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Dynamic Behavior of an Hybrid Wind – Fuel Cell Generation System: Active and Reactive Power Control

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Abstract. This paper reports the investigation on a detailed model of a real wind farm together with a fuel cell generation system based on hydrogen. The modeled wind farm is made up of squirrel cage induction machines and the developed fuel cell model is based on solid oxide type. The aim of the work is to analyze the symbiosis between the wind generation and a centralized energy storage system based on hydrogen for a particular wind farm embedded in the electric power system. With this aim, it has been developed an active and reactive power control system and it has been proposed an strategy for the generation of the reference current of the fuel cell.

Key words

Wind energy, hydrogen, distributed generation, SOFC, fuel cells.

1. Introduction

The wind has become in recent decades one of the renewable sources of higher level of development and expansion. In the power generation plan published by the Spanish government, called **"Prospectiva de Generación Eléctrica 2030"**, it is expected that by 2030 the installed wind power will be 35% of the overall installed electrical generating power in Spain.

Apart from the benefits of a source of clean and sustainable energy, a high level penetration of wind power in the overall electrical system also includes a series of new problems and challenges to be tackled. To cope with these problems, a combination of wind power generation complemented with a power generation based on hydrogen would improve considerably the security of supply to the grid [1] and, as a consequence, the overall operational efficiency of the utilities that now make the role of supporting (mainly thermal) will be improved.

The problem of electricity storage is an issue that is in force nowadays. In the field of wind power generation it has been investigated in depth as a means of regulating the active and reactive power injected to the grid. Different storage technologies with sufficient dynamic responses have been investigated [2]. But, in general, these systems have low storage capacity and they accumulate energy in the range of seconds or minutes: hydraulic pumps, super capacitors, flywheels, electrochemical batteries, etc. There is also varied literature that has investigated the symbiosis between wind generation, photovoltaic generation and storage in autonomous systems and microgrids [3]-[5]. In these cases the main objective is to guarantee electricity supply at all times. For these systems higher storage capacity technologies are required such as diesel engine generators, fuel cells, as an emerging technology, or combinations of them.

The research work proposed here, aims to study the presented problematic and analyze the symbiosis between a wind park of medium power (20 MW) connected to a distribution network, and equipped with a storage system based on hydrogen power. To get this goal it will be modeled all the system that consists of: the wind park with Squirrel Cage Induction Machines (SCIM), an energy storage system based on solid oxide fuel cells (SOFC), a boost dc/dc converter and a three-phase inverter with active and reactive power control (Fig. 1). In order to minimize the simulation time it has been chosen a compiled programming language such as C. Therefore, they will be developed linearized models of

