A Fuzzy Control Scheme for Integration of DGs into a Microgrid

Christina N. Papadimitriou \(^1\), Nicholas A. Vovos \(^2\)

\(^1\)Electrical and Computer Engineering Department, University of Patras
\(^2\)26500 Rion, Patras, GREECE

\(^1\)chpapad@upatras.gr
\(^2\)n.a.vovos@ece.upatras.gr

Abstract—In order to integrate different distributed generations (DGs) into a microgrid connected to a weak distribution grid, this paper proposes local controllers based in fuzzy logic. The integration of the DGs is achieved through the «plug and play» procedure. The understudy microgrid includes an hybrid fuel cell-battery system and a Doubly Fed Induction Generator (DFIG). Through the proposed controllers the DGs provide primary frequency control and local bus voltage support to the local grid in both cases either the microgrid operates in islanded mode or in connected mode when local disturbances occur. Using MATLAB/Simulink software the response of the system is recorded when the microgrid from the connected mode is transferred to the islanded operation and the system presents a good performance.

I. INTRODUCTION

Power Systems, at the past, mainly consisted of large generation plants supplying distant loads through the utility grids. A number of factors, though, the last years lead this structure to change gradually. Small generators of some MW have already dispersed (DG) throughout the transmission grid. The new concept is the distribution of smaller units throughout the distribution system as near as possible to the consumer loads.

The DGs have to change from passive appendage to primary energy supply remaining connected to the grid and offering ancillary services. Under this operation philosophy DGs must support grid for local disturbances, as central generation station support high voltage systems in the transient period. This can be achieved through the control of the DGs electronic interface to the main grid and the energy storage devices. These controllable DGs (<100kWe) connected to the distribution grid, the energy storage devices and the local loads comprise the concept of a microgrid. In other words, the microgrid can be seen as a miniature of a large interconnected grid that can provide the demanded power and can also change from interconnected to islanded mode of operation [1]. The microgrid concept is the effective solution for the control of grids with high level of DG penetration [2].

The control of the microgrid has to be reliable, flexible and according to system specifications. The DGs of the microgrid have to cooperate in order to cover the local load needs for active and reactive power either under local disturbances or under islanding operation mode. The first layer controller of the DGs is a peer- to- peer controller [3] based on local information. This way, any DG can be integrated into the microgrid operating in «plug and play» mode [4].

In former studies the usual peer-to-peer controller of the DGs converters uses the power vs. frequency droop characteristics in order to produce the active and reactive reference combined with classical PI controllers as it is mentioned in the review of state-of-the-art controllers in [3].

In [5] the classical active power regulation takes into account the phase-locked loop (PLL) dynamics in order that minor oscillations happen when a transitioning between grid and autonomous operation takes place. In [2] the primary, secondary and tertiary control algorithms are designed and tested in an experimental setup. The local controller uses the classical droop equation while the secondary and tertiary controllers aim at power quality and economic optimization respectively. For the latter, the converters of the DGs communicate via the Internet. In [4] the classical control is applied giving emphasis to the storage device algorithm in order that all microsources have unified dynamic performance. In [6] the classical local controller applied to the converters of a DFIG is combined with a pitch controller for a better dynamic response of a microgrid at the mean voltage side. In [7], the active power regulation is achieved through the classical controller combined with a frequency restoration strategy while three different strategies for reactive power regulation are adopted. The microgrid dynamic behavior and the parameters of the DGs are mathematically investigated.

The droop equation combined with classical control can lead, under certain operational conditions, the microgrid to instability while the stability enhancement for these cases needs sophisticated calculations [8]. In addition, the non-linearity of the microgrid makes the implementation of fuzzy logic controllers at the DGs converters an attractive proposal. Moreover, fuzzy logic enforce the «plug and play» operation for the DGs as the needed adjustments are minor due to the flexibility of fuzzy logic and easier due to the linguistic variables used.

This paper proposes a fuzzy based local controller for the DGs forming a microgrid integrated into a weak distribution grid. The understudy microgrid is simulated with MATLAB/Simulink software considering a real microgrid as it is described in [3]. The microgrid includes an hybrid fuel cell-battery system and a Doubly-Fed Induction Generator (DFIG). The microgrid response is recorded when a
transitioning from interconnected mode to islanding operating mode occurs.

In the following section the microgrid architecture is analyzed and the models of the DGs are presented. In the third section the designed controller is analyzed. In the fourth section the simulation results are presented and the last section concludes the paper.

