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An overview of micro-grid architecture with hybrid storage elements and its control .

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Abstract

This paper discusses the role of hybrid energy storage systems in future grids, especially micro-grids, to improve the penetration of renewable energy sources. The storage systems are essential in the future grids to improve the power quality and maintain the grid stability under high penetration of renewable sources. The use of more than one type of energy storage elements in the grids with different response times will help in improving the efficiency and reliability of the storage systems. The different control strategies for load sharing among these storage devices are also discussed in this paper.

Keywords:
Renewable energy systems, micro-grids, hybrid storage systems, hierarchical control, voltage control, frequency control.

1. Introduction

Renewable energy sources have found increased penetration into the global electric grid over the past few years. Traditionally electric grids have relied on fossil fuel based centralized generation systems over many years. This was aided by their high reliability, low capital investment and easiness in deployment. In the present scenario with the increasing fuel prices and the stringent emission norms imposed due to the effects of global warming, renewable clean energy sources have found greater prominence (Tucker and Negnevitsky, 2011). Till 2016, according to the World Wind Energy Association (WWEA) the estimated amount of wind power installation in the world is 456 GW and similarly high penetration has been observed in the amount of Photovoltaic (PV) installations in the world. The Figure 1 shows the percentage renewable and their distribution in electricity generation as obtained from Sawin et al. (2016). Unlike the conventional source of power generation an interesting feature of the renewable energies are that they can be viable in a centralized mode of generation and also in a decentralized mode where every consumer can contribute to the generation through small installations (Denholm et al., 2010). This distributed generation is an integral part of micro-grids.

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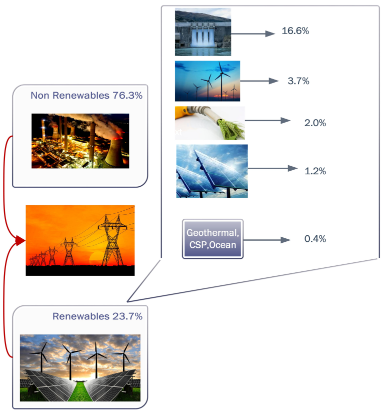

Figure 1: Renewable energy share as of 2015 in electricity generation

1.1. *Micro-grids*

A micro-grid can be defined as a network comprising of many distributed generating units, its load and intermediary energy storage units mostly connected to an Low Voltage (LV) network (Lopes et al., 2006)(Vafaei, 2011). The micro-grids are highly prominent in islanded systems where the possibility of connecting these systems through long transmission lines cannot be economically viable. The micro-grids with its self sustaining structure is an attractive solution (Katti and Khedkar, 2007). Nowadays in main grids certain portions can be isolated and realized as micro-grids with the distributed generation. Many such examples of these implemented physically are highlighted in Lidula and Rajapakse (2011). The micro-grids have two modes of operations, a normal interconnected mode where it is connected to main grid and exchanges power with the it. The second mode is the emergency mode which is the islanded mode of operation usually done during events of fault in main grid (Lopes et al., 2006). This also improves the reliability of the system

1.2. Issues with increased penetration of renewable systems

As discussed above the renewable energy systems provides the obvious advantage of a clean source of energy. The main disadvantage with the renewable systems is the lack of inertia which was provided by the conventional synchronous generator to the grid. This can lead to serious stability issues in the grid during load fluctuations if the renewable sources are not able to meet the load requirements quickly (Jain and Agarwal, 2008). The major drawbacks of the renewable energies especially in Distributed Generation (DG) are :

- *The frequency* variation and voltage variation caused due to imbalance in supply and demand which becomes prominent with lack of system inertia.
- *The power quality* supplied to the grid can be affected since renewable sources producing DC power need power electronic converters for grid connection. These converters inject harmonics into the grid causing degradation of power quality. Converter with active filter have helped mitigate this issue to great extent but at the cost of increased system complexity.
- *Protection* is another issue with renewable sources in DG as every system needs to be protected against fault both internal and external. This makes design of system more complicated (Coster et al., 2011),(Lopes et al., 2007), (Driesen and Belmans, 2006).

