Interconnection of a Fuel Cell to the power grid

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Abstract

The concepts of microgrid and islanding operation imply the use of control methods in order to maintain the voltage and frequency levels within acceptable limits. This is obtained using inverters with a conventional droop-control method which has the ability to operate in parallel with the utility grid or islanded. As this type of systems is usually fed by batteries, the use of controllable loads and controllable power sources are indispensable to maintain the energetic balance of the microgrid. In this paper, a Proton Exchange Membrane (PEM) fuel cell model and the converters needed to connect it to the utility grid are described and simulated. A 3 phase voltage source inverter with a droop-control method is also described, in which a voltage control with an internal current control to protect against overcurrent is proposed. Finally, a microgrid operation is simulated. Voltage amplitude and frequency behavior, when islanding and reconnecting the microgrid with the MV grid, are also evaluated.

Keywords: Fuel-cell, hydrogen, microgrid, VSI, islanded network.

I. Introduction

MICROGRIDS are low voltages distribution systems with distributed low power generation, storage devices and controllable loads that can work connected to the MV distribution grid or in island mode.

The most common microgeneration systems used in microgrids are photovoltaic panels, fuel cells, variable speed wind turbines, microturbines and energy storage devices like batteries and flywheels. Most of these systems are connected to the ac system with inverters. Therefore, the lack of inertia systems in the microgrid makes it difficult to maintain the frequency within acceptable values [13].

In order to allow the microgrid to work in island mode, two conditions are needed:

1. Power generation and loads must be balanced;
2. Microgeneration dynamics must maintain the microgrid synchronism after entering island mode as well as keep voltage amplitude and frequency within acceptable values.

Inverters with droop-control method emulate the behavior of a synchronous generator with inertia, allowing the second condition above to be achieved. These are called voltage source inverters. However, the parallel connection of voltage source inverters is sensitive to voltage and frequency variations of the utility grid, and can be damaged by overcurrent.

In order to keep the power generation and loads balanced, controllable power sources are needed.

In this paper, a fuel cell, being one of the most clean and efficient technologies to produce electricity, is studied as a controllable power source.

From the fuel cell models developed in [7,15], an air compressor model is developed and the cathode channel dynamic is enhanced, taking on account the main three gases that constitute the air: $O_2$, $N_2$ and $H_2O$. Energy consumption associated with the air compressor and the refrigeration fan is integrated within this model. Energy consumed by these devices is supplied by the fuel cell itself, and interferes with the output voltage dynamic behavior.

New simulation models are developed, enabling the simulation of inverters and inverter’s controls that convert DC voltage generated by the fuel cell into AC, thus enabling the connection of the microgenerator to the grid.

Furthermore, a power control model and a Voltage Source Inverter are developed, the latter using the droop method, and a microgrid operation is simulated. Voltage and frequency behavior, when islanding and reconnecting the microgrid with the MV grid, are also evaluated.

Considering the low value for the power supplied by the fuel cell, its inverters are designed and studied considering a single phase connection (monophasic). The VSI, which is three-phasic, is dimensioned considering the same fuel cell power per phase.

II. PEM Fuel Cell Model Development

A PEM fuel cell stack is constituted by several cells connected in series. Each cell has two electrodes, the anode (negative electrode) and the cathode (positive electrode). The anode is continuously fed by a reagent
(hydrogen) and the cathode by an oxidant (oxygen from the air). The equation (1) describes the reaction that takes place inside the fuel cell.

$$2H_2 + O_2 \rightarrow 2H_2O + \text{heat} + \text{electric energy}$$ (1)

In the anode, each molecule of hydrogen ($H_2$) is divided in two electrons ($e^-$) and two protons ($H^+$) with the help of a catalyst, a noble metal like platinum.

$$H_2 \rightarrow 2H^+ + 2e^-$$ (2)

While the protons are conducted through an electrolyte membrane, the electrons are forced to travel around an electric circuit, thus generating electric current. In the cathode, the electrons and protons are recombined with the oxygen ($O_2$), forming water molecules ($H_2O$) [9].

$$2H^+ + 2e^- + \frac{1}{2}O_2 \rightarrow H_2O + \text{heat}$$ (3)

The output voltage of a single cell can be defined as the voltage produced by the chemical reaction, denominated by open circuit potential or thermodynamic potential ($E_{nernst}$), minus the voltage drop related to internal losses. These voltage drops are due to the activation of the anode and the cathode ($V_{act}$), which have a dominant role in low current density; Ohmic voltage drop ($V_{ohm}$) due to the resistance of the collector plates and the electrodes to the passage of electrons and the resistance to the passage of the protons through the PEM electrolyte membrane; and voltage drop resulting from the decrease of pressure of the reacting gases inside the anode and cathode, when the current and thus the consumption of hydrogen and oxygen increases ($V_{conc}$), called concentration loss.