II. ARCHITECTURE OF THE MICROGRID

The microgrid concept was put forward in 2001. Since then several microgrids with multi-energy generators (MGMEG) and storages have been built in labs in universities and institutes all over the world [3]. The majority of the DGs are connected to the microgrid via electronic converters e.g. voltage source inverters (VSI). The structure of the simulated microgrid resembles those developed in labs and includes two different microsources. The hybrid fuel cell-battery system is connected to the ac feeder via a VSI and the DFIG connected directly to the feeder. In both DGs the «peer-to-peer» controller is based on fuzzy logic and the VSI local controllers are designed in «plug and play» operation mode. The «peer-to-peer» controllers imply that through the electronic interface, the DGs can provide the local grid with the demanded active and reactive power in absence of a central controller and communication links among microsources. The «plug and play» operation mode implies that a microsource can be added to the microgrid without reengineering the control and protection of units that are already part of the system. It is expected that in steady state a microgrid central controller should coordinate DG to optimize operation minimizing active power losses and maintaining flat voltage profile. The structure of the understudy microgrid is presented in Fig. 1 and the data are given in the appendix.

A. Description and Modelling of the Hybrid System

The configuration of the dc-side for the hybrid system is shown in Fig. 2.

The hybrid system of this study is consisted of a proton exchange membrane type (PEM) fuel cell system (FCS) and a battery bank. The adopted mathematical model of the FCS is fitted to this paper requirements. The FCS includes the following four main flow systems that are responsible for four main transient phenomena:

1. Hydrogen supply system to the anode
2. Air supply system to the cathode
3. De-ionized water as a coolant
4. De-ionized water to the humidifier to humidify the membrane.

It is assumed in our study that for the first flow system a compressed hydrogen tank is available and that the hydrogen flow in the anode is adjusted according to the air flow in the cathode through a valve. For the second flow system, the “Chopper 2” (Fig. 2) controls the supplied dc power to a dc motor that drives a compressor which controls the air flow in the cathode. Therefore the rate of change of the power at the output of the FCS is limited by the overall inertia of the compressor and the motor. In our case, the study period of the system lasts for a few seconds. So, for the third subsystem it is assumed that the temperature of the fuel cell stack remains constant (80°C) as the thermal dynamics are very slow with a time constant of about 10^2 sec. About the fourth system, it is assumed that the membrane of the model is fully humidified as the membrane hydration has a transient phase of about 10 sec. It has to be mentioned, that the air flow dynamics and the humidity management define the FCS response. By assuming that the membrane is fully humidified, the designed controller for the second subsystem can be safely decoupled from the humidity. Also, the “double-layer charging effect” has been neglected taking into account that its time constant is almost 10^-19 seconds. The FCS is designed to be self-powered meaning that every auxiliary components of the FCS must be supplied by the FCS power and this is especially applied for the air supply system. At the output of the FCS, the “Chopper 1” is connected so that the dc voltage is boosted and to regulate the FCS’s output, without exceeding the FCS
The battery bank is connected in order to support the dc voltage, to keep its deviations into certain limits and to support FCS’s performance under fast load changes as FCS dynamics are slow.

Since the FCS has low dynamic response, the battery is covering the fast load changes and the FCS oxygen starvation is avoided. In addition, when our system reaches steady-state, the battery current is forced to zero in order that the FCS supplies the whole demanded power. Battery also supports dc voltage as it keeps the dc voltage deviations into certain limits.

The model of the battery used in the study is adopted from the MATLAB software package (SimPowerSystems library) and is parameterized according to the system requirements. The battery is modeled using a controlled voltage source in series with a constant resistance.

The hybrid system already described interfaces with the ac-side system through a voltage source inverter (VSI) in order to achieve the independent control of the active and reactive power. An L-C filter is located at the VSI output followed by a step-up transformer. The transformer is connected to the ac feeder of the weak distribution grid.

B. DFIG Description and Modelling

The Doubly Fed Induction Generator system can independently provide voltage and frequency regulation capabilities via the rotor current control. The basic configuration of the DFIG system is presented in Fig. 3. The main parts of the system are: The wind turbine model, the model of the inverters and the induction generator model.

The mathematical equations of the wind turbine model are given below.

