A Dc-Coupled Wind/Hydrogen/Super capacitor Hybrid Power System

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Abstract— In this paper A dc-coupled wind/hydrogen/super capacitor hybrid power system is proposed is control the system and is to coordinate these different sources, particularly their power exchange, in order to make controllable the generated power. The generated power does not depend on the grid requirement but entirely on the fluctuant wind condition. As a result, an active wind generator can be built to provide some ancillary services to the grid. The control system should be adapted to integrate the power management strategies. Two power management strategies are presented and compared experimentally. In this paper, a dc-coupled HPS has been studied with the three kinds of energy sources: 1) a WG as a renewable energy generation system; 2) SCs as a fast-dynamic energy storage system; and 3) FCs with ELs and hydrogen tank as a long term energy storage system. The structure of the control system is divided into three levels: 1) SCU; 2) ACU; and 3) PCU. Two power-balancing strategies have been presented and compared for the PCU

I.INTRODUCTION

Renewable energy sources (RES) and distributed generations (DGs) have attracted special attention all over the world in order to reach the following two goals: 1) The security of energy supply by reducing the dependence on imported fossil fuels; 2) The reduction of the emission of greenhouse gases (e.g., $CO2$) from the burning of fossil fuels. Other than their relatively low efficiency and high cost, the controllability of the electrical production is the main drawback of renewable energy generators, like wind turbines and photovoltaic panels, because of the uncontrollable meteorological conditions. In consequence, their connection into the utility network can lead to grid instability or even failure if they are not properly controlled.

like frequency and voltage regulations of the local grid. Wind power is considered in this paper. Wind energy is the world's fastest growing energy source, expanding globally at a rate of 25%–35% annually over the last decade.

1) Energy storage systems are used to compensate or absorb the difference between the generated wind power and the required grid power. 2) Power management strategies are implemented to control the power exchange among different sources and to provide some services to the grid. Hydrogen technologies, combining fuel cells (FCs) and electrolyzes (ELs) with hydrogen tanks are interesting for long term energy storage because of the inherent high mass–energy density. In the case of wind energy surplus, the EL converts the excess energy into $H2$ by electrochemical reaction. The produced $H2$ can be stored in the hydrogen tank for future reutilization. In the case of wind energy deficit, the stored electrolytic $H2$ can be reused to generate electricity by an FC to meet the energy demand of the grid. Thus, hydrogen, as an energy carrier, contributes directly to the reduction of dependence on imported fossil fuel.

II. HPS AND CONTROL SYSTEM

In this paper, we use a dc-coupled structure in order to decouple the grid voltages and frequencies from other sources. All sources are connected to a main dc bus before being connected to the grid through a main inverter .

Power-electronic converter in order to get possibilities for power control actions. Moreover, this HPS structure and its global control system can also be used for other combinations of sources.

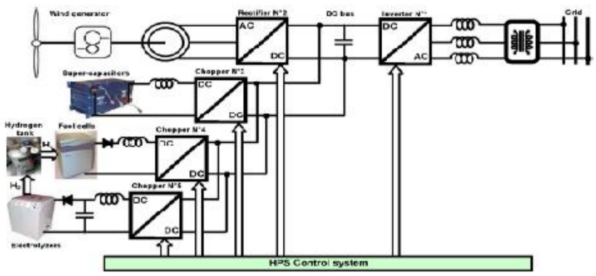

Fig. 1 . Structure of the studied wind/hydrogen/SC HPS.

Structure of Control System: Power converters introduce some control inputs for power conversion. In this case, the structure of the control system can be divided into different levelsThe switching control unit (SCU) is designed for each power converter. In an SCU, the drivers with optocouplers generate the transistor's ON/OFF signals from the ideal states of the switching function {0, 1}, and the modulation technique (e.g., pulse width modulation) determines the switching functions from the modulation functions (m).