This last loss is related to the physical characteristics of the system, which input limits the maximum produced current. The maximum current allowed corresponds to the current produced when the air flow injected in the fuel cell reaches its maximum and all the oxygen is consumed in the reaction [4, 12].

As the physical characteristics are considered in this model, the pressure drop of the reagents are taken into account so the concentration voltage drop $V_{conc}$ is not considered in the equation.

$$V_{Cel} = E_{nernst} - V_{act} - V_{ohm}$$ (4)

$$V_{PC} = N \times V_{Cel}$$ (5)

The open circuit potential $E_{nernst}$ can by calculated using the modified Nernst equation:

$$E_{nernst} = -\frac{\Delta G^0}{2F} + \frac{\Delta S^0}{2F}(T - T_{ref}) + \frac{RT}{2F} \times \left(\ln \left(\frac{p_{H_2}}{p^0}\right) + \frac{1}{2} \ln \left(\frac{p_{O_2}}{p^0}\right) - \ln \left(\frac{p_{H_2O, ca}}{p_{H_2O}}\right)\right)$$ (6)

where

$\Delta G^0$ - Variation of standard Gibbs energy ($G^0_{H_2O} - G^0_{H_2} - 1/2G^0_{O_2}$) $\Delta S^0 = -237, 180 \text{ kJ/mol}$.

$\Delta S^0$ - Variation of standard entropy ($S^0_{H_2O} - S^0_{H_2} - 1/2S^0_{O_2}$) $\Delta S^0 = -163.135 \text{ kJ/kmol K}$.

$F$ - Faraday’s constant; $F = 96485 \text{ C/mol}$

$T_{ref}$ - Reference temperature; $T = 298 \text{ K}$

$T$ - Operating cell temperature; [°K]

$R$ - Universal gas constant; $R = 8.31447 \text{ J mol}^{-1} \text{K}^{-1}$

$p_{H_2}$ - Hydrogen partial pressure [atm].

$p_{O_2}$ - Oxygen partial pressure [atm].

$p^0$ - Reference pressure; $p^0 = 1 \text{ atm}$.

$p_{H_2O, ca}$ - Water vapor partial pressure in the cathode.

$p_{H_2O}$ - Water saturation pressure.

The water saturation pressure in standard atmosphere unit is related to the temperature in degree Celsius (°C) and can be calculated from (7).

$$p_{H_2O}^{sat} = 10^{-2.1794 + 0.029537 - 9.1837 \times 10^{-3} T^2 + 1.4454 \times 10^{-7} T^3}$$ (7)

The active voltage drop is calculated using an empirical method from [2], which is based on electrochemical, kinetics, and thermodynamic laws of the reaction on the electrodes.

$$V_{act} = -\left[\xi_1 + \xi_2 T + \xi_3 T \ln(CO_2) + \xi_4 T \ln(I_{cel})\right]$$ (8)

The parametric coefficients $\xi_1, \xi_2, \xi_3 \text{ e } \xi_4$ are calculated using a multiple linear regression model, based on experimental data from the fuel cell stack $Nexa^TM \ Power \ Module$ from BALLARD, with 1, 2kW nominal power.

$$\xi_1 = -1, 0347$$

$$\xi_2 = 6.9023 \times 10^{-3}$$

$$\xi_3 = 2.9536 \times 10^{-4}$$

$$\xi_4 = -1, 3316 \times 10^{-4}$$

The ohmic voltage drop can be calculated by the following equation:

$$V_{ohm} = (R_c + R_m) I_{cel}$$ (9)

where $R_c$ corresponds to the collectors plates and the electrodes resistance and $R_m$ to membrane resistance.

$$R_c = 0, 0003 \ \Omega$$ (10)

$$R_m = \rho_m \ T \ A$$ (11)

$l$ is the membrane thickness ($l = 183 \times 10^{-4} \ cm$) [10], $A$ is the membrane active area ($A = 74 \ cm^2$), $\rho_m$ is the membrane specific resistivity, which can be obtained by (12):

$$\rho_m = \frac{181.6 \left[1 + 0.03 \left(\frac{L}{A}\right) + 0.062 \left(\frac{L}{A}\right)^2\right]}{[1 - 0.634 - 3 \left(\frac{L}{A}\right)] \exp \left(4, 18 \left(\frac{T}{903}\right)\right)}$$ (12)
\( \lambda \) is a parameter related with the humidity of the membrane. In this model, it is used the value of \( \lambda = 23 \) [10].

