Optimal Load Sharing Strategy in a Hybrid Power System based on PV/Fuel Cell/ Battery/Supercapacitor

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Abstract—This paper presents an optimal load sharing strategy for a PV/FC/battery/supercap hybrid power system that optimizes the system performance. The fuel cell is used to complement the intermittent output of the PV source while the battery storage is used to compensate for part of the temporary peak demand which the PV and fuel cell can’t meet thus avoiding oversizing of fuel cell. Supercapacitor energy storage is employed to relieve the battery of narrow and repeated transient charging and discharging ensuring longer battery life. Both the battery and the supercapacitor cover the slow power response of the fuel cell. A power flow control strategy is developed and simulation results are presented to demonstrate its effectiveness.

Index Terms—Hybrid, Fuel cell, Photovoltaic, Battery, Supercapacitor, MPPT, DC/DC Converter.

I. INTRODUCTION

Depletion of conventional energy sources as fossil fuels, growing awareness of impact of environmental pollution and abundance of renewable energy have motivated immense interest towards alternative energy sources [1]. Solar (photovoltaic) energy is a major renewable energy source at the forefront of stand-alone and distributed power systems.

Photovoltaic (PV) power systems are, however, dependent on climatic conditions making them an intermittent power source. Their output varies with the amount of solar radiation available and ambient temperature. Therefore, the generated power depends on the time of year, time of day and the amount of clouds. A stand-alone PV-based power system needs, therefore to be hybridized with either other complementary energy-sources or storages to ensure a reliable power supply. Use of fuel cells (FC) in combination with a PV generator may ensure an uninterruptible power supply as long as the fuel cell power can meet the power deficit. Fuel cells show a particular promise as they can operate on hydrogen with zero emissions, have a relative high efficiency (30-60%), and have a limited number of moving parts with a flexible modular structure [1],[2]. The fuel cell can either be supplied with hydrogen from purchased gas containers or be produced from water in an electrolyzer which is supplied with surplus power from the PV system. In fuel cells, the power and energy is decoupled, which is opposite to when secondary batteries are used as energy storage. In this paper the case with fuel cell supplied from a hydrogen container is considered.

One problem with the fuel cell is its relative slow dynamics caused by the time constant of the hydrogen and gas supply systems that can be in the order of several seconds [3]. If a fuel cell was connected to a step increase in load, it would provide the current, but the voltage could instantaneously drop off the V-I curve and the fuel cell would take several seconds until it begins feeding the required power. In the mean time the fuel cell may be starved of fuel which is not good for the electrocatalyst shortening its life [4]. Therefore, the fuel cell should be operated under controlled dynamic regimes, ensuring an optimum performance and durability of the fuel cell.

Batteries and supercapacitors (SCs) respond faster than a fuel cell for a fast step increase or decrease in power demand. Thus using these energy storage(s) together with fuel cells improves performance and fuel cell life by absorbing faster load changes and preventing fuel starvation of the fuel cell. Adding these storages will enable the hybrid system to follow fast changing loads while allowing the fuel cell to respond at a slower rate. In addition, by sizing the battery to supply the peaking load in surplus of what can be met by the fuel cell and PV, the fuel cell can be sized only for the base (average) load. This avoids oversizing of the fuel cell as long as the battery swing can cover the deficit peaking load duration increasing the peak power capability of the system. To guarantee an increased lifetime of the battery, a supercapacitor is used in parallel to relieve the battery of stresses due to steep, shorter and more frequent transients while the battery takes on more extended peak loads. The supercapacitor can have almost unlimited cycling capability but lower energy density as opposed to the battery with limited cycling and higher energy density[5].

The hybrid power system proposed in this paper can be an attractive option for remote applications away from utility AC mains. One such application is remote telecommunication systems. Most of the hybrid power systems in use today for remote applications have a diesel genset as an important component. Using fuel cells instead of the traditional diesel generator as back up for reliability of power availability has advantages. In addition to being environmental friendly, fuel cells require much less maintenance as opposed to diesel
engines which would require regular maintenance which is very expensive at a remote site.

II. PROPOSED HYBRID POWER SYSTEM

The architecture in Fig. 1 is proposed for the hybrid power system which is based on the centralized DC-bus system [1],[6]. In the centralized DC-bus configuration, all the sources and storages are coupled to a common DC bus before they are connected to the load. The load in the figure stands for either a DC-load or a voltage source inverter depending on the application.

