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Fuel cell grid connected system with active power generation and reactive power compensation features

***Abstract**. This article presents a control of a three-phase low voltage grid connected fuel cell system which participating in the improvement of the quality of energy at the connection point by ensuring the reactive energy compensation, the active power control and the harmonic filtering functionalities. A p-q theory based control has been developed to control the injected fuel cell active power and to allow the system to provide the reactive energy compensation function. The system is structured around a proton exchange membrane (PEM) fuel cell system and a three-phase voltage inverter.*

Streszczenie.** W artykule przedstawiono sterowanie trójfazową siecią z podłączonym ogniwem paliwowym z kompensacją mocy biernej I redukcją harmonicznych. Zastosowano ogniwo z protonową membraną wymienna PEM. (**Sieć z podłączonym ogniwem paliwowym z kompensacją mocy biernej I redukcją harmonicznych)

Keywords: fuel cell, grid, active power, reactive power, control.
Słowa kluczowe: ognowo paliwpowe, kompensacja mocy biernej

Introduction

Nowadays, many of the global primary energy supplies are provided from fossil sources (oil, coal and natural gas) [1]. Consumption of these fuels lead to greenhouse gas emissions and also to increase the atmospheric pollution. In addition, excessive consumption of these non-renewable resources penalizes future generations. As a solution, the use of renewable energy sources continues to strengthen and become a viable alternative to fossil fuels. In this context, hydrogen is one of the technologies that focus on development efforts. As an energy carrier, and associated with fuel cell technology, hydrogen can play a leading role in the energy mix in the future. It has several advantages: it has the highest gravimetric energy density of all known fuels (about 35 kWh /kg), and its combustion, which produces only water, can be considered "clean" [2].

Research efforts advanced in power electronics and reduction in fuel cell costs have led to successful transition from stand-alone fuel cell systems to grid-connected fuel cell systems. Different types of fuel cells have been studied for the integration into the electrical grid [3-5]. The most used are PEMFC and SOFC fuel cells. The integration of fuel cell systems into the electrical grid has opened up a wide field of research to identify all the related technical impacts. As in other decentralized generation grid connected systems, the problem of injected harmonics is more encountered in the literature [6-8]. The issue of active and reactive power control has also great importance in this area, so several studies have proposed different control strategies [9, 10]. A fuel cell generates a high direct current under a low voltage. This specificity has prompted researchers to focus on power electronics associated with their integration to the grid [11-15]. In addition, artificial intelligence techniques are called upon to play a role in the improvement of the quality of energy in these systems [15-18].

In grid connected fuel cell system, the main function of the inverter is to inject active power to the grid as needed. It can, in addition and provided that the inverter is oversized, satisfies part of the grid's demand for reactive power. In fact, in public grid, several electrical loads such as motors require both active power (doing useful work) and reactive power (storing energy in the magnetic field). This reactive energy is continually exchanged between the load and the source. Therefore the grid must produce and transport not only active energy but also reactive energy, which results in an over-sizing of its components. In order to totally or partially relieve the generator and the grid, and to avoid this over-sizing, the reactive power is locally generated (near the inductive loads) most often by capacitor banks. When already installed to provide active power, fuel cell grid connected systems can be in addition replace these capacitor banks by injecting reactive power to the grid. This is possible by controlling the amplitude and the phase of the injected current.

In this work, proposed control allows the inverter to inject active power from the fuel cell, at the same time to exchange reactive power with the grid. This added function contributes to the improvement of the power factor of the grid and allows a significant economic gain as there will be no need for capacitors.

System configuration

Several configurations of grid-connected fuel systems are encountered in the literature. In this work, the system shown in Fig. 1 is chosen. It consists of a Ballard Mark V 35 cells-5kW proton exchange fuel cell system, a DC-DC boost converter, an inverter and LCL filters. The LCL filters are inserted between the inverter and the grid to minimizing the effect of harmonics created by switching process. The DC-DC boost converter is necessary to increase the voltage at the inverter input (at least 400V DC to generate 220V AC), and it operates in continues conduction mode.