The “charge double layer” phenomenon is also considered in this model. This phenomenon is responsible for the dynamic behavior of the fuel cell voltage, due to the first order delay on the activation voltage.

\[
\frac{dv_d}{dt} = \frac{1}{C} I_{cel} - \frac{1}{\tau} v_d
\]  

(13)

\( v_d \) represents the dynamic activation voltage, \( C \) is the equivalent electrical capacitance \( (C = 0, 54) \) which is obtained from experimental results, and \( \tau \) is the time constant associated to first order delay, that is obtained from (14):

\[
\tau = CR_a = C \frac{V_{act}}{I_{act}}
\]  

(14)

where \( R_a \) is the equivalent resistance and \( V_{act} \) is the activation voltage drop without the delay.

Considering the dynamic behavior, the voltage produced by one cell is given by:

\[
V_{Cel} = E_{nernst} - v_d - V_{ohm}
\]  

(15)

The figure 1 synthesizes the calculations to obtain the fuel cell stack voltage.

![Figure 1: Fuel cell voltage calculation model.](image)

The flow rates of the reactants and products are also evaluated in this model. The air compressor that feeds the cathode is simulated, considering the compressor inertia and the control system to keep the airflow aligned with its reference value. The behavior of the compressor considering these facts, has impact on the fuel cell response.

The compressor model used in this model is described on [14] and it is based on the thermodynamic principals.

\[
J_{cp} \frac{d\omega_{cp}}{dt} = \frac{1}{\omega_{cp}} (P_{cm} - P_{cp})
\]  

(16)

where \( J_{cp} \) is the inertia of the compressor \( (J_{cp} = 1, 6 \times 10^{-6} \text{ kg/m}^2) \); \( \omega_{cp} \) is the rotational speed; \( P_{cm} \) is the power delivered to the compressor; and \( P_{cp} \) is the compressor power load.

The compressor power load is calculated by (17):

\[
P_{cp} = -W_s = \frac{C_p T_{amb}}{\eta_{cp}} \left( \frac{p_{ca}}{p_{amb}} \right)^{\frac{\gamma}{\gamma - 1}} - 1 \dot{m}_{cp}
\]  

(17)

where:

- \( \gamma \) - heat capacity ratio of the air \( C_p/C_v; \gamma = 1, 40 \).
- \( C_p \) - air heat capacity at constant pressure; \( C_p = 1005 \text{ J/(kgK)} \).
- \( \eta_{cp} \) - compressor adiabatic efficiency; \( \eta_{cp} = 0, 80 \).
- \( p_{ca} \) - pressure inside the cathode [atm].
- \( p_{amb} \) - atmospheric pressure; \( p_{amb} = 1 \text{ atm} \).
- \( T_{amb} \) - ambient temperature; [°K].
- \( \dot{m}_{cp} \) - compressor mass air flow [kg/s].

The compressor mass air flow is determined through a compressor flow map described in [14], which is a function of the ratio between the pressure upstream and downstream and the rotational speed, \( \dot{m}_{cp}(p_{ca}/p_{atm}, \omega_{cp}) \).

A DC permanent magnet motor is considered to calculate the power delivered to the compressor.

\[
P_{cm} = \omega_{cp} \eta_{cm} \frac{k_m}{R_a} (v_{cm} - k_m \omega_{cp})
\]  

(18)

\( k_m = 2 \times 10^{-3} \text{ V/(rad/s)} \) is the torque constant of the motor and is a function of motor geometry and magnet properties, \( R_a = 150 \text{ mF} \) is the armature circuit resistance and \( \eta_{cm} = 0, 80 \) is the motor efficiency. This values are taken from [6] as typical values to this kind of motors. \( v_{cm} \) is the voltage applied to the motor, used to control the mass air flow according to its reference value. A PI controller is used to obtain the \( v_{cm} \) voltage:

\[
v_{cm} = K_p (m_{ref} - \dot{m}_{cp}) + K_i \int (m_{ref} - \dot{m}_{cp}) \]

(19)

where \( K_p = 2 \times 10^4 \) and \( K_i = 32 \times 10^4 \).