Fig. 1. Architecture of proposed hybrid power system.

The PV generator is coupled to the DC bus via a buck-based DC/DC maximum power point tracker (MPPT) to track the maximum power point where the PV plant generates the maximum possible power output for a given irradiance, ambient temperature and loading condition. This enables to utilize the renewable energy to the maximum.

The low and highly variable load dependent voltage of the PEM fuel cell stack is boosted to the DC-bus level via a phase shifted PWM (PSPWM) transformer isolated DC/DC converter. The converter is current controlled to shape the fuel cell output to safe magnitude and rate.

A low volt-ampere(VA) rated buck DC/DC converter steadily charges the Lithium-ion battery during light loading when the bus voltage becomes higher than the battery voltage. When the bus voltage goes below the battery voltage which is indication of a heavier loading in surplus of the power output from the fuel cell and PV combined, the diode becomes forward biased discharging the battery. During the longer period of normal loading, the low VA DC/DC converter having smaller inductor charges the battery slowly at steady-state. The battery charger is also current controlled to control the charging current depending on the status of the bus voltage compared to the battery voltage.

With a maximum supercapacitor voltage never exceeding the bus voltage, a bidirectional half bridge DC/DC converter is used which operates in boost mode when discharging and buck mode when charging the supercapacitor. This converter is also current controlled.

A large conventional capacitor acting as an immediate power buffer is used to form the DC-link voltage to and from which all sources and storages feed and take power.

III. LOAD SHARING STRATEGY

For reliability and balance of power, the relation in (1) should be met at all times.

\[ I = I_{FC} + I_{Bat} + I_{SC} \]  

where I is the load current minus the PV current, and all currents are seen from the DC-bus. The values and signs of the currents seen from the DC-link depend on the type of loading at that instant and which strategy that is used.

The basis for the load sharing strategy adopted should be in line with the following objectives:

1) Maximum utilization of PV source
2) The fuel cell source is used to complement or replace the PV and should be used as minimally as possible to save fuel
3) Battery is used as a temporary energy storage to shave the peak load requirement in excess of PV plus fuel cell
4) The supercapacitor is used to supply or sink high, narrow and more frequent transient loads
5) High degree of availability of power supply
6) Safe operation of fuel cell stack and battery

Based on the above objectives the fuel cell is sized to supply the steady state or average load demand and always fills the valleys of the fluctuating PV power output by automatically adjusting its output. The battery is sized such that the maximum allowed charge swing should cover the peaking duration even without the PV generator. The supercapacitor is sized to swing between the voltages \( V_{\text{min}} \) and \( V_{\text{max}} \) while supplying the energy given in (2) which should be sufficient to compensate for the duration of the power transients where \( V_{\text{min}} \) and \( V_{\text{max}} \) are the minimum and maximum voltages and \( C \) is the capacitance of the supercapacitor.

\[ E = \frac{1}{2} \left( V_{\text{max}}^2 - V_{\text{min}}^2 \right) \]  

IV. POWER FLOW CONTROL

An effective, active control of power flow from sources and to/from storage devices is required to maintain power balance at all times while satisfying the objectives described in section 3. This should keep the DC bus voltage within a given band around a nominal voltage.
This can be achieved by having a lower level control of the component converters which directly modulates the switches and a higher level supervisory monitoring to decide how and in which mode the converters should be controlled. Each component has its own embedded controller incorporated into its converter to directly control the amount, direction and rate of power flow. The supervisory control is effected within a power flow management center (PMC) which takes as input the instantaneous bus voltage, and currents and voltages from battery, supercapacitor, fuel cell and PV and outputs appropriate signals to the different subsystems. The bus voltage is used as the main control parameter to indicate the level of loading at any instant to prompt more or less power output from the FC, battery or supercapacitor.

A. PV Subsystem

To fully utilize the renewable energy from the PV, it should normally be operated at the maximum power point. A buck converter based MPPT is used to achieve this. The MPPT adopted in this paper uses the one reported in [7] due to its simplicity and effectiveness. Any surplus PV (plus FC) energy than required by the load is used to charge the battery and supercapacitor. But excess energy, may still overcharge the DC bus. Therefore, during times of very high PV output and low loading where the PV energy becomes excess of what is required for charging and meeting the load demand, some of the PV energy is dumped by deviating the PV operating point away from the MPP or using a dump load.

