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POWER CONDITIONING SYSTEM TOPOLOGY FOR GRID INTEGRATION OF WIND AND FUEL CELL ENERGY

Marian GAICEANU

Member IEEE, Department of Electrical Engineering, Politecnico di Torino,
C-so Duca degli Abruzzi, TO 10129 ITALY (phone: +39-011-5647118; fax:+39-011-5647199; e-mail: Marian.Gaiceanu@ polito.it

Abstract: This paper shows the topology of the hybrid grid-connected power system and the performances of the front-end three-phase power inverter. The renewable sources of the hybrid power system consist of a solid oxide fuel cell and a wind-turbine. This type of combination is the most efficient one. The proposed topology benefits of the one common DC-AC inverter which injects the generated power into the grid. The architecture diminishes the cost of the power conditioning system. Moreover, due to the power balance control of the entire power conditioning system the bulk dc link electrolytic capacitor is replaced with a small plastic film one. The final power conditioning system has the following advantages: independent control of the reactive power, minimize harmonic current distortion offering a nearly unity power factor operation (0,998) operation capability, dc link voltage regulation (up to 5% ripple in the dc-link voltage in any operated conditions), fast disturbance compensation capability, high reliability, and low cost. The experimental test has been performed and the performances of the grid power inverter are shown.

Keywords: Renewable energy, fuel cell, SOFC, wind-turbine, power conditioning, grid-interface

1. INTRODUCTION[1]

The conventional energy sources (oil, natural gas, coal and nuclear) are finite and generate pollution. Alternatively, the renewable energy sources (anything other sources than deriving energy via fossil fuel combustion) are clean and abundantly available in nature. Various forms of alternative energy sources are: wind, fuel cell, solar, biogas/biomass, tidal, geothermal, hydrogen energy, gas micro turbines and small hydropower farms (Joos, *et al.*, 2000; Mcdermott, *et al.*, 2003; Brei, *et al.*, 2002; Enslin, 2005). The basic principle of the alternative energy relates to issues of sustainability, renewability and pollution reduction. The low energy conversion and the cost of the photovoltaic systems compared with the wind power make to promote in using the wind power systems. In the recent years the fuel cell power systems have attracted a lot of attention. The fuel cell generation systems are most efficient one over other types of renewable sources (EG&G Services Inc, 2000). In addition the fuel cell power systems offer low pollution and reusability of exhaust heat (Agbossuo, *et al.*, 2001). The aforementioned advantages conduct to the forming of a hybrid power system which includes both of

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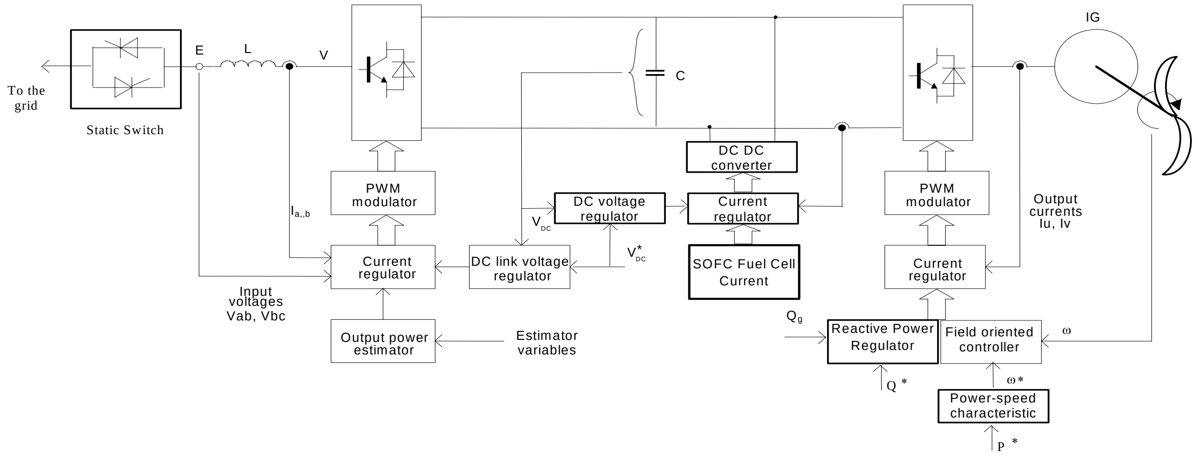

Fig. 1 Control block diagram of the Grid Connected Wind-Turbine/Fuel Cell Power Conditioning Units.

renewable energy: wind and fuel cells. In order to meet the continually increasing demand of renewable power sources the power conditioning units are necessary. The main objective of the power conditioning system is to convert DC power from the fuel cell/wind power converter to AC feeding to grid at maximum efficiency. Additional requirement for a power distribution system is to exchange the power between the source and load. The grid connected in spite of the stand alone power conditioning system has the advantage of not using the batteries and, thus, an increased efficiency is obtained.