The power obtained from a given wind speed is expressed by the following equation:

\[ P_w = 0.5 \rho \pi R^2 v^3 C_p (\lambda, \beta) \]  

with \( \rho \) being the air density, \( R \) the effective area covered by the turbine blades, \( v \) the mean value of the wind speed at the height of the rotor axis, \( C_p \) the power coefficient of the wind turbine and \( \beta \) the pitch angle.

The tip speed ratio is defined as

\[ \lambda = \omega_w R/v \]  

The mechanical torque is defined as

\[ T_w = P_w/\omega_w \]  

with \( \omega_w \) being the wind turbine rotor speed.

The coefficient \( C_p \) is defined as:

\[ C_p = c_1 \left( \frac{c_2}{\lambda} - c_3 \lambda - c_4 \right) e^{-c_5/\lambda} + c_6 \lambda \]  

The coefficient values are given in the appendix.

The model of the converters is the analytical model for voltage source converters given in the software package MATLAB (SimPowerSystems library). The wound induction generator model and its parameters were adopted by the same library, too.

III. FUZZY CONTROLLER ANALYSIS

As briefly mentioned in the introduction, the local controllers are based in fuzzy logic due to its flexibility and adaptiveness and to the non-linearity of the system. The fuzzy controllers are non linear in nature and it is expected to have a robust performance under disturbances. Analytically, the four main flow subsystems that briefly mentioned in the previous section and the auxiliary subsystems that are beyond this paper scope to be mentioned, establish a non linear FCS. In addition, the presence of non linear and cross-coupling terms of the DFIG dynamics form a microgrid intensively non linear.

Some key points of great significance for the system efficiency and performance outlined below enhance the application of a fuzzy based intelligent control. As far as for the hybrid system, it is significant for the compressor motor controller (“Chopper 2”) to have a good dynamic response during fast load changes so that the FCS voltage does not drop dramatically leading to oxygen starvation. Secondly, the “Chopper 1” controller has to act simultaneously with the fuel flow control achieving stability and accuracy while minimizing overshooting and current rippling. The VSI controllers of the DFIG and of the hybrid system have to meet the same requirements too. The design of the fuzzy controllers does not require a precise mathematical modeling or sophisticated computations that in many cases lack efficiency and good performance. The latter remark makes fuzzy logic suitable and practical in real systems where the engineer tunes the local controller easier via the linguistic variables (easy engineering).

A. Hybrid System Controller

The local controller of the hybrid system consists of five different fuzzy local controllers. The fuzzy controllers (Fc) are designed from a heuristic knowledge of the system. Of course, they are thoroughly iterated by system simulation study in order to be fine tuned. The advantage of this method is the fast
convergence as it provides adaptively decreasing step size in the search of the adequate output. The analytical description of the controllers has been done in a former study of ours [9]. The already designed controller didn’t change in order that the hybrid system becomes integrated into the microgrid but some membership functions (MF) of the controllers were tuned for good response enhancement. In this study, the controllers are described briefly.

1) “Chopper 1” control: As already mentioned, the battery bank supports the FCS when fast transient phenomena occur as the FCS has slow dynamics and certain technical limitations. In steady state, the FCS of the study has to provide itself the whole demanded power and the battery bank supplying current has to be zero. The Chopper1 control includes the Fc 1 and 2. The Fc2 ensures through the duty cycle of “Chopper 1” that the FCS provides the demanded power by the ac-side and the demanded power by the dc-side converter (Crotor) and the pitch control (Fig.4). In this study, the pitch control is not applicable as the wind speed is certain wind speed. In this study, the droop equation has been incorporated into the active power controller and the generator speed can be different from its optimum value. This way the electronics rating remains low. Moreover, limiters are placed in order that the currents don’t exceed the electronics limitations.

2) “Chopper 2” control: The Fc3 constitutes the Chopper 2 control and determines through its duty ratio the power that the dc-motor absorbs and therefore regulates the air flow supplied by the compressor to the FCS. According to the pressure variation of the supplied air, the supplied hydrogen from the hydrogen tank is regulated through a valve and this regulates the output power of the FCS according to the demanded power by the system without oxygen starvation. In our study, the hydrogen flow is regulated to the oxygen flow through a simple PI controller. The indication of an oxygen starvation is the excess oxygen ratio λO2 which is the ratio of oxygen supplied to oxygen used in the cathode. The optimum value of λO2 is taken equal to 2 where for our chosen FCS the net deliverable power is about maximum.