The reference mass air flow \( \dot{m}_{ar,ref} \) is given by a cubic equation, obtained by a basic fitting of experimental values.

\[
\dot{m}_{ar,ref} = 4, 4 \times 10^{-8} I_{PC}^3 - 3, 45 \times 10^{-6} I_{PC}^2 + 1, 05 \times 10^{-4} I_{PC} - 2, 03 \times 10^{-5} [\text{kg/s}]
\]  

(20)

The fuel cell potential depends on the partial pressures of hydrogen, oxygen and water vapor, which depend on the consumption rate of the reactants. Thus,
the mass air flow is studied in order to obtain the dynamic behavior of the fuel cell.

Using the principles of mass conservation, the mass air flow of each reactant is obtained for the cathode.

\[
\frac{dm_{O_2}}{dt} = \dot{\dot{m}}_{O_2,\text{in}} - \dot{m}_{O_2,\text{out}} - \dot{\dot{m}}_{O_2,\text{reac}} \tag{21}
\]

\[
\frac{dm_{N_2}}{dt} = \dot{\dot{m}}_{N_2,\text{in}} - \dot{m}_{N_2,\text{out}} \tag{22}
\]

\[
\frac{dm_{H_2O,\text{ca}}}{dt} = \dot{\dot{m}}_{H_2O,\text{in}} - \dot{m}_{H_2O,\text{out}} + \dot{\dot{m}}_{H_2O,\text{prod}} \tag{23}
\]

From the integration of the reactants mass variation inside the cathode, the partial pressure of each element can be derived, applying the ideal gas law:

\[ p_i = \frac{RT_{PC} m_i}{V_{ca} M_i} \tag{24} \]

where \( i \) indicates the element; \( V_{ca} = 3,3 \times 10^{-4} \) \( m^2 \) is the cathode channel volume; \( R \) is the gas constant; \( T_{PC} \) is the temperature of the fuel cell and the gas elements; \( m_i \) is mass of each element inside the cathode channel; and \( M_i \) is the molar mass of each element.

The partial pressure of hydrogen inside the anode channel can be considered equal to the total pressure, since the input mass flow is 99% pure hydrogen. According to [14], the valve control responsible to keep constant the pressure inside the anode channel has a very fast response, so it can be considered always constant: \( p_{H_2} = 1,35 \) \( atm \).

Combining the Faraday’s law with the relation between electric charge and current, the reactants consumption and product production mass flows can be calculated.

\[
\dot{\dot{m}}_{O_2,\text{reac}} = \frac{M_{O_2}}{4F} N \tag{25}
\]

\[
\dot{\dot{m}}_{H_2O,\text{prod}} = \frac{M_{H_2O}}{2F} N \tag{26}
\]

\[
\dot{\dot{m}}_{H_2,\text{reac}} = \frac{M_{H_2}}{2F} N \tag{27}
\]

where \( N = 47 \) is the number of cells and \( F = 96485,3C/mol \) is the Faraday’s constant.

The input mass air flow from the compressor can be divided in each element mass air flow (oxygen, nitrogen and water), based on the relative humidity of the air \( HR_{\text{amb}} \) and the oxygen molar fraction \( x_{O_2} \).

First, the pressure of the air upstream the compressor is divided in dry air partial pressure and water vapor partial pressure.

\[
p_{\text{air}} = p_{\text{dry,air}} + HR_{\text{air}} p_{\text{H}_2O} (T_{\text{amb}}) \tag{28}
\]

where \( p_{\text{H}_2O} \) is the water saturation pressure.

From these partial pressures, the mass fraction of dry air and water vapor can be calculated. With the oxygen molar fraction, the mass fraction of oxygen and nitrogen of the dry air can be also evaluated.

\[
y_{\text{dry,air}} = \frac{p_{\text{dry,air}} M_{\text{dry,air}}}{p_{\text{dry,air}} M_{\text{dry,air}} + p_{\text{H}_2O} M_{\text{H}_2O}} \tag{29}
\]

\[
y_{O_2,\text{dry,air}} = \frac{x_{O_2} M_{O_2}}{x_{O_2} M_{O_2} + (1 - x_{O_2}) M_{N_2}} \tag{30}
\]

where \( M_{\text{dry,air}} = 28,850 \) \( g/mol \) is the molar mass of the dry air and is calculated by:

\[
M_{\text{dry,air}} = x_{O_2} M_{O_2} + (1 - x_{O_2}) M_{N_2} \tag{31}
\]

