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CONTROL STRATEGIES FOR HYBRID ENERGY STORAGE SYSTEMS IN DC GRID

UJJAL MANANDHAR

**SCHOOL OF ELECTRICAL AND ELECTRONIC
ENGINEERING**

A thesis submitted to the Nanyang Technological University
in partial fulfillment of the requirement for the degree of
Doctor of Philosophy

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarised materials, and has not been submitted for a higher degree to any other University or Institution.

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UJJAL MANANDHAR

Supervisor Declaration Statement

I have reviewed the content and presentation style of this thesis and declare it is free of plagiarism and of sufficient grammatical clarity to be examined. To the best of my knowledge, the research and writing are those of the candidate except as acknowledged in Author Attribution Statement. I confirm that the investigations were conducted in accord with the ethics policies and integrity standards of Nanyang Technological University and that the research data are presented honestly and without prejudice.

7-Feb-2019

Date

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Authorship Attribution Statement

The thesis contains materials from 3 published journal papers and 1 under revision journal paper, in the following peer-reviewed journals, where I was the first and the corresponding author.

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The contributions of the co-authors are as follows:

- I have developed the basic concept and built an experimental platform for validation. I processed the experimental results and prepared the manuscript.
- Dr. Narsa Reddy Tummuru, Dr. Sathish Kumar Kollimalla and Mr. Kalpesh Chaudhari helped me to setup the experimental platform and got the initial results.
- Dr. Abhisek Ukil and Assoc. Prof. Hoay Beng Gooi closely supervised all the process, gave suggestions for the organisation of the manuscript and reviewed the manuscript for the final submission.

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The contributions of the co-authors are as follows:

- I have developed the basic concept and built an experimental platform for validation. I did the experiment, analyse the results and prepared the manuscript.
- B. Wang helped me to implement the control method in the experimental platform

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- Dr. Abhisek Ukil and Assoc. Prof. Hoay Beng Gooi closely supervised all the process, gave suggestions for the initial direction of the project and reviewed the manuscript for submission.

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The contributions of the co-authors are as follows:

- I developed the concept and implemented in the experimental setup. I produced the results and prepared the manuscript.
- Dr. Wang Benfei assisted in editing the manuscript. He helped me during revision of the manuscript.
- Dr. Abhisek Ukil and Assoc. Prof. Hoay Beng Gooi closely supervised all the process, gave suggestions for the organisation of the manuscript and reviewed the manuscript for the final submission.

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- I have developed the basic concept and implemented the idea in the experimental platform. The obtain the simulation and experimental results in the paper. I prepared the manuscript.
- Dr. Narsa Reddy Tummuru and Dr. Benfei Wang helped me to setup the experimental platform and got the initial results.
- Dr. Sathish Kumar Kolimalla and Mr. Kalpesh Chaudhari helped me during the revision of the paper.
- Dr. Abhisek Ukil and Assoc. Prof. Hoay Beng Gooi closely supervised all the

process, gave suggestions for the organisation of the manuscript and reviewed the manuscript for the final submission.

7-Feb-2019

Date

UJJAL MANANDHAR

To My Family.

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Abstract

This thesis presents the study of different types of control strategies for the hybrid energy storage system (HESS). The proposed control methods are applied in the standalone and grid-connected mode of operation of HESS. The control strategies studied are mainly focused on the effective power-sharing among 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 sources and energy storage devices. The photovoltaic (PV) and winds are the two most popular renewable energy sources (RESs). 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 energy storage systems (ESSs) which ensure a continuous power 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 implemented to maintain the power balance through the HESS. Hence, the proper 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 presented for the effective control of the battery and SC based HESS in the DC microgrid applications. The HESS handles the excess or deficit power to maintain the power balance in the system. In general, the battery

supports the slow varying power requirement and the SC supports the high-frequency power demand. To extract the slow varying power demand and the transient power demand from the total power demand low-pass filter (LPF) is used. 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 handled by the SC system. This improves the overall system response to the PV generation fluctuations and load disturbances providing a faster DC link voltage restoration.

