Abstract

This thesis presents the study of different types of control strategies for the hybrid energy storage system (HESS) in the standalone and grid-connected mode of operation. The control strategies studied are mainly focused on the effective power-sharing between the battery and supercapacitor (SC) based HESS, tight DC link voltage regulation with the improved dynamic response and simple controller design.

Over the years, DC microgrids have been widely investigated due to their flexibility in integrating the renewable energy sources (RESs) and energy storage systems (ESSs). Among various types of RESs, photovoltaic (PV) and wind are the most popular ones. The main issue with these RESs is their intermittent nature. The power generation from these RESs is easily affected by the varying environmental conditions. Thus, the microgrid requires ESSs to provide a continuous supply to the load demand. ESSs are the major part of the microgrids. ESSs complement the supply and demand mismatch and ensure the stability of the microgrid. In recent days, ESSs with the different operating characteristics are combined to form a HESS in the microgrid applications. In the HESS, the characteristics of the various ESSs can be effectively and efficiently utilized. The effective utilization of the HESS in the microgrid depends on the control techniques used to control the power flow from the HESS. Thus, the effective control method is of utmost importance for maintaining the power balance in the system with the load and generation variation.

The faster joint control strategy is proposed for the control of the battery and SC based HESS in the DC microgrid applications. To maintain the system power balance, the HESS handles the excess or deficit power. In general, the battery supports the slow varying power demand and the SC supports the transient power demand. The low pass filter (LPF) is used to obtain the slow varying power demand and the transient power demand from the total power demand. In conventional control methods, the power decomposition entirely depends on the performance of LPF. It also neglects the uncompensated power from the battery system. In the proposed control method, the uncompensated power from the battery system is diverted to the SC system. This improves the dynamic response of the overall system and provides a faster DC link voltage restoration during a step change in the PV generation and the load demand.

The model predictive control (MPC) method has been intensively studied for the industrial process control for more than four decades. During the last decade, the MPC method has been successfully applied in many power electronics topologies. The conventional MPC method uses a discrete system model and the complex optimization algorithms to solve the control objectives in the defined time period. This approach requires large computational resources to obtain optimal control parameters. This hinders its utilization for the system which requires the faster control action with the less computational burden. The enumeration-based model predictive control (EMPC) methods are generally used to solve these issues. The EMPC methods require less computational resources and can be easily implemented in the digital signal processor (DSP) control boards. The enumeration-based model predictive current control (EMPCC) method for the battery and SC based HESS in the DC microgrid applications is proposed. The proposed control method is divided into two parts: (i) DC link voltage control loop. (ii) Inner current control loop. The DC link voltage control loop is based on the PI controller which generates the total current references for the HESS. The inner current control loop is based on EMPCC method and it regulates the total current references for the HESS. The advantages of the proposed method are less computational complexity, simple controller design, direct manipulation of control signals without the pulse width modulation (PWM) modulator and faster dynamic response.

The study of the dynamic evolution control (DEC) method for the HESS control is also presented in this thesis. The DEC method uses the pre-defined trajectory known as evolution path to minimize the error state in the system. The error state is the difference between the system output and its reference value. A new power sharing approach for the HESS is also introduced to generate the current references for the battery and SC. The control equation of the DEC method consists of a predictive term and a feed-forward term which regulate the HESS current and DC link voltage. The performance of the DEC over the conventional PI-based control methods are compared based on simulation and experimental studies. The results obtained show a better dynamic performance compared to the conventional PI based control method. The proposed control method is simple to implement and requires less computational resources compared to the traditional discrete MPC methods.

The operation of HESS in the grid-connected mode is another aspect of the research work presented in this thesis. A new energy management system (EMS) is proposed for the integration and effective utilization of the HESS in the grid connected operation. The main advantages of the proposed EMS and control method are effective power sharing between the different ESSs, faster DC link voltage regulation to PV generation variations and load disturbances, dynamic power-sharing between the battery and the grid based on the battery state of charge (SOC), reduced rate of charge/discharge of the battery current, improved power quality features in AC grid and seamless mode transitions.

To validate the proposed control methods and EMS a hardware prototype is built. The experimental case studies for the proposed control methods are carefully designed and implemented using the dSPACE 1103 real-time controller platform. The simulation and experimental results for the proposed control methods are compared with the existing control methods to verify the effectiveness of the proposed methods regarding faster control response and the complexity of the control method. The short-term and long-term experimental case studies are conducted. They demonstrate the effectiveness of the proposed control methods compared to that of the conventional control methods.

List of Publications

The Author's contribution in this Ph.D thesis are summarised in the following publications:

Journal Publications:

1. U. Manandhar, N. R. Tummuru, S. K. Kollimalla, A. Ukil, H. B. Gooi and K. Chaudhari, "Validation of Faster Joint Control Strategy for Battery and Supercapacitor Based Energy Storage System," in *IEEE Transactions on Industrial Electronics*, vol. 65, no. 4, pp. 3286 3295, Apr 2018.
2. U. Manandhar, A. Ukil, H. B. Gooi, N. R. Tummuru, S. K. Kolimalla, B. Wang and K. Chaudhari, "Energy Management and Control for Grid Connected Hybrid Energy Storage System under Different Operating Modes," in *IEEE Transactions on Smart Grid*, vol. PP, no. 99, pp. 1-1.
3. U. Manandhar, B. Wang, H. B. Gooi and A. Ukil, "An Enumeration-Based Model Predictive Current Control for Battery and Supercapacitor Energy Storage Systems in DC Microgrids," in *IEEE Transactions on Industrial Electronics*. (Under review)
4. U. Manandhar, B. Wang, A. Ukil and H. B. Gooi, "A Dynamic Evolution Control Based Power Sharing Method for Hybrid Energy Storage System," in *IET Power Electronics*. (Under review)

Conference Publications:

1. U. Manandhar, B. Wang, A. Ukil, H. B. Gooi, N. R. Tummuru and S. K. Kollimalla, "A New Control Approach for PV System with Hybrid Energy Storage System," *43rd Annual Conference of the IEEE Industrial Electronics Society (IECON)*, Beijing, China, pp. 2739 2743, Oct 2017.
2. U. Manandhar, A. Ukil, H. B. Gooi, N. R. Tummuru and S. K. Kollimalla, "A Low Complexity Control and Energy Management for DC-Coupled Hybrid Microgrid with Hybrid Energy Storage System," *IEEE PES General Meeting (PESGM)*, Chicago, USA, pp. 1-5, Jul 2017.
3. U. Manandhar, A. Ukil, S. K. Kollimalla and H. B. Gooi, "Application of HESS for PV system with modified control strategy," *IEEE Innovative Smart Grid Technologies – Asia (ISGT ASIA)*, Bangkok, Thailand, pp. 1-5, Nov 2015.