The input mass flow of each element \( O_2, N_2 \) and \( H_2O \) can be calculated from equations (32) (33) and (34).

\[
\dot{\dot{m}}_{O_2,\text{in}} = y_{O_2,\text{dry,air}} \dot{\dot{m}}_{\text{dry,air}} \tag{32}
\]

\[
\dot{\dot{m}}_{N_2,\text{in}} = (1 - y_{O_2,\text{dry,air}}) \dot{\dot{m}}_{\text{dry,air}} \tag{33}
\]

\[
\dot{\dot{m}}_{H_2O,\text{in}} = (1 - y_{\text{dry,air}}) \dot{\dot{m}}_{\text{cp}} \tag{34}
\]

The mass outlet flow, formed by water vapor and oxygen depleted air, can be considered proportional to the upstream and downstream pressure [14].

\[
\dot{\dot{m}}_{\text{ca,ou}} = k_{ca} (p_{\text{ca}} - p_{\text{amb}}) \tag{35}
\]

\[ k_{ca} = 1,34 \times 10^{-3} \text{kg}^{-1} \text{atm}^{-1} \] is a typical parameter of the outlet valve and is obtained from experimental values.

From the integration of the equations (21), (22) and (23), the mass fraction of each element inside the cathode is obtained. Therefore, the mass outlet flow of each element can be also derived from \( \dot{\dot{m}}_{\text{ca,ou}} \):

\[
\dot{\dot{m}}_{O_2,\text{out}} = \frac{m_{O_2}}{m_{O_2} + m_{N_2} + m_{H_2O,\text{ca}}} \dot{\dot{m}}_{\text{ca,ou}} \tag{36}
\]

\[
\dot{\dot{m}}_{N_2,\text{out}} = \frac{m_{N_2}}{m_{O_2} + m_{N_2} + m_{H_2O,\text{ca}}} \dot{\dot{m}}_{\text{ca,ou}} \tag{37}
\]

\[
\dot{\dot{m}}_{H_2O,\text{ca,ou}} = \frac{m_{H_2O,\text{ca}}}{m_{O_2} + m_{N_2} + m_{H_2O,\text{ca}}} \dot{\dot{m}}_{\text{ca,ou}} \tag{38}
\]

The temperature of the fuel cell stack, reactants and products is also obtained using a thermal model described in [15], based on the total power generated by the fuel cell stack, electrical power produced, heat dissipation from the fuel cell surface and heat dissipation by the cooling system.

\[
\dot{Q}_{\text{FC}} = P_{\text{total}} - P_{\text{el}} - \dot{Q}_{\text{surface}} - \dot{Q}_{\text{cooling}} \tag{39}
\]

\[
P_{\text{total}} = \frac{N I_{\text{FC}}}{2F} \Delta H \tag{40}
\]

\[
P_{\text{el}} = V_{\text{FC}} I_{\text{FC}} \tag{41}
\]

\[
\dot{Q}_{\text{surface}} = \frac{T_{\text{FC}} - T_{\text{amb}}}{R_{\text{i}}} \tag{42}
\]

\[
\dot{Q}_{\text{cooling}} = \dot{m}_{\text{airflow,max}} C_{p} \Delta T_{\text{max}} \text{FFV} \tag{43}
\]
\[
\Delta H = 241,820 \text{ J/mol}
\]

\[
R_t = 0.020 \text{ K/W}
\]

\[
\dot{m}_{\text{vent,max}} = 0.0747 \text{ kg/s}
\]

\[
C_p = 1005 \text{ J/} (\text{kgK})
\]

\[
\Delta T_{\text{max}} = 17^\circ \text{K}
\]

\[
FFV = \left(\%v_{\text{cool,max}}\right)^3
\]

\[
i_{\text{act}} = m_P \sin(\omega t)
\]

\[
i_{\text{reac}} = m_Q \sin(\omega t - \pi/2)
\]

\[
i_{\text{ref}} = i_{\text{act}} + i_{\text{reac}}
\]

\[
C_{\text{inv}} = 350 \mu F
\]

\[
L_{\text{chop}} = 110 \mu H
\]

\[
C_{\text{bat}} = 1 \mu F
\]

\[
k_{P_{\text{chop}}} = 0.916
\]

\[
k_{I_{\text{chop}}} = 141.17
\]

\[
k_{P_{\text{inv}}} = 0.97
\]

\[
k_{I_{\text{inv}}} = 78.4 \mu H
\]

\[
r_L = 12.0 \text{ m\Omega}
\]

\[
V_{\text{Link,ref}} = 24 V
\]

\[
f_{\text{req,chop}} = 20 \text{ kHz}
\]

\[
f_{\text{req,inv}} = 20 \text{ kHz}
\]

The low power of the fuel cell (1.2 kW), a single phase inverter is designed [1]. The connection is presented on figure 3.

