A Fuzzy controller of an induction generator working on a passive network

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Abstract

In the field of electrical generation there are few applications of induction machines and one of the reasons is because it is very difficult to control the power quality parameters in stand-alone mode operations. The aim of the following paper is to introduce a generation system using an asynchronous machine, working in island mode, and to propose an innovative control strategy in order to reach an optimum performance on voltage and frequency in every load condition.

In the state of art the induction generator is controlled acting separately on the mechanical torque and on the reactive power. In this paper will be shown that those two parameters are correlated and they have to be controlled together. This task can be implemented with the aid of a Fuzzy controller that is a very powerful technique in this kind of application.

1. Introduction

The evolution of power electronics devices and advanced automatic controllers has implied a major presence of the induction machines in the field of variable speed control loops. This allows taking in advantage of the robustness and reliability characteristics of this kind of electric machines.

The applications of induction machines in the field of electric power generation are often the ones in which the stator winding is fed from the public electric grid. Aeolic plants and the combined heat and power systems are examples of electric power generation that use asynchronous generator.

The lack of common applications of induction machines is due to their electromagnetic construction characteristics. In fact, in the squirrel cage version, there isn’t the excitation input. Then it is mandatory to have an initial magnetism for the self excitation mechanism and a reactive power source in order to sustain the induction field at the air gap during the normal working phase.

Moreover, when the machine generates on a passive network, the frequency of the voltage is not dependent only by the rotational speed of the rotor, as it happens for the synchronous machines. Instead, the frequency is also a function of slip and load condition.

In this paper it is analyzed the implementation of a generation system that involves an asynchronous machine that is able to keep the nominal values of voltage and frequency (i.e. \( V_{\text{rms}} = 220 \, [\text{V}] \), \( f = 50 \, [\text{Hz}] \)) in every load condition.

The design of a controller able to achieve those features is implemented with soft computing techniques (i.e. Fuzzy). This kind of controllers allows designing a coupled strategy for the control variables (i.e. error on voltage and frequency) in order to obtain better performances.

The results are showed with the aid of simulations realized on a Matlab\textsuperscript{\textregistered} platform.
2. System Models

In the following figure is shown the system configuration.

![System configuration](image)

**Figure 1. System configuration**

The system is composed by five principal blocks:

1. Induction Machine;
2. Prime Mover;
3. Electric load;
4. Controller;
5. Switches.

2.1. Induction Machine

It is well-known that asynchronous machines are capable of converting electrical energy into mechanical energy or vice-versa. In the latter case they are capable of feeding either active or passive electrical networks. The corresponding operating conditions are quite different, but consumer demands are the same, because they always require electrical networks which operate with given voltage and frequency and that can supply electrical power ranging between zero and a limited top value. When asynchronous machines operate connected to a passive network, sets of capacitors are necessary and starting conditions have to be guaranteed in order to establish steady state conditions. This bond is easily understood by considering that at steady-state no external voltages are impressed on the electrical system and, therefore, real and imaginary parts of the whole impedance (load + generator) must be nil [1].

Due to the inductance of asynchronous machines, only capacitors can obtain the compensation of the imaginary part [1].

It means that the induction machine is not able to self-generate on a passive network without a reactive power source. Moreover, this reactive power has to be adapted with the load changing in order to obtain constant values of voltage and frequency. Real parts are compensated by negative equivalent resistance of the rotor [1]. For what concerns the starting conditions some experimental tests have shown that induction generators are able of self-generating an active electrical network only on the basis of a residual magnetic flux density or of an initial electrical charge of a capacitor set.

Usually the model used to simulate the behavior of an induction machine, supplied by a traditional sinusoidal voltage with constant maximum amplitude and frequency, is a magnetically linear model. However, it is easily seen that the air-gap magnetic flux density has quite different maximum amplitudes when the machine either operates as a motor or as a generator [2].