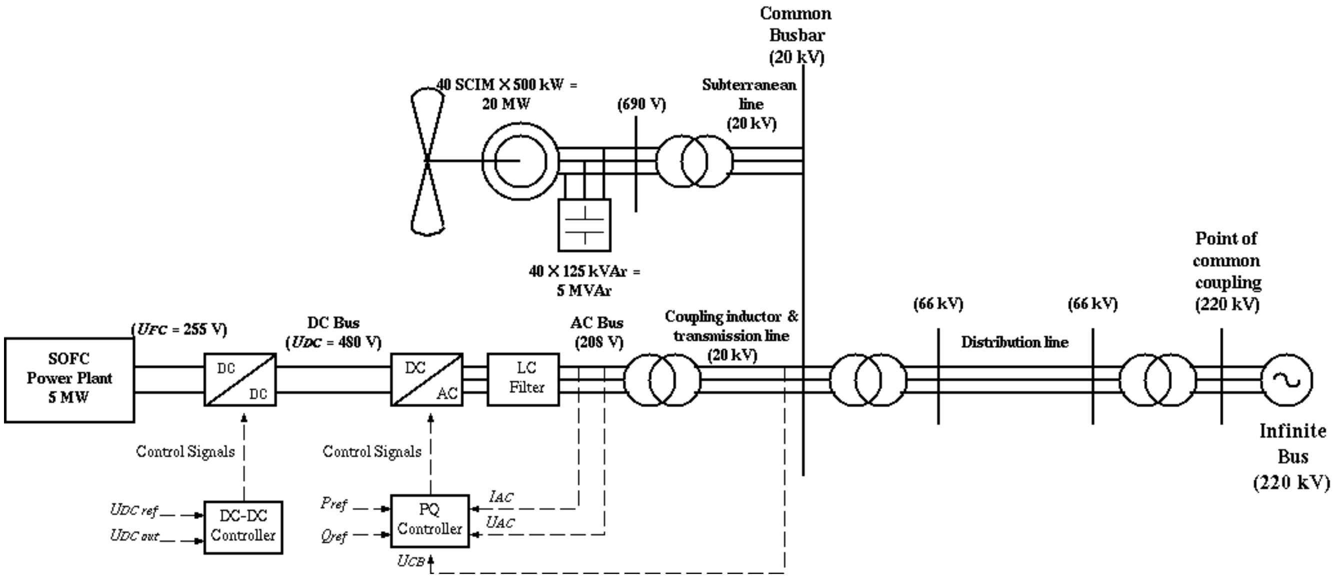

Fig. 1. Schematic of the modeled system consisting of an hybrid wind farm and a fuel cell joined to the grid.

the proposed systems as C-MEX S-Functions for MatLab© - Simulink©.

For the modeling of the park the aggregated model [6] has been used. The aggregated approach represents a wind farm by one equivalent machine with re-scaled power capacity. This simplification is perfectly acceptable under normal operation of wind farms, given the constant speed characteristic of the SCIMs. This wind farm considered consists of 40 ABB G39-500 SCI generators of 500 kW and a nominal voltage of 690 V, with 125 kVAR capacitive compensation. After a step-up Ynyn transformer of 690/20000 V, each induction machine is connected through subterranean lines with the common bus at 20 kV. The developed electromagnetic transient simulation model of the wind farm allows to predict its behavior under normal operating conditions and also under electrical disturbances.

2. Dynamic model of SOFC stack

SOFCs are advanced electrochemical energy conversion devices operating at a high temperature, converting the chemical energy of fuel into electric energy at high efficiency. They have many advantages over conventional power plants and show great promise in stationary power generation applications [7]. The energy conversion efficiency of a SOFC stack is in the 45 - 60 percent range, and its overall efficiency, when used in combined heat and power (CHP) applications, i.e., as an integrated SOFC and a combustion turbine system, can even reach 70% [8]. Despite slow start-up and thermal stresses due to the high operating temperature, SOFC allows for internal reforming of gaseous fuel inside the fuel cell, which gives its multi-fuel capability.

The high operating temperature from 600 – 1000 ºC allows internal reforming, promotes rapid kinetics with non-precious materials, and produces high quality by-product heat for cogeneration or for use in a bottoming cycle. The high temperature of the SOFC, however, places stringent requirements on its materials. The development of suitable low-cost materials and low-cost fabrication of ceramic structures is presently the key technical challenge facing SOFC commercialization.

The SOFC model developed in this work has been based on [9]-[11]. The rated power is 4 MW (20% of the rated power of the park).

A. Brief overview

Fuel cells are electrochemical devices that convert the chemical energy of a reaction directly into electrical energy. The basic physical structure, or building block, of a fuel cell consists of an electrolyte layer in contact with a porous anode and cathode on either side. A schematic representation of a fuel cell with the reactant / product gases and the ion conduction flow directions through the cell is shown in Fig. 2.

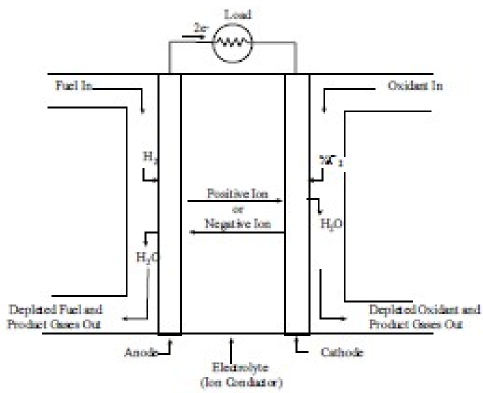

Fig. 2. Schematic of an individual fuel cell.

In a typical fuel cell, gaseous fuels are fed continuously to the anode (negative electrode) and an oxidant (i.e., oxygen from air) is fed continuously to the cathode (positive electrode); the electrochemical reactions take place at the electrodes to produce an electric current. The electrolyte in the SOFC is a solid, nonporous metal oxide, usually Y2O3-stabilized ZrO2. Typically, the anode is Co-ZrO2 or Ni-ZrO2 cermet, and the cathode is Sr-doped LaMnO3 [8]. The basic reactions at the two electrodes of a SOFC can be described as :

Anode: $H_2 + O^{=} \rightarrow H_2O + 2\,e^-$

Cathode: $\frac{1}{2}\,O_2 + 2\,e^- \rightarrow O^{=}$ (1)

DC current (I_{FC}) in the electrical circuit connected across the two electrodes is generated due to the releasing of the electrons (2 e^-) at the anode.