A power source controller with a current source controller is designed to maintain the active and reactive power according to the reference values. As the voltage amplitude is imposed by the grid and can be considered constant, the active and reactive power are proportional to the amplitude of the in-phase current component and to the quadrature current component respectively, being called from now on as active and reactive currents.

A PLL is used to obtain a sinusoidal signal in phase with the voltage and another in quadrature. These signals are the base to set up the reference active and reactive currents. Two proportional and integral controllers are used to calculate the amplitude of each reference signal \( m_P \) and \( m_Q \), based on the measured and references active and reactive power difference.

In order to protect against over-currents and short-circuits, a limiter is used to limit the current between \(-15\) and \(15\) amperes.

The output of the proportional integral current controller \( PI_i \) is the input for the Pulse-Width Modulation (PWM) block, responsible to generate the control pulses for the single-phase IGBTs two-arm bridge. For the DC-DC chopper converter, a simple PI voltage controller is applied. The output of the PI controller is compared with a tooth saw shaped signal.

Figure 4 presents the block diagram of the proposed control and table 1 presents the values used for each variable.

<table>
<thead>
<tr>
<th>param.</th>
<th>value</th>
<th>param.</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C_{\text{in}})</td>
<td>350 (\mu F)</td>
<td>(k_{P_{\text{chop}}})</td>
<td>0.0023</td>
</tr>
<tr>
<td>(L_{\text{chop}})</td>
<td>110 (\mu H)</td>
<td>(k_{I_{\text{chop}}})</td>
<td>0.217</td>
</tr>
<tr>
<td>(C_{\text{bat}})</td>
<td>1 (\mu F)</td>
<td>(k_{P_{\text{inv}}})</td>
<td>0.0023</td>
</tr>
<tr>
<td>(k_{P_{\text{chop}}})</td>
<td>0.916</td>
<td>(k_{I_{\text{chop}}})</td>
<td>0.217</td>
</tr>
<tr>
<td>(k_{I_{\text{chop}}})</td>
<td>141.17</td>
<td>(k_{P_{\text{inv}}})</td>
<td>0.97</td>
</tr>
<tr>
<td>(L_{\text{inv}})</td>
<td>78.4 (\mu H)</td>
<td>(k_{I_{\text{inv}}})</td>
<td>2592.4</td>
</tr>
<tr>
<td>(r_L)</td>
<td>12.0 (m\Omega)</td>
<td>(V_{\text{Link,ref}})</td>
<td>24 V</td>
</tr>
<tr>
<td>(C)</td>
<td>0.7 (\mu F)</td>
<td>(f_{\text{req,chop}})</td>
<td>20 kHz</td>
</tr>
<tr>
<td>(n_2/n_1)</td>
<td>15</td>
<td>(f_{\text{req,inv}})</td>
<td>20 kHz</td>
</tr>
</tbody>
</table>

Figure 2: Cathode flow mass calculation model.
IV. VOLTAGE SOURCE INVERTER AND CONTROL DESIGN

A voltage source inverter (VSI) with a droop-control is also described in order to simulate a microgrid entering islanding mode and reconnecting again to the MV grid. It must have the ability to adjust its output voltage and frequency to the ac-distributed grid when the microgrid is connected to the MV grid and it must be able to maintain the output voltage and frequency between acceptable limits when the microgrid is islanded from the MV grid. [5,8]

The droop-control method consists in emulating the behavior of large power generators, which drop their frequencies when the power delivered increases. These adjustment over the output-voltage frequency and amplitude of the inverter allows the VSI to work in parallel with the ac-distributed system.