The renewable systems have a highly inconsistent nature of power supply. For example a wind turbine will not produce same power throughout day depending on the wind conditions and similar is the case with the PV systems where the power is dependent on the amount of sunlight. This issue can be mitigated to a great extend by using complementary renewable sources. An example of this is again the wind and PV systems where the PV system produce more energy during the day time and the wind power systems produce more during night time thereby providing a uniform power supply throughout the day. This is not an effective solution though (Tucker and Negnevitsky, 2011)(Lopes et al., 2006).

Therefore problems with the renewable DGs are mainly due to the inconsistent nature of its power output and the imbalance between the supply and demand. The energy storage elements are a good solution for this (Denholm et al., 2010)(Valenciaga and Puleston, 2005). This paper serves as a introduction on the storage devices and micro-grids control architecture. It discusses some of the relevant control issues and work that has been done in this area. The section 2 discusses the storage devices used most prominently and compare the different devices with each other. The section 3 discusses the control architecture and strategies for various modes of the micro-grids that has been put forward by various literatures.Section 4 provides overview of some basic converter topologies that can be used for energy storage systems. The modelling procedure is also highlighted in this section. Section 5 shows a control architecture for the storage systems. Section 6 provides an overview of some of the load sharing algorithms put forward by some of the literatures. Finally the paper is concluded in section 7.

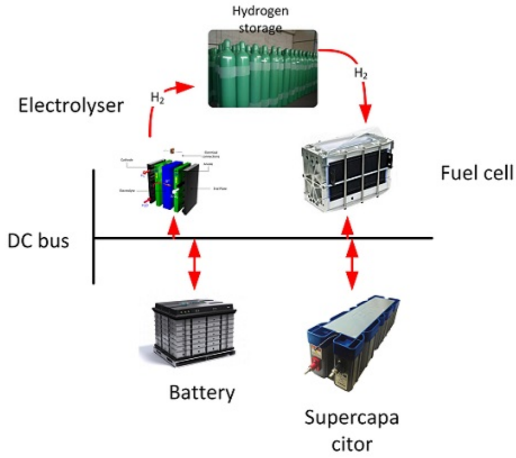

Figure 2: The connection of different storage elements in DC micro-grid

2. Overview of storage systems

Storage systems along with renewable energy sources improve the reliability and power quality of the grid. The storage elements caters to the following requirements in the grid (Lidula and Rajapakse, 2011):

- Ensure power balance in the grid
- Provide ride through capability under dynamic variations
- Enable seamless transition from islanded mode to normal modes in micro-grids.

The most commonly used energy storage devices are flywheels, fuel cells, batteries and super capacitors (Lidula and Rajapakse, 2011). Among these the flywheel is not very attractive solution nowadays mostly due to issues of its self discharge, need for vacuum chambers and maintenance for the superconducting bearings required (Fuchs et al., 2012)(Hedlund et al., 2015).

The fuel cell may not be classified exactly under the category of energy storage element. The fuel cell converts the chemical energy in hydrogen to electrical energy. The fuel cells when used with an an electrolyser can be considered as an energy storage system since the electrolyser can be used to generate hydrogen for the fuel cell by using the grid energy. The fuel cells offer high energy density as it stores energy in the form of external fuel, hydrogen (Chao and Shieh, 2012),(Little et al., 2007).The fuel cells have a considerably long lifetime of 20 years compared to other competing technologies