3) VSI control: The VSI control consists of the Fc4 and Fc5. The controllers 4 and 5 ensure through the IGBT’s switching of the VSI that the hybrid system provides a part of the demanded active and reactive power by the ac side when a local disturbance occur or after the distribution grid is disconnected. After simulation tests in our system, the dependency of the voltage magnitude from the active power was found stronger than this from the reactive power. This happens as the distribution grid of our study is weak and has a low short circuit ratio and the distribution lines has a low X/R ratio 0.5. The control of the active power is achieved through the modulation index (m) of the PWM method. The value of m is determined by the Fc4. The control of the reactive power is achieved through the shift of the phase angle of the sinusoidal reference signal of the PWM method. The Fc5 determines the shift value.

B. DFIG System Controller

The DFIG controller consists of the control applied to the grid-side converter (Cgrid), the control applied to the rotor-side converter (Crotor) and the pitch control (Fig.4). In this study, the pitch control is not applicable as the wind speed is assumed to be lower than the predefined limit (18m/s). So, the angle of the pitches remains the same during the simulation study.

1) Cgrid control: This control regulates the independent exchange of active and reactive power between the converter and the local grid. This controller focuses on regulating the dc-link voltage. The applied vector control is based on a synchronously rotating, grid-flux oriented d-q reference frame. Meaning that the d-axis is aligned with the grid voltage and the q component is zero. The d component of the converter current regulates the dc-link voltage and the q component of the converter current regulates the reactive power. The control configuration is shown in Fig. 4. The Vdc,ref signal is the reference value for the dc-link voltage and the Vdc,meas signal is the measured dc-link voltage. The deviation of the measured voltage from the reference value drives the Fc1a.

The reference value of the d component of the output current (from the grid side) is the Fc1a output. The deviation of the measured voltage from the reference value drives the Fc2a, whose output is the control signal Vgd. The reference value of the q component of the output current, Iqgref is zero. The deviation of the measured signal from the reference value drives the Fc2a and its output is the control signal Vqq. The reactive power regulation through the Crotor is preferred in order that the electronics rating remains low. Moreover, limiters are placed in order that the currents don’t exceed the electronics limitations.

2) Crotor control: This control regulates independently the active and reactive power of the stator. The applied vector control is based on a synchronously rotating, stator-flux oriented d-q reference frame. Meaning that the d-axis is aligned with the vector of the stator magnetic flux and the q axis is zero. The active power is regulated via the q component of the rotor current and the reactive power via the d component. The control configuration is shown in Fig.5.

The usual control determines the reference value of the power so that the generator speed has its optimum value for certain wind speed. In this study, the droop equation has been incorporated into the active power controller and the generator speed can be different from its optimum value. This way the DFIG can instantly supply with power the local grid in case of necessity by losing speed. The active power deviations ΔP is expressed by the following droop equation:

\[ \Delta P = -k \Delta \omega \]  (5)
with $k$ being the droop coefficient and $\Delta \omega$ the deviations of the frequency measured at the output of the DFIG from its nominal value.

$$\Delta \omega = k \Delta P$$

The power deviations are added to the initial active power production of the DFIG $P_o$, forming the reference value for active power $P_{ref}$. The deviation of the measured active power at the DFIG output $P_{meas}$ from its reference value is driven to $F_{c3a}$, whose output is the $q$ component of the reference value of the rotor current, $I_{qrref}$. The reference value is compared to the measured $q$ component of the rotor current and drives the $F_{c5a}$, whose output is the control signal $V_{rq}$. The reference value of the voltage is compared to the measured voltage at the generator output and drives the $F_{c4a}$, whose output is the $d$ component of the reference value of the rotor current $I_{drref}$. The deviation of the measured $d$ component of the rotor current from the reference value drives the $F_{c5a}$ whose output is the control signal $V_{rd}$.

This paragraph refers to the design of the $F_{c3a}$ and it is indicative for all the $F_c$ controllers that were designed in this study. So, the fuzzy variables of the input of the $F_{c3a}$ are expressed by the following linguistic variables: “positive (POS)”, “zero (OK)”,”negative (NEG)”. The fuzzy variables of the output are expressed by the following linguistic variables: “high positive (POS_H)”, “medium positive (POS_M)”, “low positive (POS_L)”, “high negative (NEG_H)”, “medium negative (NEG_M)”, “low negative (NEG_L)”. The rules of the $F_{c3a}$ are shown in TABLE I and their membership functions are shown in Figs. 6-7.