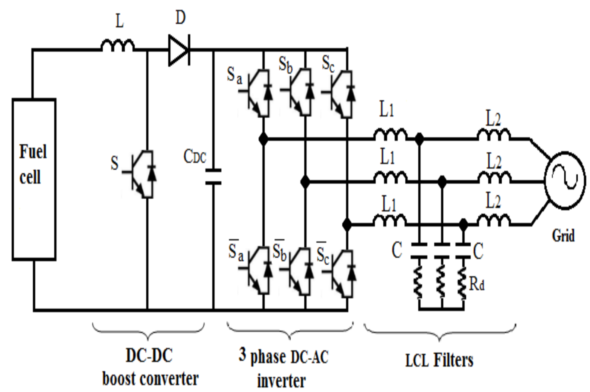

Fig.1. Proposed fuel cell grid connected system

Fuel cell model

The operating principle of the fuel cell is based on the reverse process of electrolysis of water. A redox reaction reacts hydrogen and oxygen to produce electricity, water and heat (Fig.2) [19].

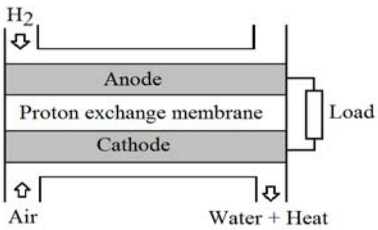

Fig.2. PEM fuel cell principle

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At the anode, hydrogen is transformed into H^+ ions by releasing electrons according to the reaction:

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

At the cathode, the H^+ ions combine with the O^- ions formed from oxygen to form water according to the reaction:

$O_2 + 4H^+ + 4e^- \rightarrow H_2O$

The overall reaction is therefore:

$H_2 + 1/2O_2 \rightarrow H_2O$ + heat + electricity

The production of electrons at the anode and their consumption at the cathode ensures the electrical potential difference which allows the current flow when the cell is supplied with air and hydrogen and is placed in an electrical circuit.

The Nernst potential (the theoretical thermodynamic potential) of a single fuel cell at 25 °C and at 1 atm is of the order of 1.229 V [19], but the real potential (E_r) of the cell decreases relative the equilibrium thermodynamic potential when the current flows. This deviation from the value of the Nernst potential is due to irreversible losses called over-voltages (or voltage drops) which are the activation over-voltage E_{act}, the ohmic over-voltage E_{ohm}, and the concentration over-voltage E_{conc} [20].

So, the expression of the voltage of a single fuel cell is expressed as follows [20] [21]:

(1) $$E_{Cell} = E_{Nernst} - E_{act} - E_{ohm} - E_{con}$$

The stack voltage E_{Stack} of n cells connected in series is:

(2) $$E_{Stack} = n.E_{Cell}$$

In the case where liquid water is the product of the PEMFC, the expression of the Nernst equation arranged with a numerical calculation is as follows:

(3)
$$E_{Nernst} = 1{,}229 - 0{,}85T^{-3}.(T - 298{,}15) + 4{,}31.10^{-5}.T.\left[\ln\left(P^*_{H_2}\right) + \frac{1}{2}\ln\left(P^*_{O_2}\right)\right]$$

where T is the absolute operating temperature of the stack (K), $P^*_{H_2}$ is the hydrogen partial pressures (atm) and $P^*_{O_2}$ is the oxygen partial pressures (atm) [20].