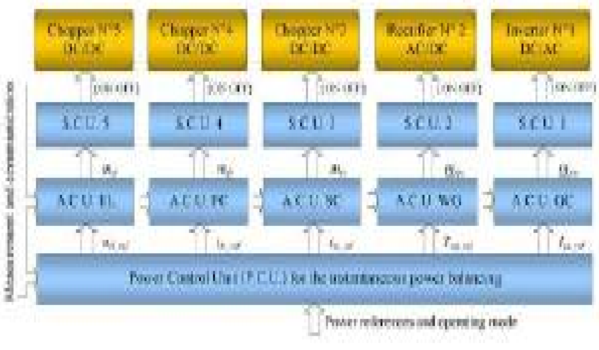

Fig. 2.Hierarchical control structure of the HPS

ACU

The control schemes in the ACUs are shown in Fig. 4 with block diagrams. 1) The EL power conversion system is controlled by setting the terminal voltage (u_{el}) equal to a prescribed reference (u_{el_ref}) through the dc chopper N◦5. The EL stack is considered as an equivalent current source (i_{el}). 2) The FC power conversion system is controlled with a reference of the FC current (i_{fc_ref}) through the dc chopper N◦4. The FC stack is considered as an equivalent voltage

source (u_{fc}).
The dc-bus voltage is described as $Cdc = dudc/ /dt= idc$.
Layout of PCU: The power modeling of the HPS can be divided into two levels: the power calculation level and the power flow level (Fig. 5). Thus, the PCU is also divided into two levels: the power control level and the power sharing level.
The PCU enables one to calculate references for the ACU from power references. The power sharing level coordinates the power flow exchanges among the different energy sources with different power-balancing strategies. They are presented here in detail with the help of the Multilevel Representation.
Power Control Level: The power exchanges with various sources are controlled only via the related five references (uel_ref , ifc_ref , isc_ref , Tgear_ref , and i_{l_ref} in Fig. 5). Therefore, the expressions of the powers should be deduced in order to obtain these power references . Only the sources' powers and the exchanged power with the dc-bus capacitor are taken into account here. For the energy storage systems, the powers are calculated by multiplying the measured currents and the measured voltages (Int3, Int4, and Int5 in Table I). The references of the controllable variables are obtained by dividing the power reference with the measured current or the measured voltages.
Power Sharing Level: The power sharing level is used to implement the power balancing strategies in order to coordinate the various sources in the HPS (Fig. 5). It plays a very important role in the control system, because the power exchanges lead directly to the stability of the HPS and impact the dc-bus voltage (u_{dc}). $dEdc/dt= Cdcudc /dc= pdc = pwg + psc + pfc - pel - pg$*...(2)* With E_{dc} stored energy in the dc-bus capacitor; p_{dc} resulted power into the dc-bus capacitor; p_{wg} generated power from the WG; p_{fc} generated power from the FC; p_{sc} exchanged power with the SC; p_{el} consumed power by the EL; p_g delivered power into the grid from the dc bus.
According to the power exchange, the power flows inside this HPS are modeled with four equations:
***Pow*1** : $p_g = p_{sour} - p_{dc}$..(3)
***Pow*2** : $p_{sour} = p_{sto} + p_{wg}$..(4)
***Pow*3** : $p_{sto} = p_{H2} + p_{sc}$..(5)
***Pow*4** : $p_{H2} = p_{fc} - p_{el}$ ....(6)
With p_{sour} "source" total power arriving at the dc bus; p_{sto} "storage" total power arriving at the dc bus; p_{H2} "hydrogen" total power arriving at the dc bus.
In this wind/hydrogen/SC HPS, five power-electronic converters are used to regulate the power transfer with each source. According to a chosen power flow, the following two power balancing strategies can be implemented.