The differences are easily explained if we consider that, due to the different sign of the real parts of the machine impedance, e.m.f. in generator operations are greater than those in motor operations. Saturation phenomena of the main magnetic circuits, which can be neglected during motor operations of traditionally designed machines, take on, by contrast, significance during generator operations [5].

For sake of generality we refer to a mathematical model of an asynchronous machine that takes into account saturation of the main magnetic circuit (figure 2.). The model suggested is as follows:

\[
\begin{align*}
\dot{\bar{v}} &= \left( r_s + l_r \frac{d}{dt} \right) \bar{i}_r + L'_m \frac{di_r}{dt} + \bar{j}_m \left( L'_m - L_m \right) \frac{di_r}{dt}; \\
0 &= \left( \bar{i}_r' + \bar{i}_t' \frac{d}{dt} \right) \frac{\dot{\bar{i}}_r}{i_\mu} + j p \omega (L_m \bar{i}_r + L'_m \bar{i}_r') + L'_m \frac{di_r}{dt} + \\
\Theta \frac{d\omega}{dt} + T_m - T_d = 0; \\
T_d &= \frac{3}{2} p L_m \Sigma m \left[ \bar{i}_r \bar{i}_r' \right] \tag{1}
\end{align*}
\]

Where:

\[
\begin{align*}
L'_m &= \frac{\Phi_m (i_r)}{i_r}; \\
L_m &= \frac{d}{dt} \Phi_m (i_r), \\
L_r' &= L'_m + L_r', \\
i_\mu &= \left| \bar{i}_r + \bar{i}_r' \right|.
\end{align*}
\]
Figure 2. Induction machine equivalent circuit.

The mathematical model expressed by eq. 1 requires a preliminary experimental evaluation of the no-load magnetic characteristic of the machine. For this reason, it has been used a $\Phi, i$ curve experimentally obtained as described in the following.

The magnetic characteristic has been obtained by means of experimental measures on a machine tested in the laboratory of the Department of Electrical Engineering of the University “Federico II” in Naples. In order to obtain the magnetic characteristic the machine is made to rotate at synchronous speed, 1500 r.p.m., and it is fed with a variable voltage. In this condition all the current that circulates in the stator windings is magnetizing current. It is then easily possible to evaluate the flux of the induction field in function of the magnetizing current. In figure 3. and 4. the variation laws of the flux and mutual inductance versus magnetizing current are reported.

2.2. Prime mover

The induction generator can be moved by different kind of prime motors, according to the particular application. In the combined heat and power generation systems (CHP), the prime motor could be an internal combustion engine (diesel, gasoline, methane etc) or a micro-turbine (for low power applications) or turbine (for biggest plants). In wind power applications the tower pales move the generator [4]. The following simulations do not refer to a specific kind of motor. It is used an ideal machine that can provide the desired torque value in all the range of speed regulation. This approximation is not a great limitation for the model. In fact, the internal combustion engines, in particular the diesel ones, are able to meet this feature, with a good degree of approximation, inside a speed range.

2.3. Electric load

The electric load is represented in figure 5.

Figure 5. Electric load and excitation group schematic representation.

When an induction machine works as generator, in stand-alone mode, the capacitors play a key role. In fact, they must provide the necessary reactive power for self-excitation during the start-up phase; moreover they must support the induction field at the air gap in steady state and provide a variable reactive power in order to meet the load demand. The last feature can be mainly realized in two different ways.

In a first case it is possible to obtain a discrete regulation of the capacitance value connecting many capacitor banks of fixed value to the machine. They can be switched on or off by contactors. The second chance is represented by electronic devices. These devices are made up of capacitors connected electronic switches [3]. Of course, the different configurations obtained connecting the capacitor set with the switches imply the implementation of different control technique. The first solution is the simplest one but it has the disadvantage of a step regulation. The step
amplitude depends on the number and on the size of the capacitors. The last solution gives a more precise regulation but introduces harmonic distortion and is more expensive than the first.

In the simulations presented, it is supposed that the capacitance value can change in a continuous mode in such a way to meet any load demand.