Activation over-voltage, predominant at low current densities, are given in the model proposed by J.C.Amphlet et al.[20], [21] by the relation:

$$E_{act} = \xi_1 + \xi_2.T\xi_3.T.ln(c_{O_2}) + \xi_4.T.ln(i_{FC})$$

where i_{FC} is the functional fuel cell operating electrical current (A). ξ, ξ_2, ξ_3, and ξ_4 are empirical coefficients. c_{O_2} is the concentration of dissolved oxygen in the interface of the cathode catalyst (mol/ cm^3), determined by:

(4) $$c_{O_2} = \frac{P_{O_2}}{5.08.10^6.e^{-\left(\frac{498}{T}\right)}}$$

The ohmic over-voltage is determined by:

(5) $$E_{ohm} = i_{FC}.(R_M + R_C)$$

where R_M is the equivalent proton-exchange membrane impedance (Ω) and R_C is the resistance between the electrodes and the proton-exchange membrane (Ω) usually considered constant. R_M is calculated as the following relation:

(6) $$R_M = \frac{\rho_M.l}{A}$$

where l is the membrane thickness (cm), A is the cell active area (cm^2), and ρ_M is the specific membrane resistivity (Ω.cm), obtained by the following relation:

(7) $$\rho_M = \frac{181{,}6.\left[1+0{,}003.\left(\frac{i_{FC}}{A}\right)+0{,}062.\left(\frac{T}{303}\right)^2.\left(\frac{i_{FC}}{A}\right)^{2.5}\right]}{\left[\psi-0{,}634-3.\left(\frac{i_{FC}}{A}\right)\right].exp\left[4{,}18.\left(\frac{T-303}{T}\right)\right]}$$

where ψ is the water content in the membrane between 0 and 23 [22], [23]. ψ may have a value order of 14 under 100% of relative humidity and up to 23 at oversaturated conditions.

At high current densities, the losses related to the kinetics of diffusion of gases through the electrodes become dominant and the voltage drops quickly. This concentration over-voltage is given by the relation:

(8) $$E_{con} = -B.\ln\left(1 - \frac{J}{J_{max}}\right)$$

where B (V) is an empirical coefficient it depends on the type of fuel cell and its operation state [21-23], J is the actual current density of the cell (A/ cm^2), and J_{max} is the maximum current density (A/ cm^2).

Using the actual model, the polarization curve (current-voltage characteristic) of a Ballard Mark V PEM fuel cell at standard temperature and pressure conditions was plotted using MATLAB-SIMULINK software (Fig.3). Table 1 shows the model parameters values used.

Table 1. Ballard Mark V Fuel cell simulation parameters [23]

Parameter	Value	Parameter	Value
T	343 K	ξ_1	-0.948
A	50.6 cm^2	ξ_2	0.0312
l	178 μm	ξ_3	0.000076
$P^*_{H_2}$, $P^*_{O_2}$	1 atm	ξ_4	-0.000193
B	0.016 V	ψ	23
R_C	0.0003 Ω	J_{max}	1.5 A/cm^2

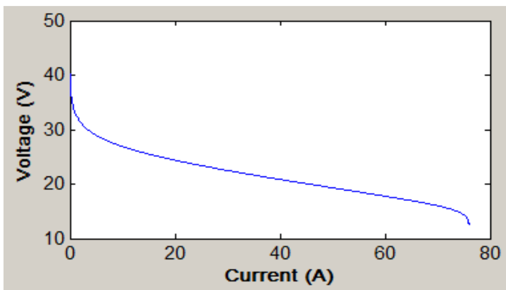

Fig.3. Polarisation curve of a Ballard Mark V PEM Fuel cell stack

Proposed control

The control is done via two loops: a loop that regulates the DC voltage at the inverter input and a loop that controls the active power and the reactive power of the grid injected current. The DC/DC converter control is shown on Fig.4.

A PI controller regulate the DC/DC output voltage by minimizing the error between the DC voltage reference (V_{DCRef}=400 V) and the actual V_{DC} voltage (varying the converter duty cycle). The PI controller tuning (proportional constant K_p and integration constant K_i values) is a compromise between a fast dynamic response and a reduced settling time (K_p=0.08, K_i=200).

The injected power control to the grid is mainly by controlling the inverter (Fig.5).

