International Journal of Engineering Inventions
e-ISSN: 2278-7461, p-ISSN: 2319-6491
Volume 2, Issue 2 (January 2013) PP: 48-56

Hybrid Wind Generator Power Systems Coordinating and Controlling

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Abstract:- Wind energy is the world's fastest growing energy source. The amount of power generated by wind energy depends on the speed of the wind. Because of the intermittent and fluctuating wind speed they are not suitable to micro grid applications unless proper power and energy management strategies are available. Hence a Suitable method of giving stable active, reactive power is required. Hybrid power systems are proposed to overcome the problems with energy storage and power management strategies. Fuel cells (FCs) and electrolyzers (ELs) have high energy storage density. This makes them suitable for long term energy storage systems. In this paper a closed loop control system is presented which is well adapted to integrate the power management strategies. Two power management strategies are presented and simulated under normal and abnormal conditions. it's observed that the "source following strategy" has better performance on the grid regulation than the "grid following strategy". With the long term energy storage systems under abnormal conditions power absorbed or compensated is according to the system requirements.

Keywords:- wind energy, micro grid, hybrid power systems, fuel cells, electrolyzers,closed loop control

I. INTRODUCTION

Renewable energy sources (RES) have been attracting special attention all over the world since decades because of the following reasons:

1. Reduces dependency on imported fossil fuels.
2. Reduction of emission of the green house gases.
3. secured energy supply at all the times.

The low efficiency and high cost are the main drawbacks of RES. There is no proper control over the produced electrical power in case of Wind generators, Photovoltaic panels. If they are integrated without proper control strategies, they may lead to grid instability or even failure of grid, which ultimately may lead to total collapse of the system.Hence it is necessary to achieve stable active, reacting power at the generators. The electrical system must provide some ancillary service when connected to a micro grid. A hybrid power system with energy storage system and good power management strategies can be a solution [1-4].

1) Energy storage systems are used to compensate or absorb the difference between the generated wind power and the required grid power so that active, reactive powers are controlled. These are long term Energy storage systems including Hydrogen technologies, combining fuel cells (FCs) and electrolyzers (ELs).

2) Power management strategies are implemented to control the power exchange among different sources and to provide some services to the grid. They also provide ancillary services to the grid.

According to researchers, wind electrolysis is a very attractive candidate for an economically viable renewable hydrogen production system [5], [6]. Hydrogen, as an energy carrier, contributes directly to the reduction of dependence on imported fossil fuel [7], [8].

Flywheel systems are also suitable for fast-dynamic energy storage [9], [10]. However, this mechanical system is currently hampered by the danger of "explosive" shattering of the massive wheel due to overload (tensile strength because of high weight and high velocity). SCs are less sensitive in operating temperature than batteries and have no mechanical security problems.This paper develops a wind generator (WG), including three kinds of sources: they are

A RES: WG; 2) a fast-dynamic storage: SCs; and 3) a long-term storage: FC, EL, and H2 tank. Energy management strategies are implemented in the control system to satisfy the requirements while maximizing the benefits of RES and optimizing the operation of each energy unit [11].The power management strategies of the HPS control the DC bus voltage and also satisfying micro grid power requirements. These requirements are formulated as active, reactive power and calculated by a centralized secondary control unit in order to co-ordinate power dispatch of several power plants in a control area[12]-[15].The high reliability and high efficiency achieved with high reliable communication systems in the micro gird[16].In Sections II and III, the studied HPS structure is presented. The structure of the control system is closed loop. A closed loop system is better for integrating grid to the power management strategies. Two power management strategies are presented in Section IV. The simulation results are presented comparing their normal and abnormal performances in Section V, and conclusions are given in Section VI

II. HYBRID POWER SYSTEM (HPS) AND CONTROL SYSTEM

A. Structure of HPS

In this paper a DC coupled structure is use to decouple the grid voltages and frequencies from other sources. All sources are connected to main DC bus before being connected to the main grid inverter (fig1).Every source is electrically connected with a power electronic converter to get the best possible power control actions. The HPS structure and its global control system can be used for various combinations of sources [17], [18].