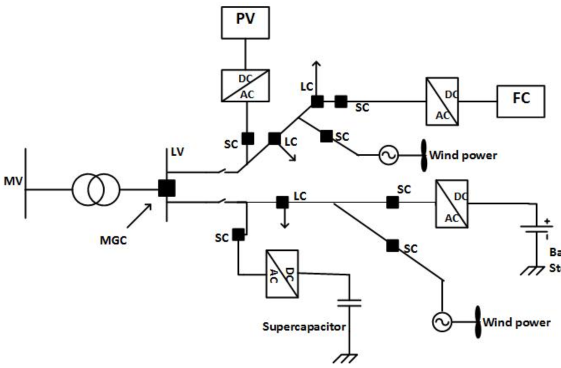

Figure 3: A general micro-grid layout with control elements

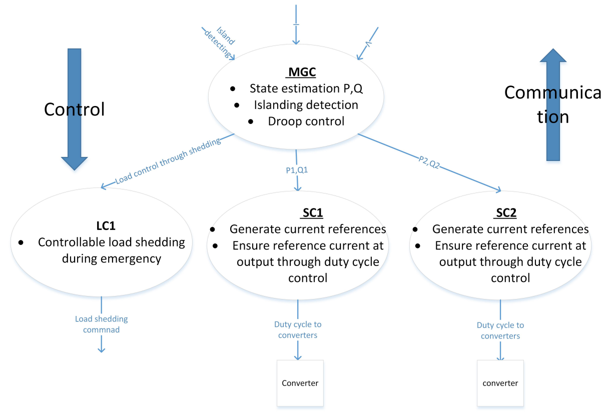

Figure 4: Hierarchical control architecture

(Tucker and Negnevitsky, 2011). The fuel cell though will incur high costs especially for the electrolysers and efficiency issues (Fuchs et al., 2012). The major disadvantage of the fuel cell is that it cannot be subjected to fast load variations as this can lead to fuel starvation in the cells leading to lower cell lifetime (Nayeripour et al., 2011)(Thounthong and Raël, 2009). The batteries as storage elements has good energy densities but suffer from long recharging times, discharge currents and low power densities compared to super capacitors. Another storage element, the super capacitor has higher power density but low energy density (Zandi et al., 2011). The Figure 2 shows the integration method of various storage elements to the DC micro-grid. It also outlines the energy storage mechanism in the form of hydrogen gas in a fuel cell.

The use of all the storage elements like fuel cell, battery and super capacitor, together in the same grid as a *hybrid storage system* will help overcome the drawbacks of each individual storage element and help achieve better reliability, efficiency and also reduce the cost of installation of storage systems. The hybrid storage systems as discussed also helps in the increased penetration of the renewable sources ensuring the grid stability (Thounthong and Raël, 2009).

3. Overview of micro-grid control architecture

The Figure 3 shows a general architecture of the micro-grid and its control elements. The micro-grid elements are connected to the LV network. The micro sources in the grid shown are PV systems and wind power systems. There can be combined heat and power (CHP) systems connected to the grid. All the micro sources have source controllers (SC) connected along with them controlling the power converters connected to the source. The SC also controls the power flow of the storage elements. The load controllers (LC) are used for the controlling controllable loads in the grid. The LC enables shedding of loads to allow the power balance in the grid (Lopes et al., 2006). The micro-grid shown in Figure 3 is an AC micro-grid. DC micro-grids are also becoming popular nowadays. The DC micro-grids do not require an inverter stage to connect the source to the grid. The micro-grids employ a hierarchical management and control scheme as shown in Figure 4. At the top the pyramid is the micro-grid control (MGC). The MGC monitors the grid parameters, fault detection and calculates the state of the grid. The MGC determines the power distribution among the sources, storage elements and also controls the protection system. The next level in the hierarchy are the LC and SC located at the loads and the sources respectively. The LC as mentioned before aids in controlling load through shedding while the SCs control the active and reactive power supplied by the sources and the power flow in and out of the storage systems. The LCs and SCs communicate information with MGC enabling the overall control of micro-grid (Lopes et al., 2006).

The major element in the second level of the hierarchical control is the power converter control for the sources. In an AC grid the power converter can be controlled using two methods:

· *PQ control*: In this mode the active power (P) and reactive power (Q) output from the converter are controlled by controlling the direct and quadrature axis current of the converter output. The reference PQ values will be set my MGC. In this mode the converter is controlled as a current controlled voltage source (Lopes et al., 2006).