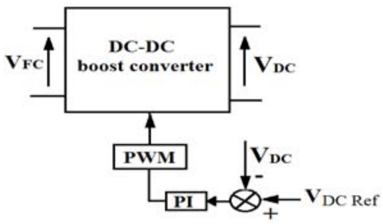

Fig.4. DC/DC converter control

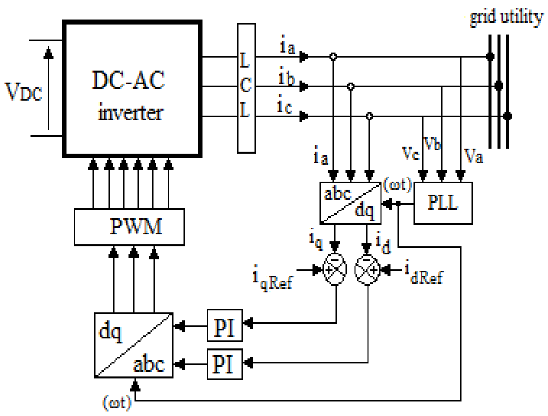

Fig.5. Inverter control

The proposed control consists in applying the dq0 transformation for the line phase currents. The dq0 transformation allows transforming a balanced three-phase system to an equivalent tow-axis representation, thus, it considerably simplifies the calculations and the control. In the dq0 rotating reference frame, the active power and the reactive power at steady state are given respectively by:

(9) $$P = \frac{3}{2} V_d . I_d$$

(10) $$Q = -\frac{3}{2} V_d . I_q$$

where i_q is the current quadrature axis component, i_d is the the direct axis component current and V_d is the direct axis component voltage [24].

Therefore the control of the active power is done by controlling (I_d) while the control of the reactive power is done by controlling (I_q). The advantage of this control is the fact that the control of the active power is decoupled from the control of the reactive power. The error between the actual values and the reference values of I_q and I_d currents are introduced to PI controllers. The PI outputs must undergo a dq0 reverse transformation in order to have vector control in the natural three-phase reference frame. The obtained three signals are compared with a high frequency triangular signal to generate the PWM signals.

Simulation results

Simulations are done using the system parameters values shown on the Table 2.

The proposed control is firstly tested in the case where operation at a unit power factor (PF=1) is desired. For this reason, it suffices to impose a zero set point to the injected reactive power (i_{qRef} = 0). In this case, the three-phase output currents of the inverter and the mains voltages are synchronised (Fig.6).

Table 2. Important simulation parameters

Parameter	Description
400 V	Inverter input DC voltage
220 V	Single phase RMS grid voltage
50 Hz	Grid frequency
10 kHz	PWM switching frequency
L_1=3.5 mH, L_2= 2 mH, C=3 μF, Rd=7Ω	LCL filter design

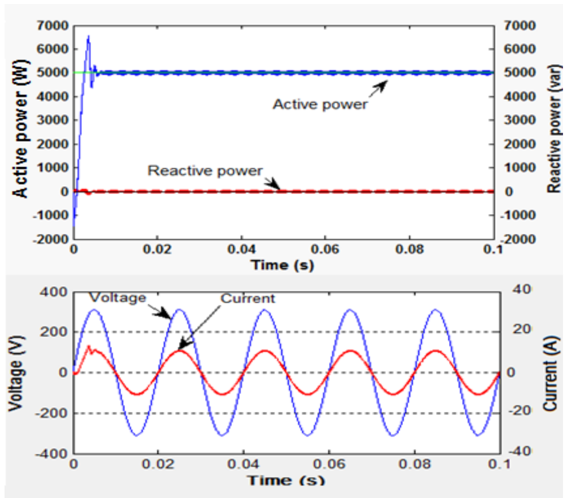

Fig.6. Powers, and single phase current / voltage (PF=1)

Finally, the proposed control was tested in the case of abrupt changes of active and reactive power demand of the grid. Fig.7 shows the actual active power and reactive power, and the corresponding three phase currents.