The first case can be handled by having two modes of control for the PV converter where the control changes from MPPT mode to MPP deviate mode when the bus voltage exceeds a given reference and back to MPPT mode when the voltage goes below this reference. Therefore, the duty cycle of the PV converter is generated for maximum power within the PMC during MPPT mode and directly in the converter control for bus voltage control during MPP deviate mode. The PV subsystem control is depicted in Fig. 2.

B. Fuel Cell Subsystem

The fuel cell DC/DC converter boosts the fuel cell voltage to the DC bus voltage level. The converter should be controlled to keep the bus voltage around a set point. It should control the fuel cell power output such that when the DC link voltage is low as in, for example, heavy loading or low battery or supercap charge, more power flows from the fuel cell into the bus while the current flow from the FC decreases as the DC link gets full, as in light loading and full battery and supercap charge.

The control objective is carried out by using an external DC-link state of charge control loop which takes the bus voltage set point as reference and produces a FC current reference. This outer control can be a simple proportional controller with gain set to a value which would draw maximum fuel cell current when the DC link reaches the maximum depth allowed. The maximum depth of discharge translates into the lower limit of the bus voltage band. A very fast internal current control loop implemented as PI is employed which uses the FC reference current set point to control the FC output current as shown in Fig. 3. The FC stack reference current is also continuously fed back to the hydrogen and air supply system to generate the required flow rates to meet the demanded power.

Use of a current controller also makes it possible to regulate the safe current limit of the FC. The external control is also equipped with a rate limiter to produce a ramping current reference allowing the fuel cell to respond at the required rate. The rate employed can depend on the type of the fuel cell used and the fuel and air supply time constants or whether the FC is cold or is required to power a step load.

C. Battery Subsystem

The battery is charged during low loading from the PV and fuel cell via a smaller buck converter. It is rated for a lower charging current rather than a large discharge current which would be the case if a bidirectional buck/boost were used. Therefore, the converter will be
able to charge the battery slowly but with a smaller charging current.

The PMC decides whether the battery is charged or discharged depending on the voltage of the DC bus with respect to the battery voltage. It compares the two voltages and gives a charge or discharge signal to the battery controller in the form of a switch on or off of the converter PWM. The possible scenarios at some instant of time are explained below.

When \( V_{batt} < V_{bus} \), assuming the bus nominal voltage is equal to the full charge voltage of the battery, this condition occurs when the battery is not full. In this case the PMC switches on the buck converter PWM. The battery controller now generates the switch duty cycle depending on charging current reference set by an outer battery voltage control as was done for the fuel cell subsystem. The reference voltage to the outer loop is set around the full charge battery voltage. Magnitude and rate limit of the reference current inherently keeps charging current within safe limit and allows the supercapacitor to take only narrow power spurts by delaying the rate of battery charging. A fast hysteresis controller is used for the inner current control as shown in Fig. 4.

![Fig. 4. Battery Subsystem](image)

The condition \( V_{batt} > V_{bus} \) occurs during a higher loading as in peak load which may have drawn some of the immediate energy in the DC link or during a step increase in load which the FC can’t immediately respond to. In this case the PMC sends a discharge signal switching the converter off. The diode naturally becomes forward biased to allow discharging until the DC link voltage reaches the nominal value either due to the peaking duration is over or the fuel cell has now started supplying sufficient power.

**D. Supercapacitor Subsystem**

With maximum capacitor voltage never exceeding the bus voltage a bidirectional half bridge DC/DC converter is used which operates in boost mode when discharging and buck mode when charging the supercap. The buck boost converter is also current controlled whose set point is determined by the status of the DC bus voltage.

The control strategy for the SC subsystem is shown in Fig. 5. The PMC produces a reference voltage to the controller such that its value is the minimum supercap voltage if the bus voltage goes below the nominal value and maximum supercap voltage otherwise producing two sets of reference currents for the inner loop.

![Fig. 5. Supercapacitor Subsystem](image)

These operations correspond to a discharge and charge operations respectively.

**V. SIMULATION RESULTS**

To test the effectiveness of the control strategy, the system is simulated in SIMULINK/SIMPOWER over a 1000 second cycle for the load profile shown in Fig. 10. The load has an average value of 1.1kW, a peaking portion of double the average value over a duration of 150s and a power spurt over 10s of 2.4kW. The load profile is designed to test whether all objectives have been satisfied. A conventional capacitor of 0.3F is used for the 48V DC bus.