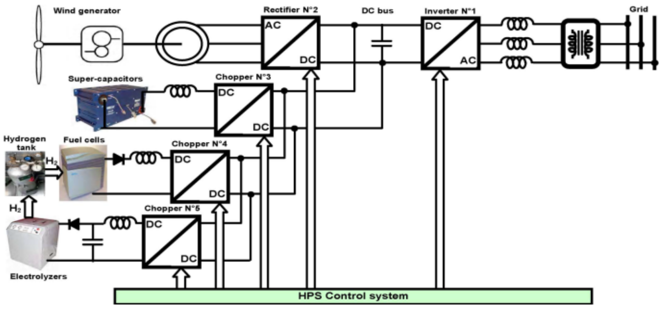

Fig1. Structure of the studied wind/hydrogen/SCHPS

B. Structure of Control system

Power converters introduce some control inputs for power conversion. In this paper, the structure of the control system can be divided into different levels (Fig. 2)

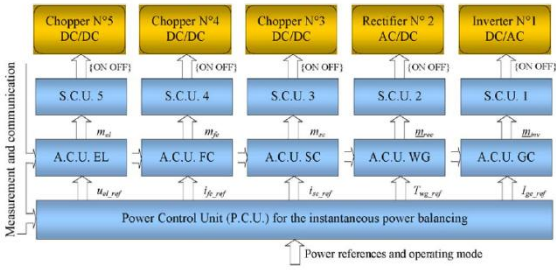

Fig.2. Hierarchical control structure of the HPS

The switching control unit (SCU) is designed for each power converter. In an SCU, the drivers with opto couplers 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).

The automatic control unit (ACU) is designed for each energy source and its power conversion system. The ACU consists of control algorithms to calculate the modulation functions (m) for each power converter according to their reference values.The power control unit (PCU) is designed to perform the instantaneous power balancing of the entire HPS in order to satisfy the grid requirements. These requirements are real- and reactive-power references, which are obtained from the secondary control center and from references of droop controllers. In a PCU, some power-balancing algorithms are implemented to coordinate the power flows of different energy sources. The different power-balancing algorithms correspond to a number of possible operating modes of the HPS and can be gathered.The purpose of this Paper is to present the power-balancing strategies in the PCU. In order to focus on the power-balancing strategies of the HPS, the control schemes of the power conversion systems through different power converters are not detailed. However, some explanations of the ACUs are given in the following paragraphs in order to make the controllable variables of the power conversion systems appear.

The control schemes in the ACUs are shown in Fig. 3 with block diagrams.

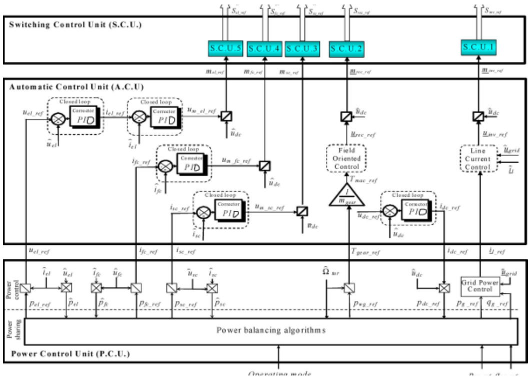

Fig3. Modeling and control of the HPS by the Energetic Macroscopic Representation

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-ref}).
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}).
3) The SC power conversion system is controlled with a current reference (i_{sc_ref}) through the dc chopper N◦3. The SC bank is considered as an equivalent voltage source (u_{sc}).
4) The wind energy conversion system is controlled with a reference of the gear torque ($T_{gear\_ref)}$ by the three-phase rectifier N◦2.
5) The grid connection system consists of a dc-bus capacitor and a grid power conversion system. The grid power conversion system is controlled with line-current references (i_{l_ref}) by the three-phase inverter N◦1, because the grid transformer is considered as an equivalent voltage source (u_{grid}).

The dc-bus voltage is described as In order to control the dc-bus voltage, a voltage controller must be used. The output of the voltage controller is a current reference i_{dc_ref} (Fig. 3).

$c_{dc} = \frac{du_{dc}}{dt} = i_{dc}$ ………………………………..(1)

III. P.C.U

A. Lay out of PCU

The power modeling of the HPS can be divided into two levels: the power calculation level and the power flow level (Fig. 4). 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 (Fig. 4), which was developed by Peng Li in 2008[19].

