage at the machine terminals, due to the residual induction, and the output voltage of the inverter could be not synchronized and out of phase. In order to avoid heavy transients, it is better to insert a short delay between the opening of *K1* and the closing of *K2* and *K3*. Another complication arise if general purpose inverters are used for these generation systems. These inverters are generally equipped with undervoltage and overvoltage protections which shut down the converter if the dc bus voltage goes out of a fixed threshold. The inverter, connected to the machine, would try to set the voltage of the network discharging the dc link capacitor and would shut down itself.

Therefore, the switching problems connected to the voltage of the machine terminals can be avoided waiting for the time necessary to the significant decreasing of this voltage.

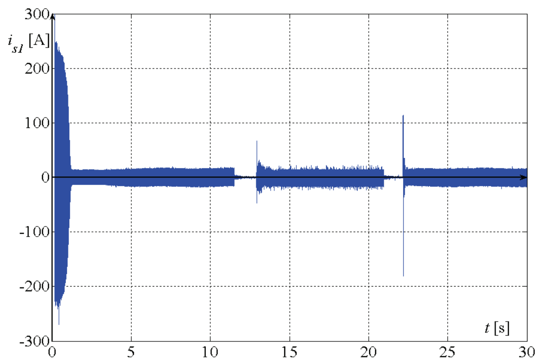

Fig.11. Phase current of the induction machine under test

The transition from stand alone to grid connected operations presents problems similar to those pointed out for synchronous machines. Therefore, the closing of *K1* is subjected to the condition that the voltage of the machine is decreased significantly in order to avoid flowing of high current into the network due to the out of frequency and phase of the voltages. Fig. 12 shows respectively grid and machine voltages in the transition to grid connected operations. Fig. 13 shows the voltage diagram of the inverter dc bus.

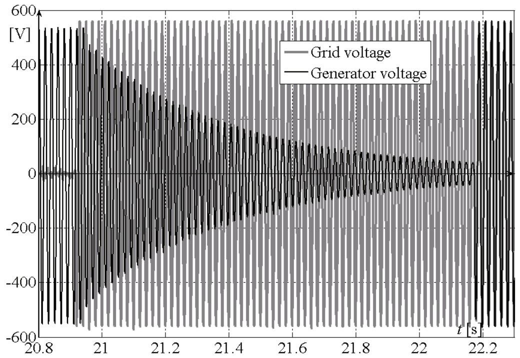

Fig.12. Mains voltage and induction machine voltage at the reconnection of the network

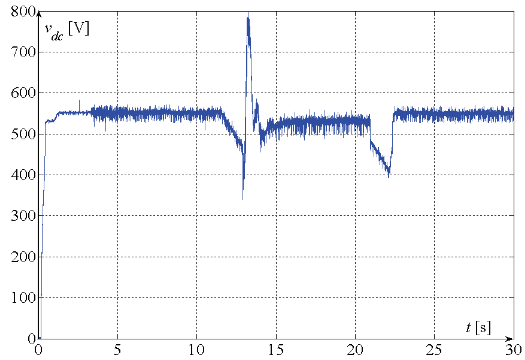

Fig.13. Voltage diagram of the inverter dc bus

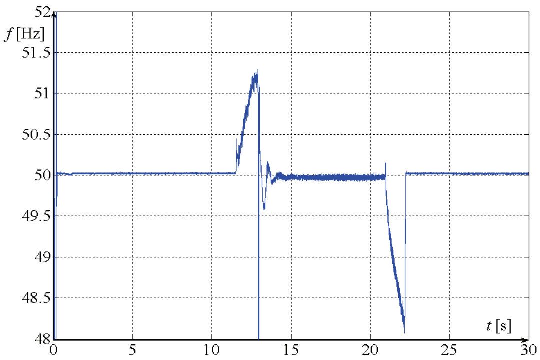

Fig.14. Frequency of the voltage generated by the induction machine

The rated values of voltage and frequency of the voltage generated by the induction machine are guaranteed by the mains during grid connected operations and by the inverter during stand alone periods. Figs. 14 and 15 shows the diagrams of the *rms* value and frequency of the voltage at the machine terminals. The analysis of the figures points out the two short voltage sags introduced by the delay operated during the commutation of the contactors. The behaviour of the machine after the opening of contactor *K1* at the time t = 12 *s* can be explained considering that the frequency of the voltage is different from 50 *Hz* because it is dependent on the speed, whereas the amplitude is dependent on the residual magnetism and is decreasing because the energy stored into the rotor circuits is gradually dissipated. When the inverter is connected to the machine terminal, there is a short transient after that the inverter itself sets the amplitude and the frequency of the voltage at the rated values.

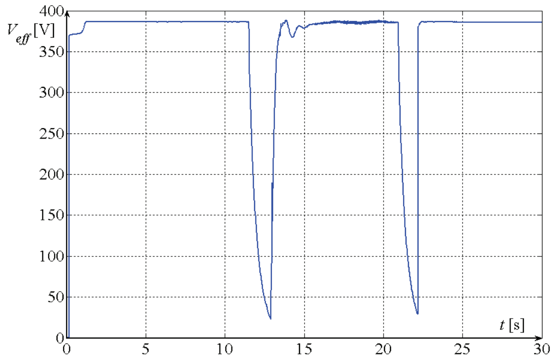

Fig.15. Rms value of the voltage generated by the induction machine

Conclusions

In the paper distributed generation systems with synchronous and induction machines have been analyzed. Both systems are widely treated in literature and is well-known that synchronous are better for stand-alone generation systems, induction machines are better for grid-connected systems. On the other side, to avoid problems due to possible fault conditions, the standards (i.e. Italian CEI 1-20) that refers to distributed generation indicates some limits in the connection of the above considered systems to the grid. In the paper are proposed two different configurations of generation systems based respectively on synchronous and induction machine that, by using simple control systems and grid-connection, realize solutions able to operate both stand-alone and grid-connected, avoiding problems during commutation from an operation to another.

The proposed configurations have been analyzed by simulation of fault conditions and restoration of the grid. The test of the two generation systems was experimentally done by arranging in laboratory proper test benches. The experimental results, presented in the paper, demonstrate the control simplicity and the effectiveness of the proposed configurations.

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