The model predictive control (MPC) method has been intensively studied for the industrial process control for more than four decades. The MPC method has been extensively applied in many power electronics topologies in last few decades. 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 a faster control action with 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 applied 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 and (ii) Inner current control loop. The PI compensator is used to design the DC link voltage control loop. The PI controller generates the total current references for the HESS. The inner current control loop is based on EMPCC method. The inner current control 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 better 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 difference between the reference value and the measured system output is known as error state. A new power-

ABSTRACT

sharing approach for the HESS is also introduced to calculate the current references for the battery and SC. The current is regulated using the DEC method. The control equation of the DEC method consists of a predictive term and a feed-forward term which handle the current from HESS to stabilize the DC link voltage. The performance of the DEC is compared with the conventional PI-based control methods with the simulation and experimental case studies. The results obtained exhibit a better dynamic performance compared to that of the conventional control techniques. The DEC method is simple to implement as it requires less computational resources.

The grid-connected mode of operation of the HESS is another aspect of the research work presented in this thesis. A new energy management system (EMS) is proposed which help in effective and efficient utilization of the HESS in the grid-connected mode of operation. The main advantages of the proposed EMS and control method are better DC link voltage restoration to PV generation and load disturbances, efficient power balance between the battery and SC, dynamic power-sharing based on the battery state of charge (SOC), decreased rate of charge/discharge of the battery current, enhanced power quality in AC grid and smooth mode transitions.

The scaled down experimental platform is built to verify the proposed control methods. The experimental case studies for the proposed control methods are carefully designed and implemented using the dSPACE 1103 real-time controller platform. The obtained simulation and experimental results are compared with that of the existing control methods. The results validate the effectiveness of the proposed control methods. The results are compared in terms of faster dynamic response and the complexity of the control method. The short-term and long-term experimental case studies are conducted. They show the proposed control methods are effective than the conventional control methods.

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Abbreviations and Symbols

Abbreviations

ANN	Adaptive neural network
CCM	Continuous current conduction mode
DEC	Dynamic evolution control
DOD	depth of discharge
DSP	Digital signal processing
EDC	Extended droop control
EMPC	Enumerated model predictive control
EMPCC	Enumeration-based model predictive current control
EMS	Energy management scheme
ES	Energy storage
ESS	Energy storage system
EV	Electric vehicle
FC	Fuel cell
FS-MPC	Finite control sets model predictive control
HESS	Hybrid energy storage system
HEV	Hybrid electric vehicle
HPF	High pass filter

HPS	Hybrid power system
HWT	Haar wavelet
IGBTs	Insulated-gate bipolar transistors
LPF	Low-pass filter
MBT	Moving block technique
MIMO	Multiple-input multiple-output
MISO	Multiple-input single-output
MPDPC	Model predictive direct power control
MPP	Maximum power point
MPVC	Model predictive voltage control
NiCd	Nickel cadmium
NiMH	Nickel metal hydride
NiZn	Nickel zinc
PI	Proportional-integral
PV	Photovoltaic
PWM	Pulse width modulation
RESs	Renewable energy sources
SC	supercapacitor
SIMO	Single-input multiple-output
SMC	Sliding mode control
SOC	State of charge
THD	Total harmonic distortion
UPS	Uninterruptable power source
VRB	Vanadium redox flow batteries

VSC Voltage source converter

Symbols

α	Compensation factor for battery error current
β	Compensation factor for the DC link voltage error
δ_b	Duty cycle for battery converter control
δ_{sc}	Duty cycle for SC converter control
ω_c	Cut-off frequency of LPF
γ	Sharing coefficient
C_{dc}	DC link filter capacitance
$\frac{di_b}{dt}$	Rate of change of battery current
f_{sw}	Switching frequency
H_b	Higher SOC limit for battery
H_{sc}	Higher SOC limit for battery
i_{acl}	AC load current
i_{avg}	Average current component of total current
i_b	Output current from the battery
$i_{b,ra}$	Rated charging current for battery
i_{bref}	Current reference for battery current controller
i_{dcl}	DC load current
i_g	Grid current
i_{pv}	Output current of PV array
i_{pvo}	Short circuit PV current
i_{sc}	Output current from the SC