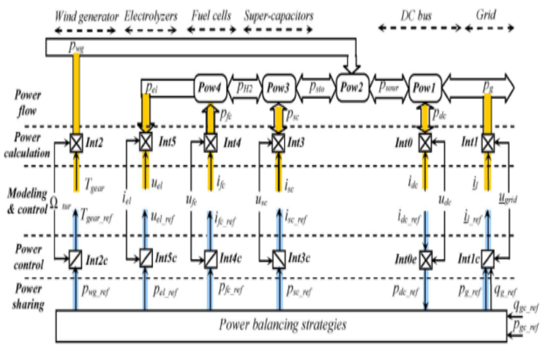

Fig 4 Multilevel representation of the power modeling and control of the HPS

A.Power Control Level:

To achieve maximum amount of power from wind energy conversion system, maximum power point tracking system is used [20]. 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). The powers expressions are derived and given in Table I. 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 (Int3c, Int4c, and Int5c in Table I).

TABLE I SUMMARY OF EQUATIONS FOR POWER CALCULATION

Generator or storage system	Power calculation	Power control
DC BUS VOLTAGE	Int0: $p_{dc} = u_{dc}.i_{dc}$	Int0e: $p_{dc-ref} = u_{dc} i_{dc-ref}$
GC GENERATOR	Int1: $p_g = u_{13} i_1 + u_{23} i_2$ $q_g = \sqrt{3(u_{13} i_1 - u_{23} i_2)}$	$i_{i1-ref} = \frac{(2u_{13} - u_{23})p_{g-ref} + \sqrt{3}u_{23}q_{g-ref}}{2u_{13}^2 - 2u_{13}u_{23} + 2u_{23}^2}$ $i_{i2-ref} = \frac{(2u_{23} - u_{23})p_{g-ref} - \sqrt{3}u_{13}q_{g-ref}}{2u_{13}^2 - 2u_{13}u_{23} + 2u_{23}^2}$
WG WIND GENERATOR	Int2 : $p_{wg} = \Omega_{gear} t_{gear}$	Int2c: $t_{gear-ref} = \frac{p_{wg-ref}}{\Omega_{gear}}$
SC SUPER CAPCITOR	Int3 : $p_{sc} = u_{sc} i_{sc}$	Int3c: $i_{sc-ref} = \frac{p_{sc-ref}}{u_{sc}}$
FC FUEL CELL	Int4 : $p_{fc} = i_{fc} u_{fc}$	Int4c: $i_{sc-ref} = \frac{p_{sc-ref}}{u_{fc}}$
EL ELECTROLIZER	Int5 : $p_{el} = i_{el} u_{el}$	Int5c: $u_{el-ref} = \frac{p_{sc-ref}}{i_{fc}}$

The maximal-power-point- tracking (MPPT) strategy extracts the maximum power of the available wind energy according to a nonlinear characteristic in function of the speed. It receives the measured rotational speed (Ω_{tur}) and sets a desired power reference (p_{wg_ref}) (Int2 and Int2c in Table I).

The output of the dc-bus voltage control loop is the current reference (idc_ref) of the dc-bus capacitor, and its product with the measured dc-bus voltage gives the power reference (p_{dc_ref}) for the dc-bus voltage regulation (Int0e). The powers, which are exchanged with the grid, can be calculated with the "two-wattmeter" method (Int1 and Int1c in Table I). In order to focus on the power exchanges with the different sources around the dc bus, the instantaneously exchanged power with the choke, the losses in the filters, and the losses in the power converters are neglected.

C. 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}).

$\frac{de_{dc}}{dt} = c_{dc} u_{dc} \frac{du_{dc}}{dt} = p_{dc} = p_{wg} + p_{sc} + p_{fc} - p_{el} - p_g$ ……………(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: $p_g = p_{source} - p_{dc}$ ………(3)

POW2: $p_{source} = p_{sto} + p_{wg}$ …… (4)

POW 3: $p_{sto} = p_{h2} + p_{sc}$ ……….. (5)

POW4: $p_{h2} = p_{fc} - p_{e;}$………….. (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.

1) The grid-following strategy uses the line-current loop to regulate the dc-bus voltage.