The fuel cell is a 1.2kW, 12-20V, PEM. A steady state model based on a nonlinear fit of measured data to the well known equation (3) is implemented [8].

\[
E = E_o - b \log i - Ri - m \exp(mi) \tag{3}
\]

The PV source is modeled as an output of an MPPT over 1000s and is implemented with SIMPOWER controlled current source block. The PV output is a variable power source with average value around 1.2kW.

A 11Ah, with full charge voltage 48V Lithium ion battery is used. A user defined model of SIMPOWER is implemented by calibrating the model to charge/discharge curves given by the manufacturer.

A simple SIMPOWER capacitor with ESR and leakage resistances is used to model the supercapacitor.
The capacitance of the supercapacitor bank was calculated to supply 2.4kW (50A) constant power for 10s using equation (2) with a charge swing from maximum voltage of 48V to minimum voltage of 24V as shown in (4) where losses have been neglected. A maximum depth of 50% of nominal voltage allows a 75% energy utilization while keeping the converter switch rating reasonably lower [9].

\[
\begin{align*}
\frac{1}{2} C (V_{\text{max}}^2 - V_{\text{min}}^2) &= \Delta t \times V \times I \\
\frac{1}{2} C (48^2 - 24^2) &= 10 \times 48 \times 50 \\
C &= 27.77 F
\end{align*}
\]

The gain of the bus voltage controller for the fuel cell subsystem should be able to produce the maximum fuel cell reference current for the lower limit of the bus voltage band. It is calculated as in (5).

\[
\text{Gain} = \frac{I_{f_{\text{cell}}}^{(\text{max})}}{V_{\text{bus}(\text{ref})} - V_{\text{bus(min)}}}
\]

All converters are modeled as switched models in SIMPOWER. Currents and voltages have been low pass filtered.

Fig. 6. and Fig. 7. show how accurately the battery and fuel cell current controllers follow the trajectories of their current references. The intended rates as well as limits of the fuel cell and battery currents have been achieved with very good accuracy. The charging current of the battery has been limited to 30A and the fuel cell current to 25A.

The DC link voltage is also well controlled and kept within 45 to 50V throughout the whole period as shown in Fig. 8.

\[
SOC(t) = SOC_0 + \frac{1}{C_{\text{rated}}} \int_{0}^{t} i_{\text{batt}}(t) dt
\]

Fig. 8. DC-link voltage.

Fig. 10. shows how the load current is shared among the different sources and storages. All currents are with respect to an almost constant 48V bus voltage. At t=0s, the battery is 50% SOC, the fuel cell is producing almost zero power and the supercapacitor is fully charged. Initially the PV power is sufficient to meet the load requirements. However, more power is required to charge the battery. This power can only come from the fuel cell and it is shown that the fuel cell slowly ramps up to 25A (full capacity). At 25s, the battery is being charged at a combined PV/FC current of 30A.
At around t=173s, because of the surplus PV power the FC starts saving power. A power spurt of 10s at 200s initiates the supercap to respond fast while the battery smoothly reduces its charging current but never discharges.

Fig. 9. State of charge of battery.

Around 350s, the peaking duration starts. Initially the supercap relieves the battery of steep power change. The fuel cell operates at full capacity and ultimately the battery supplies the rest of the peaking load for the remaining of 150s duration.

Starting t=800s, the fuel cell starts saving power since the combined PV/FC power is surplus of the load and maximum battery charging current. Towards the end of the 1000s, the fuel cell is almost fully at power save mode as the battery gets fully charged.

Note that the supercap quickly gets charged after discharging as the bus voltage restores to nominal value which is the control requirement for the charging of the supercapacitor.

VI. CONCLUSIONS

An effective load sharing and control strategy has been developed for a PV/FC/Battery/Supercap hybrid power system that optimizes availability, performance, fuel economy and safety. The simulation results show that the control strategy is effective in meeting high degree of power availability, and reduced cycling of battery. The battery is also relieved from steep charging currents by slightly delaying the current reference improving charging efficiency and enabling the supercapacitor efficiently to take the steep currents. A near full controllability of battery, supercap and fuel cell enables operation of the units within safe limits in addition to making it possible to shape the trajectories of their power responses.

REFERENCES