The ideal performance of a fuel cell is defined by its Nernst equation, in the case of SOFC:

$$E = N_0 \left(E_0 + \frac{RT}{2F} \ln \frac{p_{H_2} p_{O_2}^{1/2}}{p_{H_2O}} \right) \quad (2)$$

where E_0 is the ideal standard potential for the cell reaction, E is the ideal equilibrium potential at other temperatures and partial pressures of reactants and products, N_0 is the number of stack cells in series, R is the gas constant (8.31 J / mol ºK), T is the SOFC operating temperature typically in the range of 600 ºC – 1000 ºC, F is the Faraday constant (96487 C/mol), p_{H_2} , p_{O_2} and p_{H_2O} are the reactant partial pressures of hydrogen, oxygen and water, respectively.

Fuel cell stacks contain an electrical interconnect which links individual cells together in series or parallel. Applying Nernst's equation and Ohm's law (to consider ohmic losses), the stack output voltage is represented by the following expression:

$$V_{FC} = N_0 \left(E_0 + \frac{RT}{2F} \ln \frac{p_{H_2} p_{O_2}^{1/2}}{p_{H_2O}} \right) - rI_{FC} \quad (3)$$

Based on the work reported in [9]-[11], a SOFC power plant dynamic model suitable for use in power system studies is shown in Fig. 3.

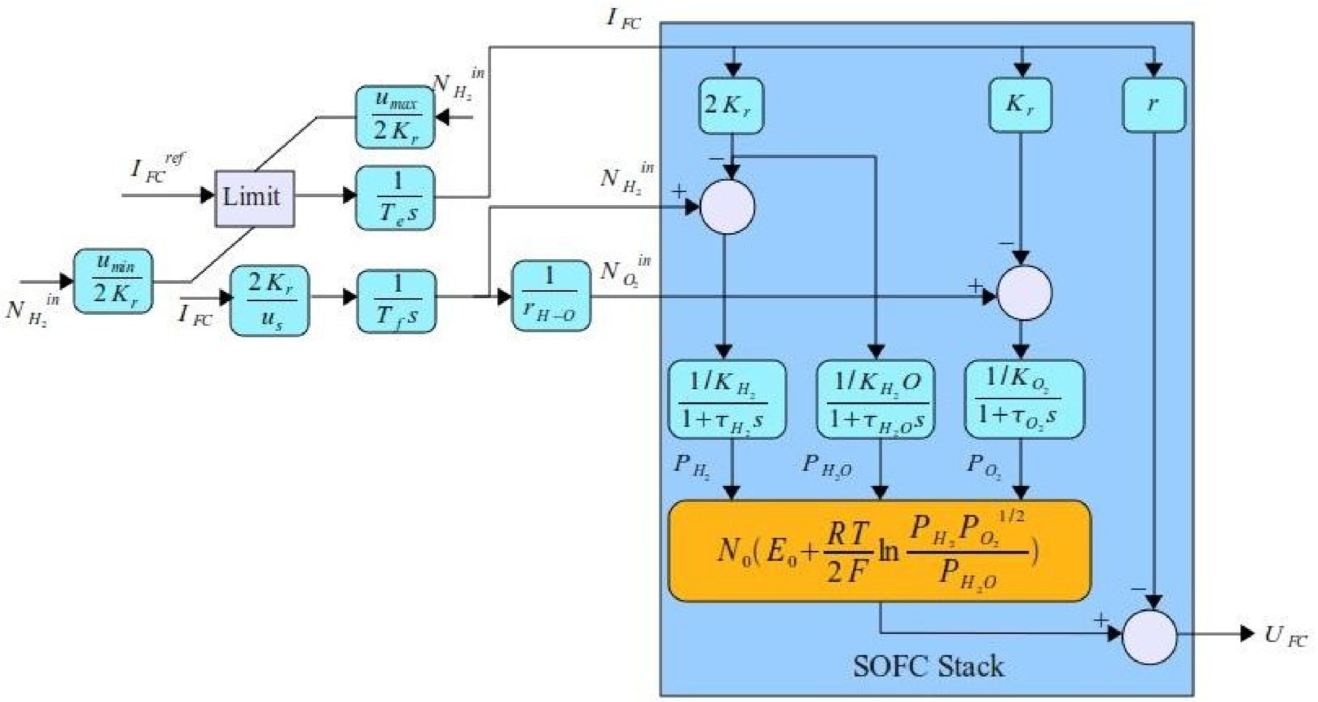

Fig. 3. SOFC stack dynamic model.