2) The source-following strategy uses the line-current loop to control the grid active power, and the dc-bus voltage is regulated with the WG and storage units

IV. POWER BALANCING STRATAGIES

A. 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 ($p_{dc\_ref} \rightarrow p_{g\_ref} \rightarrow p_g \rightarrow p_{dc}$). Thus, the required power for the dc-bus voltage regulation (pdc_ref) is used to estimate the grid power reference (p_{g_ref}).

POW 1E: $P_{g\text{-}ref} = p_{source} - P_{dc\text{-}ref}$ ....(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

Pow 2E: $p_{source} = P_{wg}+P_{sto}$..................... (8)

The energy storage systems help the wind energy conversion system satisfy the power references, which are asked by the microgrid operator

POW 3E: $P_{sto} = P_{sc}+P_{h2}$................. (9)

POW 4E: $Ph_2 = P_{fc} - P_{el}$.................... (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 (p_{gc_ref}), it must be equal to the sources' power reference (p_{sour_ref}),as shown inFig6 .

POW 1 C: $P_{source\text{-}ref} = p_{g\text{-}ref} = p_{gc\text{-}ref}$ ... (11)

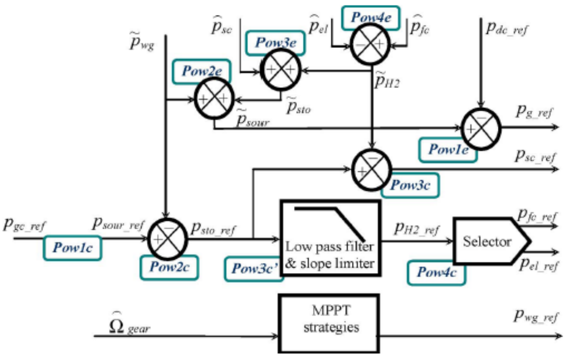

Fig.5 Block diagram of the grid-following strategy

In order to help the wind energy conversion system respect the active-power requirement, the energy storage systems should be coordinated to supply or absorb the difference between this power requirement (pgc_ref) and the fluctuant wind power (pwg), as shown in Fig. 6

POW 2C: $p_{sto-ref} = p_{sour-ref} = p_{wg}$...... (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. For efficiency reasons, the FC and the EL should not work at the same time. The activation of the FC or the activation of the EL depends on the sign of the reference (p_{H2_ref}). Thus, a selector assigns the power reference (p_{H2_ref}) to the FC (p_{fc_ref}) or to the EL (p_{el_ref}) according to the sign of pH2_ref (Fig. 6)

Pow4C:

IF: $p_{h2-ref} > \varepsilon 1, p_{fc-ref} = p_{h2-ref}; p_{el-ref} = 0$

IF: $p_{h2-ref} > \varepsilon 1, p_{fc-ref} = 0; p_{el-ref} = 0$

IF: $p_{h2-ref} < \varepsilon 1, p_{fc-ref} = 0; p_{el-ref} = p_{h2-ref}$

However, the power reference (p_{sto_ref}) is a fast-varying quantity due to the fluctuant wind power (pwg) and the varying grid power (pg). In order to avoid the fast-chattering problem when it is close to zero, it should be slowed down. Moreover, the FCs and the ELs have relatively slow power dynamics, and fast-varying power references are not welcome for their operating lifetime. Therefore, a low-pass filter (LPF) with a slope limiter should be added (Fig. 6)

POW3C: $P_{h2\text{-}ref} = 1/(1+Ts)*p_{sto\text{-}ref}$ ……………(14)
where τ is the time constant of the LPF and should be set large enough by taking into account the power dynamics of the FCs and the ELs, as well as the size of the SCs. The SCs are not made for a long-term energy backup unit because they have limited energy storage capacities due to their low energy density. However, they have very fast power dynamics and can supply fast-varying powers and power peaks. They can be used as an auxiliary power system of the FCs and ELs to fill the power gaps during their transients
POW3C ' : $p_{sc-ref} = p_{sto-ref} - p_{h2} = p_{sto-ref} - p_{fc} + p_{el}$ …………….. (15)
The block diagram of the grid-following strategy for the active WG is shown in Fig. 7.