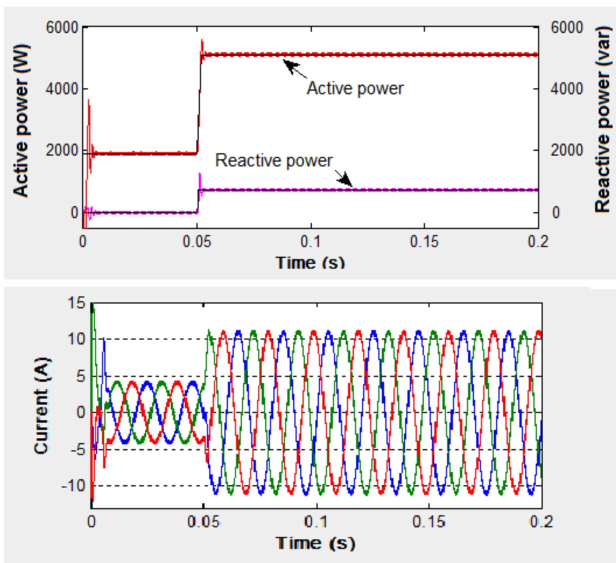

Fig.7. Active/reactive power and grid injected current

It is clear that the actual power follows the set power values with good dynamics. The three-phase currents injected into the network have a sinusoidal shape.

In order to evaluate the quality of the power injected into the grid, Fig.8 shows the harmonics spectrum of the injected current. It has been verified that the produced THD (Total harmonic distortion) is very low.

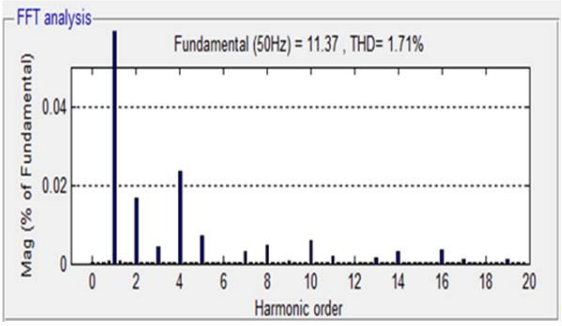

Fig.8. Injected current harmonic spectrum

Conclusion

In this paper, a PWM-PI current control is proposed for a fuel cell grid connected system. It offers a good steady-state response, fast dynamic response, and highly sinusoidal injected current waveform with very low current ripple. The proposed model will be used for studies on fuel cell systems under grid faults.