The mathematical model of the bank of capacitors is the classic characteristic of a capacitor:

$$\ddot{v}_c = \frac{d}{dt} (C \ddot{v}_c) = C \frac{d}{dt} \ddot{v}_c + \dddot{v}_c \frac{d}{dt} C$$

In the following the second term of the (3) has been neglected with respect to the first term because of the slow variations of the capacitance that is the control variable.

The electrical load is a classic three phase ohmic inductive series load and it is supposed symmetric. It is simply modeled by the following equation:

$$\ddot{v}_l = R_l \ddot{i}_l + \frac{di_l}{dt}$$

written in terms of symmetric components.

2.4. Switches

The switches allow the system to work in grid-connected mode, if they are closed or in island mode if they are opened. In our case, then, they are always opened and so it is possible to write the following equations:

$$\ddot{v}_s = \ddot{v}_l = \ddot{v}_c$$
$$\ddot{i}_s = -(\ddot{i}_l + \ddot{i}_c)$$

So, considering the equations (3), (4) and (5), the equation (1) becomes:

$$\begin{cases}
\ddot{v}_s = \left(r_s + L_s \frac{d}{dt} \ddot{i}_s + L_s \frac{di_s}{dt} + \frac{i_s (L_m - L_s)}{i_m} \frac{di_m}{dt} \right) \ddot{i}_s + \left(r_m + L_m \frac{d}{dt} \ddot{i}_m + L_m \frac{di_m}{dt} + \frac{i_m (L_m - L_s)}{i_s} \frac{di_s}{dt} \right) \ddot{i}_m + \left(r_c + L_c \frac{d}{dt} \ddot{i}_c + L_c \frac{di_c}{dt} \right) \ddot{i}_c + j \omega (L_m \ddot{i}_m + L_s \ddot{i}_s) + L_s \frac{di_s}{dt} + L_m \frac{di_m}{dt} \frac{i_m (L_m - L_s)}{i_s} \frac{di_s}{dt} \frac{d}{dt} \frac{di_s}{dt} + \frac{i_s (L_m - L_s)}{i_m} \frac{di_m}{dt} \frac{d}{dt} \frac{di_m}{dt},
0 = \left(r_s + L_s \frac{d}{dt} \ddot{i}_s + L_s \frac{di_s}{dt} + \frac{i_s (L_m - L_s)}{i_m} \frac{di_m}{dt} \right) \ddot{i}_s + \left(r_m + L_m \frac{d}{dt} \ddot{i}_m + L_m \frac{di_m}{dt} + \frac{i_m (L_m - L_s)}{i_s} \frac{di_s}{dt} \right) \ddot{i}_m + \left(r_c + L_c \frac{d}{dt} \ddot{i}_c + L_c \frac{di_c}{dt} \right) \ddot{i}_c + j \omega (L_m \ddot{i}_m + L_s \ddot{i}_s) + L_s \frac{di_s}{dt} + L_m \frac{di_m}{dt} \frac{i_m (L_m - L_s)}{i_s} \frac{di_s}{dt} \frac{d}{dt} \frac{di_m}{dt} + \frac{i_s (L_m - L_s)}{i_m} \frac{di_m}{dt} \frac{d}{dt} \frac{di_m}{dt},
\frac{di_s}{dt} = \ddot{v}_s - R_s \ddot{i}_s,
\frac{di_m}{dt} = \ddot{v}_m - R_m \ddot{i}_m,
\frac{d\omega}{dt} + T_m - T_m = 0;
\frac{d\omega}{dt} + T_m - T_m = 0;
\end{cases}$$