IV. SIMULATION RESULTS

The data for the microgrid are given in the appendix. In steady state the microgrid is interconnected with the distribution grid. The 23% of the active power and the almost 100% of the reactive power of the loads is fed by the distribution grid. The DFIG feeds almost the 66% of the demanded active power and the hybrid system feeds the rest 11%. The DGs don’t feed the loads with reactive power during the interconnected mode of operation. The R-L loads absorb their nominal active and reactive power and the induction motor operates at a slip of 2% and absorbs 10kW and 3kVar. At 0.5 sec, the microgrid is disconnected and the DGs are forced to cover the loads needs. In new steady state, the hybrid system feeds the 14% of the active power that the distribution grid fed previously and the DFIG feeds the rest 86%. The DFIG feeds the 85% of the demanded reactive power and the rest 15% is fed by the hybrid system.

### TABLE I

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>POS</td>
<td>(POS_H)</td>
</tr>
<tr>
<td>POS</td>
<td>(POS_M)</td>
</tr>
<tr>
<td>POS</td>
<td>(POS_L)</td>
</tr>
<tr>
<td>OK</td>
<td>(OK)</td>
</tr>
<tr>
<td>NEG</td>
<td>(NEG_L)</td>
</tr>
<tr>
<td>NEG</td>
<td>(NEG_M)</td>
</tr>
<tr>
<td>NEG</td>
<td>(NEG_H)</td>
</tr>
</tbody>
</table>

It has to be mentioned that the kinetic energy stored in WT inertia gives the turbine the possibility to support primary frequency control for a short period. This means that the DFIG is capable of delivering for some sec power greater than the optimum (maximum) power extracted from the wind, as seen in the results below. However, the DFIG has to return eventually in optimum power absorption scenario and the FCS has to deliver the excess power in steady state. The latter is beyond of this paper scope to be shown. In a further study the proposed controller should be combined with the classical optimum power absorption controller. This way, during the transient period the inertia of the machine is exploited via the proposed controller and in steady state the classical optimum power absorption mode is restored. Some representative results are shown below.

In Figs. 8 and 9, at 0.5 sec, the voltage and the frequency drop about 10% and 1% respectively, due to the unbalance of active and reactive powers in the system and return to their nominal values after some oscillations within 0.5 sec. Both, frequency and voltage are recorded at the point of common coupling (PCC) where microgrid is interconnected with the distribution grid. In Fig.10 the battery bank current increases rapidly in order to supply the demanded power and returns to zero within 1 sec. The FCS power is shown in Fig.11. It has to be remarked that the FCS cover the dc motor power needs, too. In Fig. 12 the DFIG active power is presented. It is shown, that the DFIG response rapidly to cover the load needs because of speed loss of its rotor. In Fig.13 the DFIG reactive power is presented.
V. CONCLUSION

This paper proposes a local controller based in fuzzy logic for the integration of DGs into a microgrid according to the «plug and play» operation mode. The designed controller is evaluated during the transitioning from interconnected mode to islanding mode of operation either because of a fault at the mean voltage side or because of an intentional disconnection e.g. maintenance work. The simulation results prove that DGs can provide voltage and frequency support at the distribution grid. The system response was analysed and revealed good performance. The proposed local controller can be complemented with a microgrid central controller in order to optimize the system performance at steady state.

APPENDIX

c1 = 0.5176, c2 = 116, c3 = 0.4, c4 = 5, c5 = 21 & c6 = 0.0068.

FCS PEM: 30 kW, 200 cells, 200A, 150V, 280cm²/cell.

DFIG & turbine: The electric models parameters were adopted from SimPowerSystems library for a 100Hp induction generator and the corresponding wind turbine.

Distribution lines: AAAC type (4*185), X(Ω/km)=0.236, R(Ω/km)=0.204

AC system: 380 V, 50 Hz, base p.u.:100 kW, 380 V.

R-L load1: 35kW, 13kVar, 380 V

R-L load2: 36kW, 10kVar, 380 V

Squirrel- Cage Induction Motor: 20hp, 400 V, 50 Hz, 1460 rpm

DC Motor: 5 hp, 500 V, 1750 rpm, field: 300 V

Battery Bank: 234 HV Nickel-Metal Hybride cells of 1.2 V, 2 Ah, 280 V.

Transformer: 50kVA, 190:380 V, 50 Hz.

REFERENCES