The relation between voltage frequency and amplitude between two nodes and the active and reactive power transited between them, depends on the type of line used. In high voltage the lines have a high inductive component. On the other hand, in low voltage the lines are mainly resistive, which changes the relation referred. Equations (49) and (50) presents these relations:

\[
P = \frac{U_{VSI}}{R_L^2 + X_L^2} [R_L (U_{VSI} - U_{grid} \cos \delta) + X_L U_{grid} \sin \delta]
\]

(49)

\[
Q = \frac{U_{VSI}}{R_L^2 + X_L^2} [-R_L U_{grid} \sin \delta + X_L (U_{VSI} - U_{grid} \cos \delta)]
\]

(50)

where \(R_L\) and \(X_L\) are the resistive and inductive components of the line and \(\delta\) is the power angle.

The power angle \(\delta\) is usually small. Thus, the simplifications \(\cos \delta \approx 1\) and \(\sin \delta \approx \delta\) can be considered in order to simplify the control design.

Assuming that in high voltage lines the resistance \(R_L\) can be despised and in low voltage lines the inductance \(X_L\) can be despised, equations (49) and (50) can be simplified:

- High voltage line

\[
P \approx \frac{U_{VSI} U_{grid} \delta}{X_L}
\]

(51)

\[
Q \approx \frac{U_{VSI}}{X_L} (U_{VSI} - U_{grid})
\]

(52)
Figure 6: Voltage droop characteristics used in this model.

Figure 7: VSI control block diagram.

- Low voltage line

\[ P \approx \frac{U_{VSI}}{R_L} (U_{VSI} - U_{grid}) \]  \hspace{1cm} (53)

\[ Q \approx -\frac{U_{VSI}U_{grid}}{R_L} \delta \] \hspace{1cm} (54)

These equations show that in high voltage the active power is related to the power angle \( \delta \) and the reactive power is related to the VSI and grid voltage difference \( (U_{VSI} - U_{grid}) \). In low voltage the opposite is verified.

Since in this paper a low voltage microgrid is studied, the relation for low voltage lines should be considered. However, a voltage control with an inner loop current control as shown in figure 8 alters these relations when referred to the reference voltage signal. Thus, the high voltage line equations can be used.

Table 2: Parameters of the Voltage Source Inverter.

<table>
<thead>
<tr>
<th>param.</th>
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</thead>
<tbody>
<tr>
<td>( U )</td>
<td>750 V</td>
<td>( k_{ff} )</td>
<td>( 3 \times 10^{-4} ) radW (^{-1} )</td>
</tr>
<tr>
<td>( L )</td>
<td>12 mH</td>
<td>( k_{P_i} )</td>
<td>0.007</td>
</tr>
<tr>
<td>( C )</td>
<td>0.7 ( \mu )F</td>
<td>( k_{I_i} )</td>
<td>226.8</td>
</tr>
<tr>
<td>( f_N \equiv f_0 )</td>
<td>50 Hz</td>
<td>( k_P )</td>
<td>0.64</td>
</tr>
<tr>
<td>( V_N \equiv V_0 )</td>
<td>230 V</td>
<td>( k_{I_i} )</td>
<td>2421.33</td>
</tr>
<tr>
<td>( T_P \equiv T_Q )</td>
<td>0.1 sec</td>
<td>( f_{inv} )</td>
<td>20 kHz</td>
</tr>
</tbody>
</table>

The voltage droop characteristics used in this model are described by equations (55) and (56):

\[ f = f_0 - k_P P \] \hspace{1cm} (55)

\[ V = V_0 - k_Q Q \] \hspace{1cm} (56)

where \( k_P \) e \( k_Q \) are given by:

\[ k_P = \frac{0.01 \times f_N}{P_N} \] \hspace{1cm} (57)

\[ k_Q = \frac{0.04 \times V_N}{Q_N} \] \hspace{1cm} (58)

Figure 6 presents the relation between active and reactive power and voltage frequency and amplitude.

The voltage reference signal for each phase is obtained from the droop control as shown in figure 7. For each phase, a proportional and integral control compares the voltage reference signal \( v_{i_{ref}} \) with the real single phase voltage \( v_i \) (where index \( i \) identifies each phase). The output of the PI controller is the reference current that is imposed to the inverter.

Figure 8: Voltage control with current inner-loop control.
V. Simulation Results

MATLAB®-SIMULINK [11] was used to simulate the fuel cell model and the connection to the utility grid with the inverter described. Characteristics of the fuel cell like the polarization curve and the influence of temperature are presented in figures 9 and 10.

Figure 9: Fuel cell polarization curve.