2.5. Controller

The choice of the controller has been done as a result of some considerations about the system. In fact, in order to reach a steady-state solution of the equivalent circuit of both the induction machine and of the load at a certain frequency $f$, the real part and the imaginary part of the load impedance must be equal, respectively, to the real part and imaginary part of the machine impedance. This consideration implies the following equations:

$$r_s + \frac{\sigma \omega^2 L_m r_s}{r_m^2 + \sigma^2 \omega^2 L_m^2} = \frac{R_i}{1 + C \omega^2 (R_i C + L_i \omega^2 L_m C)} \quad (7)$$
$$\omega L_m - \frac{\sigma \omega^2 L_m^2 r_s}{r_m^2 + \sigma^2 \omega^2 L_m^2} = \frac{\omega (R_i^2 C + L_i \omega^2 L_m C)}{1 + C \omega^2 (R_i C + L_i \omega^2 L_m C)}$$

Moreover, $L_m$ is a function of $i_s$ that is a function of the load condition. Then, to solve the system, it is necessary to consider the equation of the mechanical equilibrium in steady state condition:

$$T_m = \frac{3}{2} p L_m i_s^2 - \frac{\sigma \omega^2 L_m^2 r_s}{r_m^2 + \sigma^2 \omega^2 L_m^2} \quad (8)$$

Considering that $L_m$ is a function of $V$, the so obtained system is composed of three scalar equations with seven unknown ($R_o, L_s, \omega, \sigma, C, T_m, V$).

To solve the system is necessary to fix four parameters. Generally, $R_i$ and $L_i$ are fixed from the load. The frequency and the voltage are the variables to control and so their values are fixed (e.g. $V = 220$ [V], $f = 50$ [Hz]). In this way, the number of equations is equal to the number of unknowns. The idea is to design a control system that is able to take in account the coupling effect of the capacitors and of the mechanical torque, as summarized in Figure 5.

The two control variables are the error on peak value of voltage and the error on frequency. To measure these electrical parameters it is possible to use a voltage sensor and a peak detector, as showed in fig 5.

3. Fuzzy Controller

A Fuzzy controller [6] has been implemented in order to take in account the coupling effect of the capacitors and of the mechanical torque, as summarized in Figure 5.

The two control variables are the error on peak value of voltage and the error on frequency. To measure these electrical parameters it is possible to use a voltage sensor and a peak detector, as showed in fig 5.
The frequency measurement is obtained by the voltage and frequency detector. It calculates the period between two successive zeros of the voltage derivatives. So, the calculation of frequency and voltage is synchronous. Because the control signal is updated when a new peak voltage occurs, the sampling frequency is not constant, but variable and depending on the frequency of the voltage supplied to the load. However, as this is an industrial frequency, surely there will be problems neither for the calculus speed nor for the actuators.

When the frequency and voltage peak values are available, the controller acts on them in the following way:

\[
C(t) = C(t-1) \pm \dot{C}
\]

\[
Tm(t) = Tm(t-1) \pm \dot{Tm}
\]

In this way, the system reaches a steady state condition that is a function of the load demand.

The FIS (Fuzzy Inference System) has the following features:

- Shape of input MF: Gaussian;
- N. of MF of \( v \) input: 5;
- N. of MF of \( f \) input: 5;
- Shape of output MF: Triangular;
- N. of MF of \( \dot{C} \) output: 5;
- N. of MF of \( \dot{Tm} \) output: 5;
- Implication method: min;
- Defuzzication: centroid;

As a result, the FIS is a Mamdani one. It is possible to develop this system on a microcontroller [7] with a software implementation but, probably, the CPU load could be very hard. At the moment exists some hardware solutions that are able to implement Sugeno FIS. However, this is not a problem because the conversion of a Mamdani into a Sugeno FIS is very simple.

The membership function tuning has been obtained with the “try and error” methodology both for the input and for the output MF.