· *VSI control*: In this the converter operates as Voltage Source Inverter (VSI) mimicking the operation of a synchronous generator. The droop characteristic is used for obtaining the P and Q reference (Katiraei and Iravani, 2006).

· *DC current control*: The DC converter control for the storage devices and the sources are done in a similar way to the PQ control. The P reference generates the current reference which will result in the converter working as current controlled voltage source as suggested in (Thounthong and Raël, 2009).

3.1. Overview of control under islanded mode for micro-grid

The micro-grids as discussed above can operate in the grid connected mode and islanded mode during the event of the faults. The main challenge in the islanded mode of operation is ensuring the system stability. In the absence of synchronous machines the converters have to emulate the droop characteristics and ensure frequency stability. The VSI control scheme is suited for this. The are two main control strategies under islanded mode of operation as shown in Lopes et al. (2006):

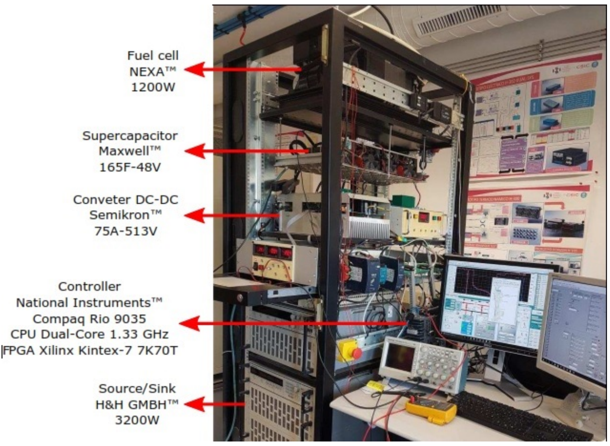

Figure 5: Experimental set up at IRI

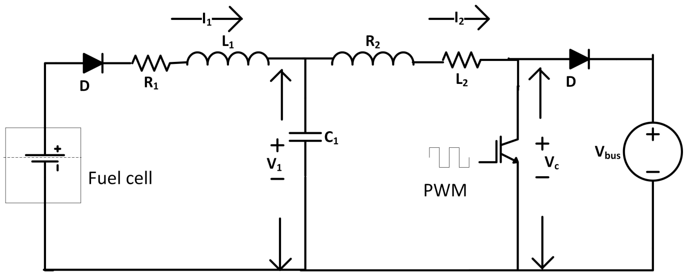

Figure 6: Boost converter topology for the FC converter

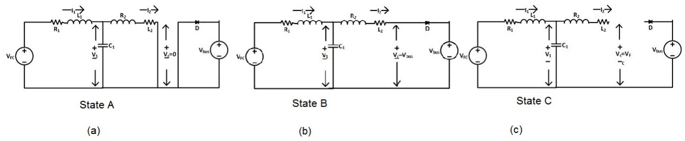

Figure 7: Boost converter equivalent during a. switch on b. switch off c. switch off and discontinuous conduction mode of the converter

- *Single master operation (SMO)* is where one converter connected to source or storage element will operate in VSI mode. This converter will therefore set a voltage and frequency reference for the grid. The other converters will work in PQ control mode.
- *Multi master mode(MMO)* In this mode more than one converter will work in VSI mode setting the voltage and frequency reference while others work in the PQ control mode.

Another control strategy for micro-grid control under islanded mode is presented in DING et al. (2014). Here the authors treat the micro-grid as an AC subgrid formed by the AC sources and its load along with a DC subgrid formed by DC sources and its load in the main micro-grid. The two subgrids are controlled through their individual droop characteristics.An interconnecting converter between subgrids enable the power transfer and stable operation under islanded mode. Most of the controls in the islanded mode utilise the droop characteristics for the stabilising the grid.

4. Converter topology and modelling for converters used for energy storage elements

This section shows the converter topologies that are used for the energy storage elements shown in Figure 5. This is a set up for integrating hybrid storage elements in grid. The set up has a fuel cell (FC) and a super capacitor (SC) connected to a DC bus. The DC bus is also provided with a source and load emulator to make it represent a real world grid. Most of the storage elements produce DC voltages and the converters shown here are the DC-DC converters connected to these elements. In case of DC micro-grids the output of the DC-DC converters are connected straight to the grid while in the case of AC grid they are connected to another DC-AC converter.In this section only the DC-DC converters are discussed as they are responsible for the power flow from the storage elements.