B. Constant fuel utilization operating mode

For the particular case of the anode, the concept of fuel utilization factor, u, can be introduced as the ratio between the fuel flow that reacts and the fuel flow injected to the stack:

$$u \equiv \frac{(N_{H_2}^{in} - N_{H_2}^{out})}{N_{H_2}^{in}} \quad (4)$$

where $N_{H_2}^{in}$ and $N_{H_2}^{out}$ are respectively the input and output flow rates of hydrogen to the fuel stack. From [9], it can be shown that u can be expressed in terms of I_{FC} as follows:

$$u = \frac{2K_r I_{FC}}{N_{H_2}^{in}} \quad (5)$$

where K_r is a modeling parameter which has a value of $N_0/4F$.

In order to implement the controller of the plant it will be defined the safe operating area which is fixed by two limits: (1) Underused fuel, if u drops below a certain limit (0.7), the cell voltage would rise rapidly. (2) Overused fuel, if u increases beyond a certain value (0.9), the cells may suffer from fuel starvation and be permanently damaged. Therefore, for a certain input hydrogen flow, the demand current of the fuel cell system can be restricted in the range

$$\frac{0.7\,N_{H_2}^{in}}{2\,K_r} \le I_{FC} \le \frac{0.9\,N_{H_2}^{in}}{2}K_r \qquad (6)$$

During power transients I_{FC} has to be kept within this allowable range. Under steady state, the input fuel flow will be controlled at its optimal value, u_s (0.8 - 0.85), so

$$N_{H_2}^{in} = \frac{2\,K_r I_{FC}}{u_s} \qquad (7)$$

3. Active and reactive power control of the PCU

The SCIM based wind farms have the great advantage of being more robust and cheaper than other systems based on Doubly Fed Induction Machines (DFIM) or Permanent Magnet Synchronous Machines (PMSM). Nevertheless, in SCIM based traditional wind farms the control of the reactive power is not possible or it is very limited. The incorporation of a fuel cell with its boost dc/dc converter and dc/ac inverter is going to allow to insert a decoupled P-Q control to the overall system [12], [13].

A. Boost dc/dc converter control

A boost dc/dc converter can be used to convert the fuel cell output voltage to the desired dc bus voltage. A state space averaging technique, proposed by [14] is widely used to develop a linear state-space model for the converter. This converter model is then used for controller design.

In this paper, a conventional PI controller is used for each dc/dc converter. The converter output voltage is compared with the desired (480 V) dc voltage. The error signal is fed to the PI controller to control the PWM pulse generator. The PWM pulse generator will generate pulse sequences with a desired duty ratio to control the power electronic switch. As a result of the controlled switching, the output voltage is regulated within the preset range (±5% in this study).

B. Three-phase voltage source inverter control

In order to meet the requirements for interconnecting the SOFC system to a utility grid and control the active and reactive power flow between them, it is necessary to shape and control the voltage source inverter output (VSI) in amplitude, angle, and frequency [15]. A sinusoidal PWM (SPWM) controller is designed for the inverter to satisfy voltage regulation as well as to achieve real and reactive power control.

A control scheme consisting of an outer voltage regulator with an inner current control loop, used for real and reactive power control, was reported in [12], [13]. This control scheme was used in this paper to control the inverter. The abc/dq0 transformation [16] is used in the control system to transform time-varying variables from stationary abc frame to dc signals in synchronously rotating dq0 frame. The dq0 signals are then used as inputs to the voltage and current controllers. The current and voltage controllers are chosen as PI compensators.