$i_{sc,ra}$	Rated charging current for SC
i_{scref}	Current reference for SC current controller
i_{tot}	Total current demand
i_{tran}	Transient current component of total current
i_{vsc}	Inverter current
J	Objective function for EMPCC
k	Positive coefficeint in DEC
K_{i_b}	Integral gain of battery current compensator
K_{i_sc}	Integral gain of SC current compensator
K_{i_v}	Integral gain of voltage compensator
K_{p_b}	Proportional gain of battery current compensator
K_{p_sc}	Proportional gain of SC current compensator
K_{p_v}	Proportional gain of voltage compensator
L_b	Filter inductor for battery DC-DC converter
L_{bc}	Lower SOC limit for battery
L_{pv}	Filter inductor for PV DC-DC converter
L_{sc}	Filter inductor for SC DC-DC converter
L_{scc}	Lower SOC limit for SC
m	Positive constant that determine the rate of system response in DEC
M_p	Overshoot in the DC link during step change in load and generation
N_c	Control horizon for EMPCC
P_{acl}	AC load power
P_{avg}	Average power demand
P_b	Power output from the battery

ABBREVIATIONS AND SYMBOLS

P_{b_uncomp}	Uncompensated power from battery system
P_{dcl}	DC load power
P_{ren}	Power output from renewable source
P_{sc}	Power output from the SC
P_{tran}	Transient power demand
$Q_b(k)$	Control sequence
R_{dc}	Total DC load
SOC_b	State of charge of battery
SOC_b^0	Initial state of charge of battery
SOC_{sc}	State of charge of SC
SOC_{sc}^0	Initial state of charge of SC
τ_{cd}	Communication delay
T_c	Low-pass filter time constant
T_s	Execution time interval
T_{ss}	Settling time to stabilize the system
v_b	Terminal voltage of the battery
v_{dc}	DC link voltage
v_e^*	Dynamic characteristic of the system in DEC
v_e	Error voltage
v_{eo}	Initial value of error voltage
v_{er}	Error voltage
v_{pv}	Terminal voltage of the PV array
v_{pvo}	Open circuit PV voltage
v_{ref}	Reference voltage

v_{sc} Terminal voltage of the SC

Chapter 1

Introduction

1.1 Background and Motivation

The use of renewable energy sources (RESs) in the global electricity grid has been growing rapidly after 2000 [1,2]. The maturity in the RESs technologies has reduced the cost of installation and maintenance dramatically. Over the recent years, the developing countries in South Asia, South Africa and Latin America are slowly moving forward in the direction of RESs. The investment in RESs within China and India is also expanding rapidly. The cost reduction in RESs and availability of the land in countries like Australia and USA has attracted the investment in the RESs. Further, the rapid expansion of the RESs in the European countries from 2006 to 2014 has escalated the penetration of renewable generation in the global power supply. In 2016, 24% of the total energy generated in the world was contributed by RESs, and in 2017 it was 25% [3].

The RESs are environment-friendly and sustainable. Thus, the governments around the globe are making policies and investments to increase the utilization of RESs as much as possible [4-7]. The RESs like solar [8-10], wind [11-14] and wave [15-17] have been extensively studied and implemented all around the globe. Among the various RESs, wind and solar are the most promising ones [2]. However, these RESs cannot be used as a long-term power solution without integrating the energy storage systems (ESSs). In general, the power generation from the RESs is stochastic and intermittent in nature. The solar and wind energy fluctuates based on the time of the day, the seasonal

environmental condition and the installed location. The ESSs are required to smoothen the output power from RESs in both the standalone and the grid-connected mode of operation. Moreover, when the input from the RESs exceeds 10% power injection into the grid, ESSs are inevitable [18]. ESSs also eliminate the need for the intermittent power generation sources to meet the sudden peak demand in the system. ESSs act as an energy buffer which stores the energy during the surplus power generation and releases the energy when there is a power deficit in the grid. Besides using ESSs in smoothing the power generation from RESs, they are also used to provide high quality power supply to the high tech manufacturing industries and data centers. The ESSs are used as an uninterruptible power source (UPS) which provides a constant frequency and voltage power supply during short power interruptions. ESSs are also the key component of the smart grid system.