Figure 10: Simulated fuel cell voltage, current and temperature compared with experimental results when the fuel cell is subjected to load varying.

Figure 11: Fuel cell voltage and current when connected to an AC system. Power load varying from no load to half load and nominal load.

The behavior of the fuel cell when connected to an AC system is also presented on figure 11, for different values of power load. Since the low pass filters from the DC-DC chopper converter and inverter have cut frequencies nearby or above 50Hz, the current from the fuel cell has a variation of 100Hz as the instantaneous power provided by the inverter.

A very simple microgrid scheme presented on figure 12 is simulated and the results are analyzed. The reliability of the microgrid when entering islanding mode is tested, including the fuel cell as a controlled power source and the behavior of the VSI to maintain the voltage amplitude and frequency in acceptable values. The line parameters used in the simulated microgrid are shown in table 3.

Figure 12: Simulated microgrid scheme.

Table 3: Line parameters.

<table>
<thead>
<tr>
<th>Line</th>
<th>resistance</th>
<th>reactance</th>
<th>R/X</th>
</tr>
</thead>
<tbody>
<tr>
<td>(L_1)</td>
<td>0.080Ω</td>
<td>0.013Ω</td>
<td>5.1</td>
</tr>
<tr>
<td>(L_{2A})</td>
<td>0.036Ω</td>
<td>0.003Ω</td>
<td>13.1</td>
</tr>
<tr>
<td>(L_{2B})</td>
<td>0.048Ω</td>
<td>0.004Ω</td>
<td>13.1</td>
</tr>
<tr>
<td>(L_{2C})</td>
<td>0.060Ω</td>
<td>0.005Ω</td>
<td>13.1</td>
</tr>
</tbody>
</table>

In table 4 the schedule of events are described. Simulation results are presented on figures 13, 14, 15, 16, 17, 18, 19, 20, 21 and 22.

Table 4: Schedule of events in the simulation.

<table>
<thead>
<tr>
<th>Time</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 sec</td>
<td>Start - VSI: (V_0 = 230) V &amp; (f_0 = 50) Hz; Util. grid: (V_{grid} = 400/230) V &amp; (f_{grid} = 50) Hz; Loads: (C_{1,2,3} = 3 \times 750) W; Fuel Cells: (P_{ref} = 0) W &amp; (Q_{ref} = 0) var.</td>
</tr>
<tr>
<td>1 sec</td>
<td>Fuel Cells: (P_{ref} = 3 \times 1000) W</td>
</tr>
<tr>
<td>2 sec</td>
<td>Loads: (C_{1,2,3} = 3 \times 1500) W</td>
</tr>
<tr>
<td>3 sec</td>
<td>(D_1) is opened - Starting islanding mode.</td>
</tr>
<tr>
<td>4 sec</td>
<td>Loads: (C_{1,2,3} = 3 \times 750) W</td>
</tr>
<tr>
<td>5 sec</td>
<td>Fuel Cells: (P_{ref} = 750) W</td>
</tr>
<tr>
<td>6 sec</td>
<td>(D_1) is closed - Reconnection to the Util. grid: (V_{grid} = 1) pu &amp; (f_{grid} = 49.9) Hz</td>
</tr>
<tr>
<td>7 sec</td>
<td>Simulation end</td>
</tr>
</tbody>
</table>
Figure 13: Frequency

Figure 14: Utility grid power.

Figure 15: VSI Power

Figure 16: VSI Voltage.

Figure 17: VSI current.

Figure 18: Voltage.

Figure 19: Fuel Cells power

Figure 20: Load Power.

Figure 21: Fuel Cells Current.

Figure 22: Utility grid current.
VI. Conclusions

A complete mathematical model of a PEM fuel cell including auxiliary systems as the air compressor and cooling fan is proposed. A DC-DC chopper converter and an inverter are dimensioned and a control is designed in order to connect the fuel cell as a power source to a microgrid. To allow the microgrid to work either connected to the MV grid or islanded, a voltage source inverter based on a droop control method is developed.

The model developed for the fuel cell presents similar response as the real one studied, Nexa™ Power Module from BALLARD, in static and dynamic behaviors.

Simulation results from the microgrid show that the fuel cell can be used as a controllable power source, and working together with a VSI allows a microgrid to work in island mode within acceptable values of voltage frequency and amplitude. Besides, the drop-control method allows the VSI to work connected to the utility grid or in parallel with other VSI, adjusting its reference voltage signal to the voltage imposed by the MV grid.

References