4.1. Converter for Fuel cell

The Figure 6 shows the boost converter used for the Fuel Cell (FC). The converter has an input filter which reduces the current ripple for the input current from the FC. As shown the converter is connected straight to a DC bus and the modelling of the converter is done considering the same. The Figure 7 shows converter equivalent during the IGBT *on* and *off* state. A third state is also presented there which also happens during the IGBT off stage called the discontinuous conduction mode. The DC-DC converters have two modes of operation. The continuous conduction mode is where the instantaneous current through the inductor of the converter ,in this case L_2, always have a finite value at any instant of the converter operation. In the discontinuous mode the instantaneous inductor current will become zero at the IGBT off stage. This results in an equivalent circuit shown in Figure 7c . The discontinuous conduction is less desirable as it can increase the ripple in the output current resulting in higher filtering requirements. The transition between the different modes of conduction is highlighted in Figure 8. The modelling of the converter is done assuming the continuous conduction mode of converter. The modelling is done using the state space analysis for continuous conduction mode method highlighted in Erickson and Maksimovic (2001), Tan (2015). The state variables for the converter are

$$\mathbf{x} = \begin{bmatrix} i_1 \\ i_2 \\ v_1 \end{bmatrix} \tag{1}$$

The state equations for the averaged model are

$$L_1 \frac{di_1}{dt} = V_{fc} - v_1 - R_1 i_1 \tag{2}$$

$$L_2 \frac{di_2}{dt} = v_1 - V_c - R_2 i_2 \tag{3}$$

$$C_1 \frac{dv_1}{dt} = i_1 - i_2 \tag{4}$$

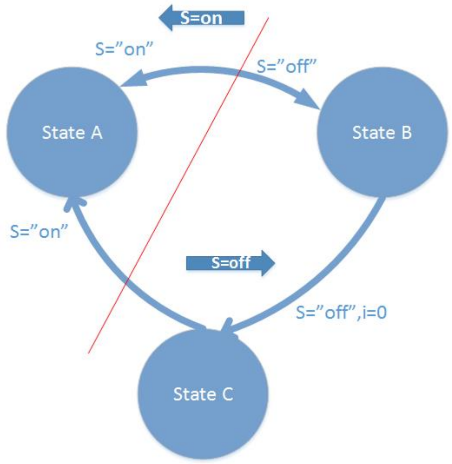

Figure 8: The conduction mode transition in DC-DC converter

In the above equation the V_c represent the voltage across the IGBT. The state space form for developing the model is shown below

$$\begin{aligned} \dot{X} &= \mathbf{A}x + \mathbf{B}u \\ y &= \mathbf{C}x + \mathbf{E}u \end{aligned} \tag{5}$$

Writing Equation 2,3,4 in the form of Equation 5 we get

$$\dot{X} = \begin{bmatrix} -R1/L1 & 0 & -1/L1 \\ 0 & -R2/L2 & 1/L2 \\ 1/C1 & -1/C1 & 0 \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ v_1 \end{bmatrix} + \begin{bmatrix} 1/L1 & 0 \\ 0 & -1/L2 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V_{fc} \\ \bar{\mathrm{d}}\ V_{bus} \end{bmatrix} \tag{6}$$

$$Y = \begin{bmatrix} 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ v_1 \end{bmatrix} \tag{7}$$

In the above equation $\bar{d}V_{bus}$ is the averaged value of V_c in one switching period, where $\bar{d} = 1 - d$. The transfer function for the above system defined using the Equation 5 is

$$G(s) = C(sI - A)^{-1}B + E \tag{8}$$

The transfer function for Equations 6, 7 is obtained as

$$\frac{\begin{bmatrix} 1 & -(CL_1s^2 + CR_1s + 1) \end{bmatrix}}{L_1L_2Cs^3 + C(L_1R_2 + L_2R_1)s^2 + (CR_1R_2 + L_1 + L_2)s + R_1 + R_2} \tag{9}$$