The typical representation of the hybrid AC-DC microgrid architecture is given in Figure 1.1. The power output from the PV source is generally DC. Whereas the power

Figure 1.1: Typical hybrid AC-DC microgrid architecture.

generation from the wind power system is generally AC. The power electronic interfaces are required to integrate the different RESs into the common grid system. Due to the different nature of RESs, the DC-DC converter and AC-DC converter systems

are inevitable before connecting them to the DC grid. The power electronic converters provide greater flexibility and control over the power output from the RESs. In order to complement the supply and demand mismatch in the system, ESSs are required. In recent days, the hybridization of the different types of ESSs is quite popular as it has several advantages compared to a single ESS. The combination of different energy storage devices are used to form hybrid energy storage system (HESS). This helps to improve the system stability to deal with the intermittent nature of RESs and load disturbances. The DC microgrid can be either operated in the standalone mode or in the grid-connected mode. The DC grid is connected to the AC grid with the bi-directional DC-AC voltage source converter (VSC). The VSC allows the bi-directional power flow between the DC and AC grid. In the standalone mode of operation, the local loads are solely supplied by the RESs and the HESS. In the grid-connected mode of operation, the bi-directional power flow between the AC grid and DC microgrid provides a greater flexibility and control over the use of the RESs and HESS. However, the stability of the system is determined by the power balance in the system. The control methods applied to control the HESS connected power electronics converters determine the effectiveness and efficiency of the microgrid operation. The detailed review of energy management techniques and control methods for the hybrid AC-DC microgrids are presented in [19]. During the generation and load variation, the foremost requirement is to regulate the DC link voltage to a predefined limit. Thus, an effective power sharing method which allocates the optimal power to the RESs, HESS, and the grid is required. The allocated power is regulated by the primary level control which generates the optimal control signals for the power electronics converters. The study presented in this thesis focuses on the study and implementation of the primary and secondary level control methods for HESS in the DC microgrid applications. The proposed control methods are developed to maintain the constant DC link voltage with the effective power-sharing between the HESS.

1.1.1 What are Batteries and Supercapacitors?

The battery technology is one of the oldest and dominant energy storage technologies. The electrical energy is stored in the form of chemical energy in the battery. In general,

the battery has high energy density which means it can support the system for a longer duration of time. It is suitable for a long-term power storage solution. However, the battery technology has a low power density and low life cycle. It requires a certain time to produce the electrochemical reaction within the cell. Thus, it is unable to deal with the fast-changing generation and load effectively. Its internal resistances are generally high which increase the internal losses. The structural integrity of the battery is changed during charging and discharging process. Thus, the cycle life of the battery depends on the charge and discharge process. Even though batteries are the most dominant ESSs in the renewable power generation and EV applications, the low power density and the poor cycle life are the major drawbacks.

The lead-acid battery is one of the oldest and mature battery types. In 1859, Gaston Plante' first reported that a current can be drawn from the pair of lead plates submerged into sulphuric acid [20]. After that, several designs for the lead-acid batteries have been proposed over the years to meet the different system requirements. However, the fundamental electro-chemistry of the lead-acid batteries has remained unchanged over 150 years [20]. It is one of the most used rechargeable battery technology for the microgrids and EV applications.

The electrochemical double-layer capacitors were firstly termed as supercapacitors (SCs) by Nippon electric company. They produced the commercial SCs in 1978 and used for a memory backup in the computers and the consumer electronics [21]. Several changes in the materials have been made over the years of development. At the beginning of the 21st century, the SCs with a high capacitance value of 1000-5000 F and a usable energy density of 3.5-4.9 Wh/kg were commercially available [21]. The SCs have a high capacitance value compared to electrolytic capacitance but with lower voltage limits. It bridges the gap between the electrolytic capacitor and the battery system. It uses a surface charge storage technology and some faradaic reactions in the bulk of the material to store electrical energy. The high power density and longer cycle life are the major benefits of the SC. In SC, the internal structural integrity is not changed during the charge and discharge process, so it has longer cycle life compared to that of the other types of energy storage devices. The major disadvantage of SC is a faster self-discharge rate. The self-discharge can account up to 20% loss of the stored energy per day even

at the no-load condition.

The operational characteristics of the battery and SC are complementary to each other. Both the battery and SC have their own advantages and disadvantages. The combination of these two energy storage devices improves the performance of both the system. The cycle life of the battery can be greatly enhanced when it is used in combination with the SC. This also minimizes the overall maintenance and replacement cost of the battery system. Thus, the use of battery and SC combination is seen as an attractive solution in the photovoltaic (PV) power generation, wind power generation, and EV system.

1.1.2 Why Hybrid Energy Storage System?

The main motivation behind the use of the HESS is to obtain the ideal ESS response from the combination of different types of energy storage devices [18]. The ideal ESS can provide both high energy density and high power density at the same time. This behaviour cannot be obtained with the use of a single type of energy storage device.