In the following Figure are shown the set of 13 rules that regulate the system:

1. \( \text{error on } v \text{ is very positive } \land \text{error on } f \text{ is positive } \Rightarrow \text{capacitor is increase much} \)
2. \( \text{error on } v \text{ is very negative } \land \text{error on } f \text{ is negative } \Rightarrow \text{capacitor is decrease much} \)
3. \( \text{error on } v \text{ is positive } \land \text{error on } f \text{ is negative } \Rightarrow \text{capacitor is decrease a little} \)
4. \( \text{error on } v \text{ is negative } \land \text{error on } f \text{ is positive } \Rightarrow \text{capacitor is increase a little} \)
5. \( \text{error on } v \text{ is positive } \land \text{error on } f \text{ is zero } \Rightarrow \text{capacitor is increase much} \)
6. \( \text{error on } v \text{ is negative } \land \text{error on } f \text{ is zero } \Rightarrow \text{capacitor is decrease much} \)
7. \( \text{error on } v \text{ is positive } \land \text{error on } f \text{ is zero } \Rightarrow \text{capacitor is decrease a little} \)
8. \( \text{error on } v \text{ is negative } \land \text{error on } f \text{ is zero } \Rightarrow \text{capacitor is increase a little} \)
9. \( \text{error on } v \text{ is zero } \land \text{error on } f \text{ is positive } \Rightarrow \text{capacitor is increase much} \)
10. \( \text{error on } v \text{ is zero } \land \text{error on } f \text{ is negative } \Rightarrow \text{capacitor is decrease much} \)
11. \( \text{error on } v \text{ is zero } \land \text{error on } f \text{ is zero } \Rightarrow \text{capacitor is stay constant} \)
12. \( \text{error on } v \text{ is very positive } \land \text{error on } f \text{ is positive } \Rightarrow \text{capacitor is increase much} \)
13. \( \text{error on } v \text{ is very negative } \land \text{error on } f \text{ is negative } \Rightarrow \text{capacitor is decrease much} \)

The rules have been written thinking at the behavior of the system. In this task there is the coupling of the control strategy. In fact, the capacitor is modified both when the frequency and the voltage varies.
4. Simulation results

The simulations were done taking in account of an induction machine with the following main parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_e$ Electric Power</td>
<td>[kW] 11</td>
</tr>
<tr>
<td>$R_s$ stator resistance</td>
<td>[Ω] 0.5</td>
</tr>
<tr>
<td>$R_r$ rotor resistance</td>
<td>[Ω] 0.328</td>
</tr>
<tr>
<td>$L_s$ stator leakage inductance</td>
<td>[mH] 3.2</td>
</tr>
<tr>
<td>$L_r$ rotor leakage inductance</td>
<td>[mH] 3.2</td>
</tr>
<tr>
<td>$P$ pole pair</td>
<td>2</td>
</tr>
<tr>
<td>$J$ Inertia momentum</td>
<td>[kg m$^2$] 0.73</td>
</tr>
</tbody>
</table>

Table 1. Main parameters of the induction machine

The system was started without load and with a fixed set of excitation capacitors and another set variable and imposed from the controller.

In Figure 9. is shown the shape of the frequency during the start-up phase. The controller acts in a way that the frequency reaches the steady state value in 1.5 s.

The performances are better on voltage. In fact, as is shown in Figure 10, the steady state value (220 V) is reached in only 0.5 s.

However, during the self excitation phase, the generator fed the active power that is necessary to cover the power losses in the windings.

After 3.5s a load step, of about 4,5 kW, has been applied. As shown in Figure 11 and 12, frequency and voltage decrease ($\Delta f \approx 3\%$, $\Delta V \approx 7\%$). The results are very good, in fact the undershoots are very low.
In Figure 13 is shown the power generated from the machine. The steady state value is equal to the one demanded from the load.

5. Conclusion

The problematic concerning the generation of electric power by an induction machine on a passive network is analyzed in this paper. It was shown that the two control variables have a coupling effect on the voltage and on the frequency steady state values. To solve this problem a Fuzzy controller has been designed. The FIS take in account of the relationship between the capacitor and the mechanical torque and act the values when a variation in voltage and frequency occurs.

The simulation results show that the controller is able to manage the start up phase in order to establish the self excitation in the windings of the induction machine. After a very short transient steady state condition ($V = 220 \text{[V]}, f = 50 \text{[Hz]}$) are reached. The system is able to reach the right steady state condition also after a load step of 4.5 kW without undershoots and with a very short transient.

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References