4.2. Converter for Supercapacitors, Batteries

The bidirectional buck-boost converter used for the Supercapacitors (SC), batteries is shown in Figure 9. The bidirectional converter is used here to facilitate both the power flow in and out of these storage devices. The Figure 10 shows the equivalent circuit during the switching state for the buck mode of operation of the converter. As with the case of the FC converter the modelling is done considering only the continuous conduction mode. The modelling of this converter is fairly straight forward. The state equations are as follows

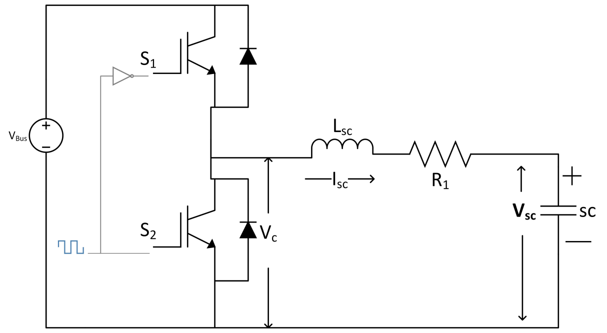

Figure 9: Converter topology used for SC

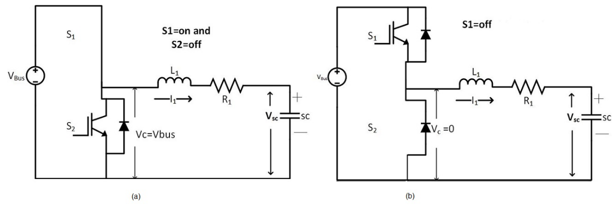

Figure 10: Switching state equivalent circuit for the converter during power flow from Dc grid to Sc(buck mode)

$$L_{sc}\frac{di_{sc}}{dt} = V_c - V_{sc} - R_1 i_{sc} \tag{10}$$

$$C_{sc}\frac{dV_{sc}}{dt} = i_{sc} \tag{11}$$

The above equation are the averaged equations for one switching period. Taking the Laplace transform of above equation gives

$$sL_{sc}i_{sc} = V_c - V_{sc} - R_1 i_{sc} \tag{12}$$

$$C_{sc}sV_{SC} = i_{sc} \tag{13}$$

From above we can write

$$V_c = sL_{sc}i_{sc} + \frac{i_{sc}}{sC_1} + R_1 i_{sc} \tag{14}$$

The transfer function is therefore

$$\frac{i_{sc}}{V_c} = \frac{sC_{sc}}{s^2L_{sc}C_{sc} + R_1C_{sc}s + 1} \tag{15}$$

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5. Control architecture for the storage elements

The Figure 11 shows a general control architecture which will be implemented for the set up shown in Figure 5. The primary level in the architecture has a management system (EM Local) which gives the reference values of current for the FC