The proposed power conditioning system is suitable in the application in which the size and the weight have significant effect. The DC bus capacitor is the prime factor of degradation of power conditioning system reliability. By replacing the DC link electrolytic capacitor (which is bulky, heavy and suffer from the degradation of electrolytic media being a source of failures) the reliability of the system is improved, the size and the cost of the power unit decreasing. The consequence is that of increasing the lifetime of the power converter. The power quality function of the power conditioning system is assured through a proper control of the power system (Uhrin and Profumo, 1996; Gaiceanu, 2004).

2. POWER CONDITIONING TOPOLOGY

2.1. Single phase versus three-phase

The problem of choosing the number of phase for the front end converter is firstly a matter of power. In this case, for a 37kW power converter three-phase line is the answer. Secondly, in case of using balanced three phase AC loads, the possibility of low frequency components in the fuel cell input current is low.

2.2. System description

The hybrid wind/fuel-cell generation system configuration is shown in Fig.1. This system consists of wind generator, fuel-cell generators and the associated power converter units. The power conditioning circuits for the fuel cells consist of DC/DC converters and inverters. The wind turbine PWM rectifier and the SOFC DC-DC converter outputs are parallel connected forming a common dc link. Therefore, only one DC-AC inverter is necessary in order to grid connect. This topology reduces the cost of the power conditioning unit of the hybrid system (Nelson, *et al.,* 2006). The reasons of using DC-DC converter are: first to boost the DC voltage of the fuel cell in order to assure the compatibility with the existent dc link voltage and the second one is the DC isolation for the inverter. The H-bridge forward converter is well developed and very stable being a matured product. In order to improve the switching loss and to reduce the size of the transformer a soft switching type is necessary.

2.2.1 Quasi sinusoidal AC/DC/AC power converter

The quasi sinusoidal AC/DC/AC power converter is responsible with conditioning the electrical energy from the wind energy generator/fuel cells and supplying it to the grid. The topology is shown in Fig. 1 and consists of two three-phase power converters with IGBT that are controlled independently each from the other thanks to the capacitor decoupling. Active and reactive power control is achieved using an adequate control of the AC/DC/AC power converter (Gaiceanu, 2004).

The dc link voltage is supplied both by the generator via a controlled rectifier and by fuel cell through DC-DC converter. The dc link is necessary to avoid disruptive connections between the grid-side inverter and the wind side converter. The dc link voltage control of the grid inverter maintains a constant dc link voltage and fits the output current to supply the required active power.

2.2.2 AC/DC active rectifier

In order to prevent the uncontrolled rectifier operation through the freewheeling diodes the dc link voltage must be higher than the generator peak value. The DC-link voltage is obtained both from the wind generator and from the fuel cell. At low speeds, the DC voltage being available from fuel cell the controlled rectifier ensures the current flow in the intermediate circuit. Additionally, an ultra capacitor or a battery can be inserted in a fuel cell power system side. The vector control scheme assures a variable control of the generator’s current vector, as well as the resulting torque.

2.2.3 Fuel Cell Power Conditioning

The fuel cell is an electrochemical device which produces dc power directly without any intermediate stage. It has high power density and zero emission of green house gases. Fuel cell stacks were connected in series/parallel combination to achieve the rating desired. The main issue for the fuel cell power converter design is the fuel cell current ripple reduction. The secondary issue is to maintain a constant dc bus voltage. The former is solved by introducing an internal current loop in the DC/DC converter control. The latter design requirement is solved through dc voltage control.

2.2.4 Grid connected inverter

The output of the fuel cell array was connected to a dc bus by using a DC/DC converter. The dc bus voltage was kept constant via a dc bus voltage controller. The DC bus voltage was then interfaced with the utility power grid and/or a custom load through a three-phase DC/AC inverter, together with its dc link voltage and current regulators. The 50 Hz frequency of the mains is assured through a phase-locked loop (PLL) control. The grid converter is a full-bridge IGBT transistor-based converter and normally operates in inverter mode such that the energy is transferred from hybrid source to the utility grid and/or to the load.