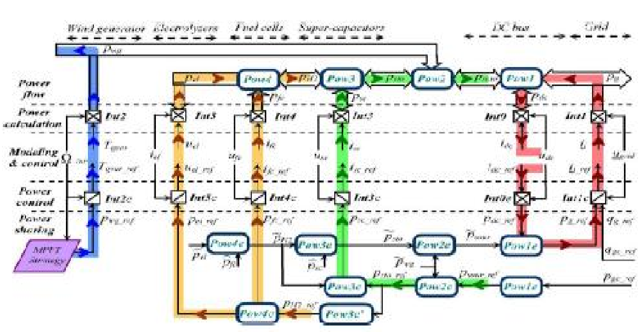

Fig. **3** . Multilevel representation of the grid-following strategy

III. POWER-BALANCING STRATEGIES

Grid-Following Strategy With the grid-following strategy, the dc-bus voltage is regulated by adjusting the exchanged power with the grid, while the WG works in MPPT strategies [27]. In Fig. 6, the dc-bus voltage control is shown by a closed loop ($pdc\_ref \rightarrow pg\_ref \rightarrow pg \rightarrow pdc$). Thus, the required power for the dc-bus voltage regulation (pdc_ref) is used to estimate the grid power reference (pg_ref)
Pow*1*e : $pg\_ref = \tilde{p}sour - \tilde{p}dc\_ref$ …………………….. (7)
The source total power ($psour$) is a disturbance and should also be taken into account with the estimated wind power and the sensed total storage power.
Pow2e: $\tilde{p}sour = \tilde{p}wg + \tilde{p}sto$……………………………….. (8)
The energy storage systems help the wind energy conversion system satisfy the power references, which are asked by the micro grid operator
Pow3e: $\tilde{p}sto = \_p\ sc + \_p\ H2$……………………………. (9)
Pow4e: $\tilde{p}H2 = \_pfc - \_p\ el$………………………………….(10)
In steady state, the dc-bus voltage is regulated, and the averaged power exchange with the dc-bus capacitor can be considered as zero in (3). Hence, in steady state, the grid power (pg) is equal to the total power from the sources ($psour$). If the microgrid system operator sets a power requirement (pgc_ref), it must be equal to the sources' power reference ($psour\_ref$),
Pow*1*c : $psour\_ref = pg\_ref = pgc\_ref$ ………………….(11)
Pow2c : $psto\_ref = psour\_ref = \tilde{p}wg$………………… (12)
Among the energy storage systems, the FCs and the ELs are the main energy exchangers because a large quantity of hydrogen can be stored for enough energy availability.
Source-Following Strategy The total power ($psour$) from the energy storage and the WG can also be used to provide the necessary dc power (pdc) for the dc-bus voltage regulation (Fig. 8) [27]. In this case, the necessary total power reference ($psour\_ref$) must be calculated by taking into account the required power for the dc-bus Voltage regulation (pdc_ref) and the measured grid power (pg) as disturbance input by using the inverse equation of
***Pow*1**ds on the sign of the reference ($pH2\_ref$). Thus, a selector assigns the power reference ($pH2\_ref$) to the FC (pfc_ref) or to the EL (pel_ref) according to the sign of $pH2\_ref$
Pow4c : if: $pH2\_ref > \varepsilon$, $pfc\_ref = pH2\_ref$; $pel\_ref = 0$ if: $|pH2\_ref| \leq \varepsilon$, $p\,fc\_ref = 0$; $pel\_ref = 0$ if: $pH2\_ref < -\varepsilon$, $pfc\_ref = 0$; $pel\_ref = |pH2\_ref|$…………………………………....... (13) However, the power reference ($psto\_ref$) is a fast-varying quantity due to the fluctuant wind power (pwg) and the varying grid power (pg).

Source-Following Strategy The total power ($psour$) from the energy storage and the WG can also be used to provide the necessary dc power (pdc) for the dc-bus voltage regulation (Fig. 8) . In this case, the necessary total power reference ($psour\_ref$) must be calculated by taking into account the required power for the dc-bus voltage regulation (pdc_ref) and the measured grid power (pg) as disturbance input by

using the inverse equation of ***Pow*1** (F
Pow*1*c : $p$sour_ref = $p$dc_ref + _p g

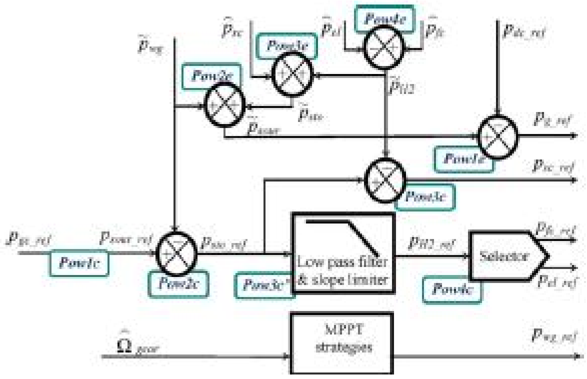

Fig. **4** . Block diagram of the grid-following strategy

IV. Result s

Experimental Platform Assessment An experimental platform of the HPS has been built to test the different power-balancing strategies. Hardware-In-the-Loop (HIL) emulations of a part of a power system enable a fast experimental validation test before implementation with the real process. Some parts of the emulator process are simulated in real time in a controller board and are then interfaced in hardware with the real devices. Such a HIL simulation has been intensively used and enables one to check the availability and reliability of the hybrid active WG (storage component sizing, power-electronic interface, and operation control).The FC and EL emulators are used to provide the same electrical behavior as the real FC stack and the EL stack. Models of the FCs and the EL have been previously validated through comparisons with obtained experimental results and simulated results from models.