4. Simulation results

With the developed models, simulations were performed to analyze the behavior of the wind farm when working in a market situation. In the modeling system the active and reactive power target to be supplied by the fuel cell system (SOFC + dc/ac inverter) is updated every minute. This setpoint is generated according to the utility grid demand and the average power generated by the wind farm. In order to reduce the excessive charge of auxiliary storage devices (i.e. batteries or super-capacitors) a simultaneous step and ramp change strategy can be attempted as proposed by [11]. The simulation performed has been an initial change in P_{FC}^{ref} between 0.5 and 0.7 p.u., following an increase of 0.3 p.u. and finally a reduction to baseline, 0.5 p.u. The reactive power (Q^{ref}) setpoint has been kept on 0.8 p.u. throughout the simulation period.

A. Simulation results for the SOFC

Fig. 4 shows the profiles of P (P_{ref} and P_{out}), I_{FC}, U_{FC} and u (utilization factor). It is seen that the output power follows perfectly the generated optimal reference and consequently the current also. In regard to the utilization factor (u), it can be seen that each time a power reference change occurs the factor rises or falls rapidly to the maximum or minimum respectively within the allowable range, and it remains there until the setpoint is reached. As a consequence of this operation inside the safe operating area (0.7 < u < 0.9) U_{FC} remains within an allowable range throughout the transient process, if these voltage variations of the FC stack are within the limits that can be handled by the VSI, the boost dc/dc converter could be dispensable [17], [18].

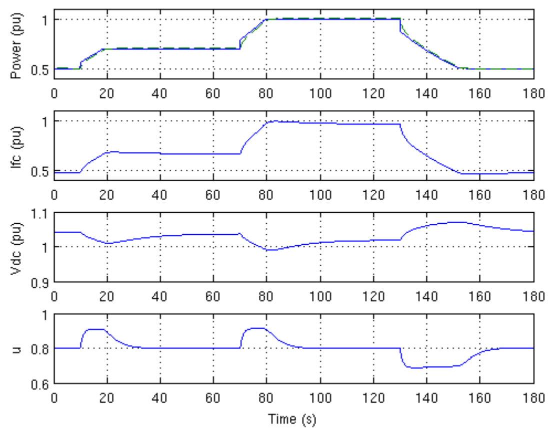

Fig. 4. SOFC response under simultaneous step and ramp change when P_{ref} changes between 0.5, 0.7, 1 and 0.5 p.u.

B. Simulation results for the VSI control

To shape and control the inverter output voltage in amplitude, angle and frequency the dq0 components of voltage and current are controlled with PI compensators.

In Fig. 5 are shown the profiles of P and Q outputs of the inverter, the direct component of the voltage (V_d) and its setpoint, and the component in quadrature of the voltage (V_q) and its setpoint. It can be seen that the time response of P and Q under the proposed setpoints is almost instantaneous, the dynamic response of the proposed control is very good. In the other two graphs can be seen as well the accuracy and rapid response of the direct and quadrature components under their respectives reference targets.

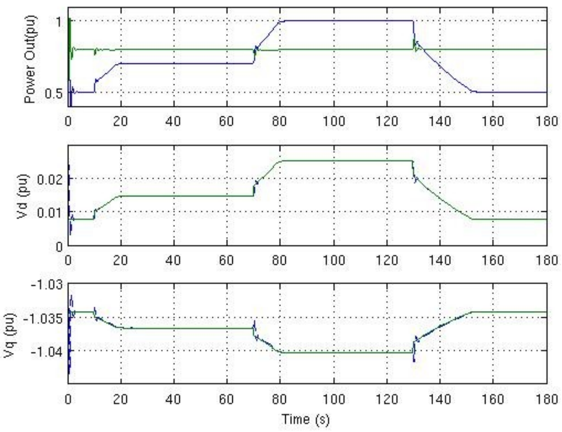

Fig. 5. Power Control response of the three-phase VSI under simultaneous step and ramp change when $P_{ref.}$ changes between 0.5, 0.7, 1 and 0.5 p.u.

5. Conclusions

In the present work have been presented a dynamic model for the study of the integration of a medium sized wind park connected to the utility grid, with an auxiliary hydrogen based SOFC.

In order to reduce the excessive charge of auxiliary storage devices (i.e. batteries or super-capacitors) and to get the fastest response of the fuel cell, a simultaneous step and ramp change strategy for the P_{FC}^{ref} has been developed. The response rate obtained is more than acceptable, given the physical limitations of the SOFC.

Besides this, it has been experimented a PQ control strategy for the three-phase VSI model. The response of this control is accurate and fast. This control adds the ability of reactive power generation to the overall system SCIM wind park + SOFC.

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