2.2.5 Grid Interface

On the grid side a di/dt-filter limits the rate of current rise during the commutation of the current from a conducting freewheeling diode to a turning-on IGBT. Its main function is the limitation of harmonic currents to a level that allows fulfilling IEEE 519-1992 even for very weak grids (down to a short circuit ratio of only 10) (IEEE Std 519-1992; Ziogas, *et al.*, 1985).

2.2.6 Static switch

To reduce the transient current during connection or disconnection of the hybrid power system to the grid the static switch has been introduced. Using firing angle control of the thyristors in the static switch the hybrid power system is smoothly connected to the grid over a predefined number of grid periods. The connection diagram for the static-switch with the fuel cell power system is presented in Fig.1. Disconnection at the static switch takes place because of deterioration of quality of electric power delivery from the utility system. The static switch consists of a three single-phase circuit adjusted by firing angle of pair of thyristors connected in inverse-parallel. In order to reduce the losses during normal operation when the hybrid power system is completely connected to the grid a contactor (K_{byp}) by-pass the static-switch (not shown in Fig1).

3. CONTROL SYSTEM

To achieve full control of the utility-grid current, the dc-link voltage must be boosted to a level higher than the amplitude of the grid line-line voltage. The power flow of the grid side inverter is controlled in order to keep the dc-link voltage constant, while the control of the wind turbine side is set to suit the magnetization demand and the reference speed. The structure of the AC/AC converter control system is shown in Fig. 1. The control structure of the AC-AC converter is vector control type and it uses the power balance concept (Sul and Lipo,1990). The control of the ac-ac converter prototype has been implemented by using two control boards (based on the dSMC 101 digital signal processors-DSP).

3.1. The grid inverter control

On the basis of a DC voltage reference V^*_{dc}, dc voltage feedback signal (V_{dc}), ac input voltages (V_{ab} and V_{bc}), current feedback signals (I_a, I_b), and the load power signal (got through a load power estimator (Gaiceanu, 2004b), the DSP software operates the dc-ac control (dc link voltage and current loops) system and generates the firing gate signals to the PWM modulator. The task of the dc link voltage and the current regulation has been accomplished by means of the Proportional-Integral (PI) controller type, because of its good steady-state and dynamic behavior with the ac-dc converter. It is important to underline that the PI controller performances are parameters sensitive, because of its design procedure, based on the DC bus capacitor and inductor values. However, in these specific applications, the system parameters values are known with reasonable accuracy. A phase locked loop (PLL) ensures the synchronization of the reference frame with the source phase voltages by maintaining their *d* component at zero (E_d=0) through a PI regulator. The control of the grid inverter is based on the minor current loop in a synchronous rotating-frame with a feedforward load current component added in the reference, completed with the dc voltage control loop in a cascaded manner. Using the synchronous rotating frame, the active and reactive power can be controlled independently by proportional-integral (PI) current controllers that ensure zero-steady state error. The load feedforward was introduced by Sul et al. (Sul and Lipo, 1990) in order to increase the dynamic response of the bus voltage to changes in load. The load feedforward component is added to the current reference of the grid inverter in order to ensure the power balance between the source converter and the load converter. Thus, improving performances are obtained during the transients. For fast control response to load changes, the feedforward component has been introduced in the inner control loop of the system. The consequence is the low-level DC voltage variation.

3.1.1 Design of the current PI controller with direct compensation of the disturbance and decoupling of the q-d axes

In order to improve the converter’s performances, it is necessary to decouple the two axes. Moreover, the main voltages components E_D and E_Q represent the disturbance signals that act on the system. Such voltages have been already measured from the system because they serve to the reference frame rotational angle. Therefore, it is possible to perform the direct compensation of such disturbs. The *d-q* axes decoupling is obtained by canceling the $(\omega \cdot L)$ signal, that acts on *d* axis, and the $(-\omega \cdot L)$ one, that acts on *q* axis (Gaiceanu, 2004). Due to the *d-q* axes decoupling, the transfer function of the system under control, P_{dis}(s), will become an integrator:

$$(1)\quad P_{dis}(s) = \frac{V_Q^*}{I_Q^*} = -\frac{1}{Ls}$$

Therefore, theoretically speaking, a pure proportional controller could be used since the transitory null error is already assured from the integral system under control. But in order to have a robust control system to eventual disturbs, the use of a proportional-integral controller is preferred. The control system under the hypothesis that the *q*, *d* axes are decoupled and with direct compensation of the disturbance, turns out:

$$(2)\quad P_{dis}(s) = -\frac{1}{Ls}$$

The transfer function of the PI controller is:

$$(3)\quad C_{PIc}(s) = K_{pc}\left(1 + \frac{1}{T_{ic}s}\right)$$

The calculation of the PI controller coefficients, K_{pc} (proportional gain) and T_{ic} (integral time), is done imposing the phase margin ϕ_{mc} (in radian) and the bandwidth, ω_c, (in radian per second). Imposing these two conditions, the following relations for K_{pc} and T_{ic} are obtained:

$$(4)\quad \begin{cases} T_{ic} = \dfrac{1}{\omega_c \cdot \tan\left(-\dfrac{\pi}{2} - \phi_{mc}\right)} \\[2ex] K_{pc} = \dfrac{-T_{ic} \cdot \omega_c^2 \cdot L}{\sqrt{1 + \left(T_{ic} \cdot \omega_c\right)^2}} \end{cases}$$

where the module and the phase (in radian), M and ϕ_c, of the system P_{dis}(s) under control were replaced by $M = \dfrac{1}{L\omega_c}$ and $\phi_c = -\dfrac{\pi}{2}$. The negative sign in the formulas derives from the fact that the gain of the system under control is negative. Because of the *d-q* axes control symmetry, the *d* axis controller is set-up exactly with the *q* axis controller parameters.

3.2. The active rectifier control

To control the generator speed (coupled to the wind-turbine through a gearbox) the speed output characteristic can be used (Chichester, 1999). The control is performed in rotor field oriented reference frame. The active and reactive power errors are processed by the PI controllers to obtain d-q current references. After adding a compensation term (in order to obtain a decoupled control), the final current references are obtained, which are compared with the measured currents. By using other PI stage the corresponding PWM reference voltage are obtained (Gaiceanu, 2006).

4. EXPERIMENTAL RESULTS

The control system emulation based on SIEI RVRUY-37 board uses SICAN 101 dSMC, VECANA DSPs and C166 μC. The capability to provide simultaneous sampling on all channels is mandatory for this application. Complementary external boards implement signal conditioning and protection circuitry.

The powerful SICAN 101 DSP provides fixed-point arithmetic and high computing power. The power stage of the 37-kW prototype unit is based on two 1200V IGBTs three-phase voltage power modules followed by SKHI drive types from Semikron. The power semiconductor switches are operated with T_s=125µs switching time.

The capacitor bank has two parallel connected 500µF film capacitors with 900V dc rating voltage. The line inductance of the converter has 0,5 mH value. By choosing the cut-off frequency f_c=600Hz and the phase margin ϕ_{mc}=1,047 rad, the following current regulator parameters have been obtained: T_{ic}=0.4594 msec, K_{pc}=-1,632.

To show the effectiveness of the proposed control strategy for the grid inverter, the stationary and transient performances are presented (Figs.2-5). Less than 5% current THD factor (under rated power level) has been obtained.

In Fig. 2 and Fig.3 the performances of the grid current controller and dc-link voltage controller are showed. Power matching control is proved by no DC voltage variation to the change of the rated load in normal (Fig.4) operation mode.

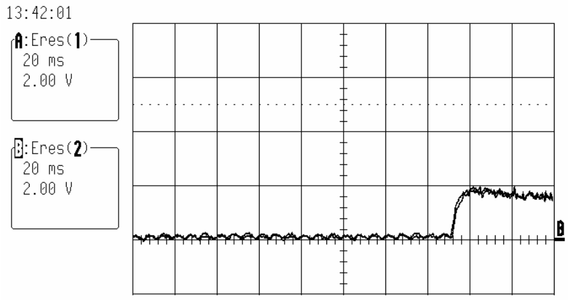

Fig.2. The inputs of the *q* axis current controller: ChA – I_{Q_REF} (the *q* axis current reference), ChB - I_Q (the actual value of the q axis current). Kp=10% (CurrP gain), K_I=9,97% (CurrI gain). 75 A/div

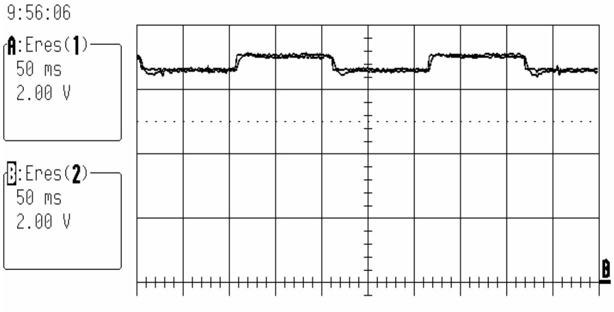

Fig.3. Reference and actual dc link voltage waveforms. Ch.1: the dc link voltage reference, V^*_{DC}. Ch.2: the actual dc link voltage, V_{DC}, 200V/div.