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REFERENCES

[1] Gielena D., Boshell F., Sayginb D., Bazilianc M.D., Wagner N., Gorini R., The role of renewable energy in the global energy transformation, *Energy Strategy Reviews*, 24 (2019), 38-50
[2] Møller K.T., Jensen T.R., Akiba E., Li H.W., Hydrogen - A sustainable energy carrier, *Progress in Natural Science: Materials International*, 27 (2017), No. 1, 34-40
[3] Wang B.C, Guo X.Q., Huang X.K, Wu W.Y, Flexible Control of Three-Phase Distributed Generation Systems for Voltage Rise Mitigation in Microgrid, *Przegląd Elektrotechniczny*, 88 (2012), nr 7b, 382-386
[4] Wang C., Nehrir M.H., Gao H., Control of PEM Fuel Cell Distributed Generation Systems, *IEEE Transactions on Energy Conversion*, 21(2006), No.2, 586-595
[5] Chen W., Han Y., Li Q., Liu Z., Peng F., Design of proton exchange membrane fuel cell grid-connected system based on resonant current controller, *International Journal of Hydrogen Energy*, 39 (2014), No. 26, 14402-14410
[6] Wu J.C, , Wu K.D., Jou H.L, Wu Z.H, Chang S.K, Novel power electronic interface for grid-connected fuel cell power generation system. *Energy Conversion and Management,* 71 (2013) 227-234
[7] Sundarabalan C.K., Puttagunta Y., Vignesh V., Fuel cell integrated unified power quality conditioner for voltage and current reparation in four-wire distribution grid, *IET Smart Grid*, 2 (2019), No. 1, 60-68
[8] Cao L., Loo K.H., Lai Y.M., Frequency-Adaptive Filtering of Low-Frequency Harmonic Current in Fuel Cell Power Conditioning Systems. IEEE Transactions on Power Electronics, 30 (2015), No. 4, 1966-1978
[9] Sun L., Wu G., Xue Y., Shen J., Li D., Lee K.Y., Coordinated Control Strategies for Fuel Cell Power Plant in a Microgrid, IEEE *Transactions on Energy conversion*, 33 (2018), No. 1, 1-9
[10] Li Q., Chen W., Liu Z., Zhou G., Ma L., Active control strategy based on vector-proportion integration controller for proton exchange membrane fuel cell grid-connected system. *IET Renewable Power Generation*, 9 (2015), No. 8, 991-999
[11] Zambri N.A., Mohamed A., Utilization of fuel cell energy source for distribution power generation: theory, modeling and review of research work, *Przegląd Elektrotechniczny*, 90 (2014), nr 5, 189-200
[12] *Shireen W., Kulkarni R.A., Arefeen M., Analysis and minimization of input ripple current in PWM inverters for designing reliable fuel cell power systems, Journal of Power Sources*, 156 (2006), No. 2, 448-454
[13] Boscaino V., Capponi G., Miceli R., Galluzzo G.R., Rizzo R., Comparison of models of fuel cells based on experimental data for the design of power electronics systems, *IET Renewable Power Generation*, 9 (2015), No. 6, 660-668
[14] Blaabjerg F., Chen Z., Kjaer S.B., Power electronics as efficient interface in dispersed power generation systems, *IEEE Transactions on Power Electronics*, 2004 (19), No. 5, 1184-1194
[15] Inci M., Türksoy O., Review of fuel cells to grid interface: Configurations, technical challenges and trends, *Journal of Cleaner Production*, 213 (2019), 1353-1370
[16] Bicer Y., Dincer I., Aydin M., Preparation Maximizing performance of fuel cell using artificial neural network approach for smart grid applications, *Energy*, 116 (2016), 1205-1217
[17] Sakhare A., Davari A., Feliachi A., Fuzzy logic control of fuel cell for stand-alone and grid connection, *Journal of Power Sources*, 135 (2004), No. 1–2, 165-176.
[18] Qureshi M.B, Qamar S., Ali S., Khalid U., Recurrent neuro-fuzzy control of grid-interfaced solid oxide fuel cell system, *International Journal of Systems Control and Communications*, 9 (2018), No. 1, 31-52
[19] Yuan X.Z., Wang H., PEM Fuel Cell Fundamentals, In: Zhang J. (editor), PEM Fuel Cell Electrocatalysts and Catalyst Layers. *Springer* (2008), 1-87
[20] Mann R.F., Amphlett J.C., Hooper M.A.I., Jensen H.M., Peppley B.A., Roberge P.R., Development and application of a generalised steady-state electrochemical model for a PEM fuel cell, *Journal of Power Sources*, 86 (2000), No. 1–2, 173-180
[21] Fowler M.W, Mann R.F., Amphlett J.C, Peppley B.A., Roberge P.R., Incorporation of Voltage Degradation into a Generalised Steady State Electrochemical Model for a PEM Fuel Cell, *Journal of Power Sources*, 106 (2002), No. 1–2, 274–283
[22] Okada T., Xie G., Meeg M. Simulation for Water Management in Membranes for Polymer Electrolyte Fuel Cells, *Electrochimica Acta*, 43 (1998), No. 14–15, 2141–2155
[23] Corêa J.M., Farret F.A., Canha L.N., Simões M.G., An Electrochemical-Based Fuel Cell Model Suitable for Electrical Engineering Automation Approach, *IEEE Transactions on Industrial Electronics* , 51 (2004), No. 5, 1103–1112
[24] Sangwongwanich A., Abdelhakim A., Yang Y., Zhou K., Control of Single-Phase and Three-Phase DC/AC Converters, in: Blaabjerg F.(editor), Control of Power Electronic Converters and Systems, *Elsevier* (2018), 153–173