Generally, ESSs with the complementary characteristics are combined to form a HESS. The combinations of ESSs depend on the power and energy requirements of the system. The battery and SC response to a step increase in the load are shown in Figure 1.2. The

Figure 1.2: Battery and SC response to a step load change in the system.

SC can discharge a high power in a short period of time but it cannot sustain the same power for a longer period of time. While the battery responses to a step load change is slow. However, it can sustain the same power output for a longer period of time. With the combination of the battery and SC, the fast and long-term power can be obtained.

Thus, the battery and SC combination can provide an ideal ESS response. In our work, we have used lead-acid battery and SC combination to form a HESS. The lead-acid battery has a high energy density, low power density, low life cycle, low self-discharge rate and low cost per watt-hour. In contrast, SC has a low energy density, high power density, high life cycle, high self-discharge rate and high cost per watt-hour.

Effective control methods are required to adequately utilize the different types of ESSs in the HESS. The control method exhibits a significant role in the enhancement of the entire HESS. The control method should operate the battery and SC under their limitations. The basic requirements for the HESS control methods are (i) it should maintain the state of charge (SOC) of the battery and SC within their safe operating region; (ii) it should maintain an effective power balance between the different types of energy storage devices; and (iii) it should provide the faster DC link voltage regulation to the load and generation variation.

1.2 Aim of the Work

The effective and efficient control method are of utmost importance for the optimum use of the HESS. The prime objective of the research work done for this thesis is to develop an effective and robust control method for the standalone and grid-connected operation of the HESS. The research work is mainly focused on the controller design, stability analysis, experimental validation and practical implementation of the proposed control methods. The other aspect of this thesis focuses on the through comparison of the proposed control methods with the conventional control methods. The comparisons are done in terms of the faster DC link voltage restoration capability, effective power balance between the energy storage devices in the HESS, simple controller design and less computational complexity.

1.3 Scientific Contributions

The scientific contributions of the research work done in this thesis can be highlighted as follows:

1. The faster joint control method is developed for the effective operation of the battery and SC. The joint control method utilizes the uncompensated power from the battery system to boost the performance of the entire HESS. The proposed control strategy provides the faster DC link voltage restoration and the effective power-sharing between the battery and SC compared to the conventional control methods. In this thesis, the system parameter selection, controller design, stability analysis and experimental validation of the joint control strategy are discussed.
2. The enumeration-based model predictive current control (EMPCC) method for the HESS is studied. In this method, the EMPCC method is used as an inner current controller. The outer voltage control is based on the proportional-integral (PI) control method. The PI controller generates the total current reference to be handled by the HESS for maintaining a constant DC link voltage. The total current reference is decomposed into low-frequency and high-frequency current references using a low-pass filter (LPF). The current references are handled by the respective EMPCC controller for the battery and SC. The EMPCC method is computationally less intense and easy to implement in the digital controller platforms compared to the conventional model predictive control (MPC) methods. The detailed EMPCC design, implementation and experimental studies are presented in this thesis.
3. The dynamic evolution control (DEC) method is implemented for the HESS control in the DC microgrid applications. The new power-sharing approach is integrated with the DEC method to regulate the DC link voltage and HESS current. The detailed controller design, stability analysis, and experimental verification are given in this thesis. The proposed method uses the predictive term and feed-forward term to calculate the duty cycle for the HESS. The calculated duty cycle regulates the current from HESS and the DC link voltage. The DEC method for HESS has several advantages such as simpler controller design, better dynamic response compared to PI-based control methods and requires less computational time to obtain optimal control parameters.
4. A new energy management system (EMS) and control are proposed for the opera-

tion of the HESS in grid-connected mode. The HESS is operated in different modes depending upon its state of charge (SOC) limits. The proposed EMS and control have several advantages such as effective power allocation between the different ESSs, faster DC link voltage regulation to the PV power fluctuations and load disturbances, dynamic power allocation between the battery and the grid based on the battery SOC, reduced rate of charge/discharge of the battery current during steady-state and transient power fluctuations, improved power quality features in the AC grid and seamless mode transitions. The improvement with the proposed control method is highlighted by both simulation and experimental case studies.