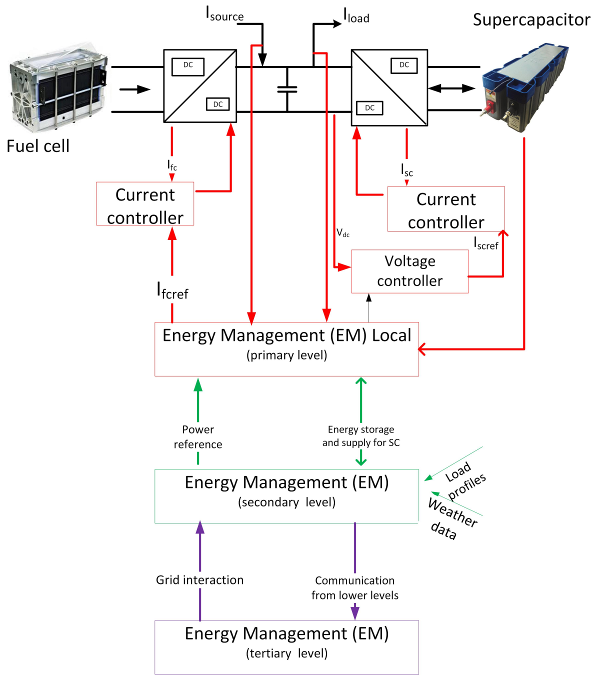

Figure 11: Control architecture for the storage elements

and SC converter thereby controlling the power in or out of the FC and SC. This unit is responsible for maintaining the DC bus voltage by generating the necessary reference signals for the SC converter. This level also takes care of the power mismatch in the grid by generating suitable current reference for the FC converter and thereby ensuring necessary power supply to the grid. Suitable control laws can be implemented in this level to ensure fast and optimal response by the storage devices.

The next level, the secondary level, of energy management is responsible for control for the first level mentioned above. This level have inputs from the local load profiles, state of various storage elements and also external inputs like weather conditions. Based on these inputs this level send the reference power for intake or supply by the storage elements. The first level will then act on these references to generate the necessary current reference for the converters.

The tertiary level of this system hierarchy deals with the grid interaction. This level monitors whether the system works in islanded mode or in grid connected mode. Based on the inputs this level provides necessary feedback to lower levels which aids them in the decision making.

6. Load sharing among storage devices in micro-grids

The discussion up to this point has been focussed on the control of micro-grid as a whole and architecture.This section focuses on the criteria for the power distribution among the storage elements and some algorithms for the same.

As discussed in the previous section storage elements are vital for the stable operation of a micro-grid. A hybrid storage system comprising of fuel cells, battery and super capacitor will provide the best solution as they will enable to overcome the drawbacks of the individual units. In the hybrid storage system the fuel cell form the element with highest energy density but it cannot be subjected to current slope variation of more than 50A/s (Thounthong and Raël, 2009). This mean that the fuel cell can respond to slow variation in the power requirements whereas fast variations has to be met by the batteries and supercapacitors. Many distribution algorithms have been presented in the literatures. One of the most widely used method for the load distribution is to consider the fuel cell as an energy source which keeps the batteries and supercapacitors charged by monitoring their State of Charge(SOC). The batteries and supercapacitors will meet the fast load demands. The fuel cell will also meet the slow load variations (Thounthong and Raël, 2009)(Thounthong et al., 2007) Fuzzy logic based algorithm for load sharing have been investigated in (Kisacikoglu et al., 2009) (Zandi et al., 2011). The fuzzy based control study the system state and make the necessary decision for load sharing. A wavelet-fuzzy based load sharing algorithm is studied in Erdinc et al. (2009). Most of the methods described above are physically implemented for hybrid vehicles. The challenge is to implement similar algorithms physically in the micro-grid environment and obtaining reliable results. A method used in micro-grids where the load profile is divided into high frequency and low frequency components using filters and used for the load distribution is studied in (Adhikari et al., 2016)

7. Conclusion

The penetration of renewable energy source and distributed generation is increasing year by year. The increased penetration of the renewable sources which are highly variable in terms of power injected into grid has resulted in the idea of introduction of storage element in the grids to balance the power flow and maintaining grid stability. The increase in the distributed generation in the grids have given prominence to the idea of micro-grids where sources, loads and storage elements connected to the LV side have capability of forming a small grid on its own and sustaining itself. The elements in micro-grids are capable of co-coordinating among themselves through monitoring, communicating and controlling each element in the grid through a hierarchical architecture and controllers associated with each element. The main challenge in micro-grids is the implementation of a robust control capable of operating in the grid connected and islanded mode of micro-grids. The load sharing algorithm among the storage elements to ensure their reliable and efficient operation is another challenge. Many algorithms for sharing the load among storage elements has been put forward and implemented in hybrid vehicles. The same need to be verified in micro-grids physically and their efficiency from the point of view of micro-grid reliability and stability needs to be studied in upcoming works.

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