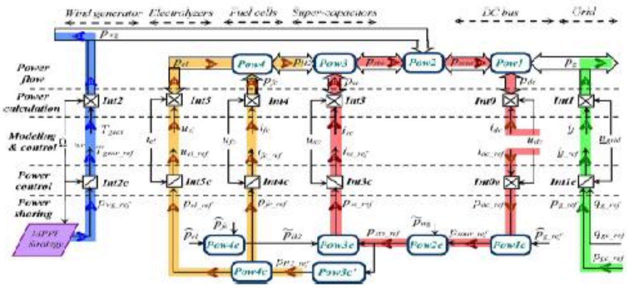

Fig. 5 . Multilevel representation of the source-following strategy.

Power Profile of Different Sources Two tests are performed experimentally for both strategies, respectively. The same fluctuant wind power profile is used during 150 s (Fig. 11). The active-power requirement from the micro grid is assumed to be p_{gc_ref} = 600W. Similar power profiles are obtained for the energy storage systems . When the generated wind power is more than 600 W, the EL is activated to absorb the power difference, but when the generated wind power is less than 600 W, the FC is activated to compensate the power difference.

Grid Following Strategy In the grid-following strategy, the dc-bus voltage is well regulated around 400 V by the grid power conversion system . The energy storage systems help the WG supply the micro grid power requirement (p_{sour} = p_{gc_ref} = 600 W).

Source-Following Strategy

In the grid-following strategy, the energy storage systems are controlled to supply or absorb the necessary powers in order to maintain the dc-bus voltage (around 400 V) against the fluctuant wind power (Fig. 13). The grid active power is also regulated and is equal to the microgrid's requirement, because the line-current control loop regulates directly the grid powers (p_g = p_{gc_ref} = 600 W).

Comparison and Discussion

With the help of energy storage systems, the dc-bus voltage and the grid powers can be well regulated with both power-balancing strategies, while the WG extracts the maximum available wind power. By comparing the two power-balancing strategies with their experimental test results , we see that the grid active power is In the grid-following strategy, the grid power varies continuously because the line current control loop regulates the dc-bus voltage and the grid power is adjusted all the time. In the source-following strategy, the dc-bus voltage is regulated by the SCs, and the grid power can be directly used to supply the same power as required by the micro grid system operator.

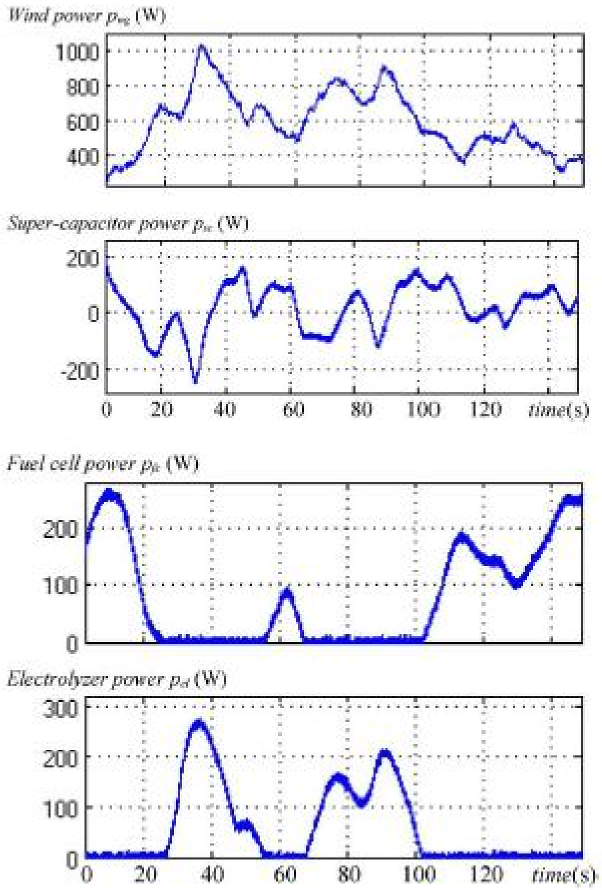

Fig. 6. Power profiles of the different sources.

CONCLUSION

The experimental tests have shown that the source-following strategy has better performance on the grid power regulation than the grid-following strategy. In this paper, a dc-coupled

HPS has been studied with the three kinds of energy sources: 1) a WG as a renewable energy generation system; 2) SCs as a fast-dynamic energy storage system; and 3) FCs with ELs and hydrogen tank as a long term energy storage system. The structure of the control system is divided into three levels: 1) SCU; 2) ACU; and 3) PCU. Two power-balancing strategies have been presented and compared for the PCU: the grid-following strategy and the source following strategy.

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