B. Source-Following Strategy:

The total power (p_{sour}) 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 (p_{sour_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 Pow1 (Fig. 8)
POW 1C: $p_{sou-ref} = p_{dc-ref} + p_g$……… (16)

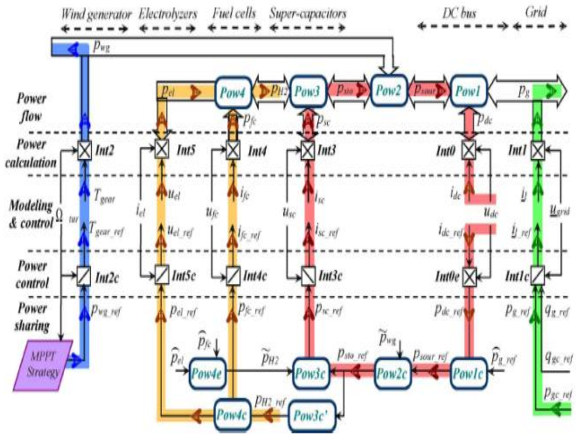

Fig.6 Multilevel representation of the source following strategy

Then, the total power reference of the storage systems is deduced by taking into account the fluctuant wind power with the inverse equation of Pow2 (Fig. 6)
POW2C: $p_{sor-ref} = p_{sour-ref} - p_{wg}$ .... (17)

Hence power is shared among the FCs, the ELs, and the SCs in the same way as explained earlier (Pow2c, Pow3c, Pow4c, and Pow'3c). In addition, now, the grid power reference (p_{g_ref}) is free to be used for the grid power control. The micro grid system operator can directly set the power requirements (p_{gc_ref} and q_{gc_ref}) for the grid connection system ($p_{g\_ref} = p_{gc\_ref}$). Therefore, the HPS can directly supply the required powers for providing the ancillary services to the microgrid, like the regulations of the grid voltage and frequency.

V. RESULTS

A. Power Profile of Different Sources

Mat lab simulation is carried out for both strategies, grid, source respectively). The active-power requirement from the micro grid is assumed to be pgc_ref = 600W. Similar power profiles are obtained for the energy storage systems Fig.9 (a), 9(b), 9(c), 9(d).

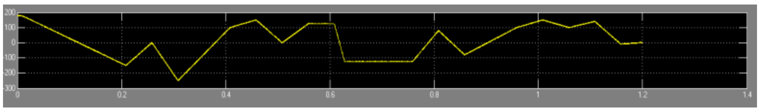

Fig.9(a): Power profile for fuel cell

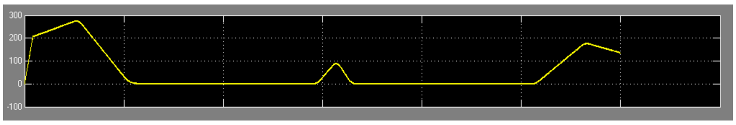

Fig.9(b): Power profile for super capacitor

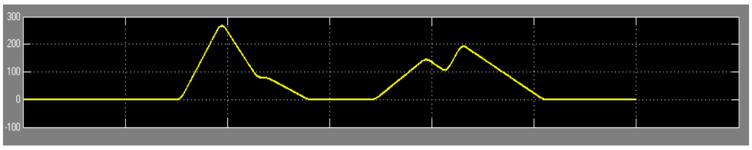

Fig.9(c): Power profile for electrolyses

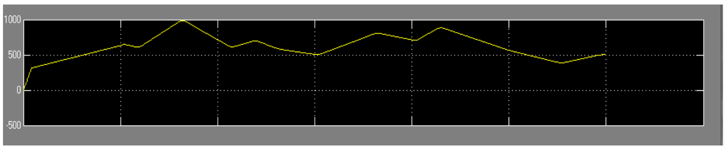

Fig.9 (d): Power profile for wind generator

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. Since the power dynamics of the FCs and the EL are limited by an LPF with a 5-s time constant, they are not able to filter the fast fluctuations of the wind power.