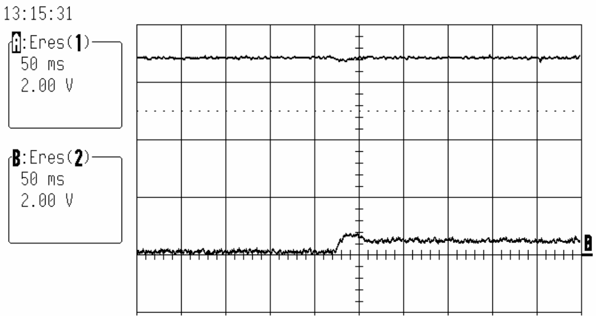

Fig.4. Ch A: Actual DC link voltage VDC_A 200V/div, ChB: DC link current reference IDC_A 75 A/div.

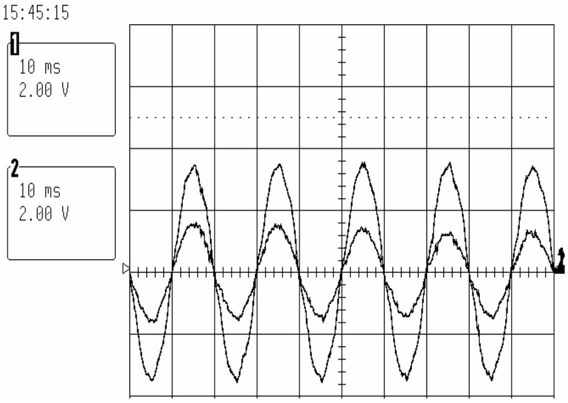

Fig.5. Stationary operation. Waveforms showing unity power factor operation. Ch.1: A phase grid voltage (V_PHASE_A=21AH)- 200V/div. Ch.2: Grid current (I1A=28dH) – 75A/div

The trace of the *A* phase of the grid current is in phase with *A* phase of the grid voltage, which clearly demonstrates unity power factor operation (Fig. 5).

The experimental test has been performed in order to present operation at distorted by 10% of the 5-th harmonic supply line voltage, operation at unbalanced line voltage, and the line current as a function of the 5-th harmonic and voltage unbalance.

Unbalance voltages give unbalance voltage amplitudes. They provide distortion of the supply voltage amplitude, *E*, and of the angle position, θ, that have negative influence on the control system, consequently provide significantly distorted line currents.

The control presented above works properly under distorted and unbalanced line voltage.

Results of the applied distorted and unbalanced line voltage are presented in (Gaiceanu, 2006). By using an adequate synchronizing control the power feed-forward loop still provides sinusoidal line current with low total harmonic distortion THD = 4.9%

5. CONCLUSION

This topology assures a constant DC link voltage, integration of the renewable energy into the grid, the power quality issues, active and reactive decoupled power control, grid synchronization.

This paper presents a practical method of quasi direct Power Control with constant switching frequency using Pulse Width Modulation (QDPC-PWM), which works properly under unbalanced and distorted line voltage conditions. The performances of the grid connected inverter are shown.

A simple and efficient current regulator design of grid inverter assures a fast disturbance rejection resulting in low dc-link ripple voltage. Maintaining a constant dc link voltage the dc link current follow the load levels requirements.

The grid connected inverter has following advantages: reduction of the lower order harmonics in the ac line current, constant dc-link voltage, nearly unity efficiency, zero displacement between voltage and current fundamental component, power reversibility capabilities as well as the good power matching control, disturbance compensation capability, fast control response and high quality balanced three-phase output voltages, small (up to 5%) ripple in the dc-link voltage in any operating conditions.

The power feed-forward control of the quasi-direct ac-ac converter still provides sinusoidal line current with low total harmonic distortion THD = 4.9% for distorted and unbalanced line voltage (Gaiceanu, 2006).

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