Therefore, the SCs supply or absorb the power difference. During transients the grid reactive power shown in fig.13.When SCs are activated grid reactive power stabilized as shown in fig.14

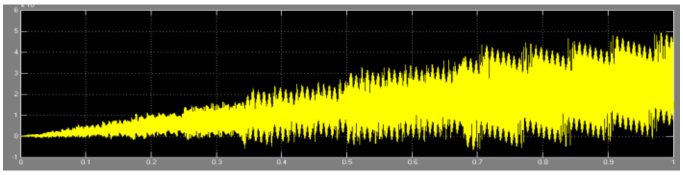

Fig.13: grid reactive power during transients

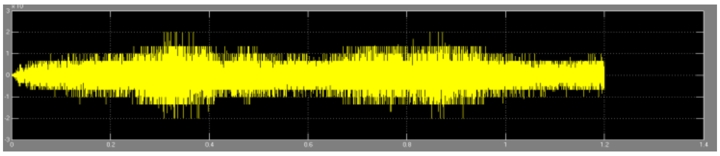

Fig14: grid reactive power after stabilization

B. Grid Following Strategy

In the grid-following strategy, the dc-bus voltage is well regulated around 510 V by the grid power conversion system (Fig. 10). The energy storage systems help the WG supply the micro grid power requirement (psour = pgc_ref = 600 W).Because of the different power losses in the filters and power converters, the grid active power is slightly less than the micro grid's requirement as shown in fig.11
(pg < pgc_ref = 600 W).

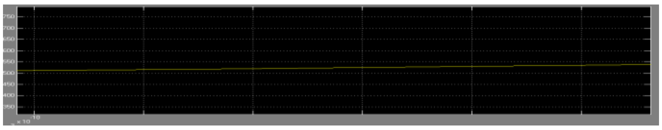

Fig.10: Output waveforms of DC bus voltage V

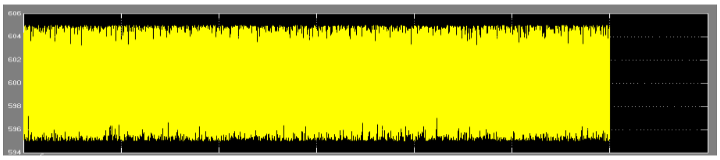

Fig.11: grid active power P_g

C. 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 (exactly 400 V) against the fluctuant wind power (Fig. 12). The grid active power is also regulated and is equal to the micro grid's requirement, because the line-current control loop regulates directly the grid powers (pg = pgc_ref = 600 W).

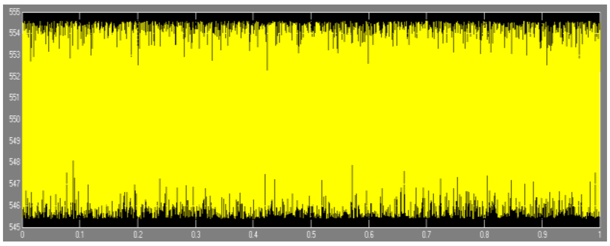

Fig.12: grid active power P_g(source following strategy)

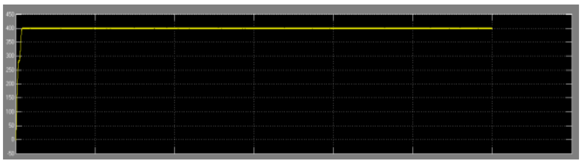

Fig.13: Output waveforms of Dc bus voltage V(source following strategy)

VI. CONCLUSION

In this paper a DC coupled HPS has been studied with the three kinds of sources:1)WG generator (WG), including three kinds of sources: 1) a RES: WG; 2) a fast-dynamic storage: SCs; and 3) a long-term storage: FC, EL, and H2 tank. The two energy management strategies the grid following and the source following are presented The Dc bus voltage is well regulated with source following strategy. The simulation results shows that he with the introduction of energy storage system, better control over the active and reactive power is observed.With the encouraging results for the grid connected sources, non conventional energy sources will be utilized frequently. Hence with proper energy balancing and power control strategies grid following or source following strategies can be used. With further advances in technologies, SC's can be made less sensitive in operating temperature than batteries and have no mechanical security problems. With the progress in technology, super capacitors (SCs) may become the best candidates as fast dynamic energy storage devices, particularly for smoothing fluctuant energy production, like wind energy generator. Therefore, the source following strategy has better performances on the grid power regulation than the grid-following strategy and it can provide ancillary services according to the micro grid's requirements as shown in fig.13.

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