1.4 Outline of the Thesis

The research work carried out for this dissertation is summarized in seven different chapters. The background and motivation behind this study, the aim of the work, the scientific contributions of the research work and the outlines of the thesis are presented in current Chapter 1.

In Chapter 2, the relevant literatures for the research work are presented in detail. The thorough review and comparison of different ESSs are presented. The possible HESS configurations in DC microgrid applications are discussed. The different types of power decomposition methods for the power allocation among different energy storage devices are discussed. The various existing control methods for HESS are also discussed. The MPC methods with their current applications are discussed. The architecture of the EMS for the standalone and grid-connected mode of operation of HESS is also presented in Chapter 2.

In Chapter 3, the proposed faster joint control strategy is discussed in detail. The joint control strategy controller design, system parameters selection, stability analysis, experimental verification and performance comparison of the joint control strategy are presented in Chapter 3.

In Chapter 4, the study of EMPCC method for HESS is discussed. In Chapter 4, the EMPCC method design, implementation algorithm, experimental study and thorough

comparison with the conventional MPC method are presented.

In Chapter 5, the DEC method for HESS is discussed. The DEC design procedure and stability analysis are discussed. The simulation case studies are presented. The short-term and long-term experimental test cases are also given in Chapter V. The performance comparisons of the DEC method with the existing control methods are also presented in Chapter 5.

In Chapter 6, the proposed EMS and control for the grid-connected operation of HESS are presented. In Chapter 6, the EMS and control operating modes are discussed in detail with the simulation and experimental studies. The performance comparisons of the proposed EMS and control with the conventional control methods are also presented.

In Chapter 7, the conclusions of the research work and its possible future directions are summarised.

Chapter 2

Literature Review

2.1 Energy Storage Technologies

2.1.1 Lead-Acid Batteries

The lead-acid battery technology is one of the most adopted rechargeable electrochemical storage device which was developed about 150 years ago [22,23]. The lead-acid battery is a popular option for energy storage in the renewable power generation and hybrid electric vehicle (HEV) technologies due to its low cost, reliability and cost effectiveness. In general, the lead-acid batteries contain negative and positive active materials submerged in an electrolyte. The lead oxide acts as a positive active material and the spongy lead acts as a negative active material during the charging process. The aqueous sulphuric acid is generally used as an electrolyte. During the discharge process, the positive and negative active materials are changed into lead sulphate [24].

The lead-acid batteries have the cycle life of 1200-1800 cycles with the efficiency ranges from 85% to 90% [25]. It has the energy density ranges from 30-50 Wh/kg. The power density of lead-acid batteries ranges from 75-300 W/kg [22]. The rated cell voltage of the lead-acid batteries is around 2 V [26]. The self-discharge rate of lead-acid batteries is $< 2\%$ of its nominal capacity per month at 25 °C. Thus, it is suitable for the long-term power storage solutions [26]. Its operating temperature ranges from -30 °C to +40 °C [27]. Despite the wide range of operating temperature, the optimal performance is

achieved when operated at 25 °C.

There are some disadvantages of the lead-acid batteries. Its lifetime is seriously affected when it is discharged $< 20\%$ of its nominal capacity [28]. Its lifetime also decreases when it is charged and discharged with high current. It has low energy and power density as it contains heavyweight lead collectors [29, 30]. Research efforts are found in these areas to build non-corrosive collectors which can provide both high energy and power density output [31]. The lead-acid battery lifetime can be enhanced to some extent with a proper control method and EMS.

2.1.2 Nickel Metal Hydride Batteries

The nickel metal hydride (NiMH) battery technology is in the list of most mature battery technology invented about 100 years ago. NiMH batteries are widely used in several applications like EV, electronic devices, UPS and electrical tools. In NiMH batteries, the positive are made of nickel hydroxide and the and negative electrodes are made of metal alloy. The aqueous solution usually made of potassium hydroxide is used as an electrolyte in NiMH batteries [26].

The cycle life of the NiMH batteries depends on its depth of discharge (DOD). If the NiMH batteries are used under 100% DOD, it has a cycle life of > 1000 . It has cycle life over 10,000,000 cycles at 10% DOD operation [32]. It has efficiency ranges from 65% to 70% [26]. It has the energy density ranges from 70-110 Wh/kg. The power density of NIMH batteries ranges from 150-300 W/kg [32, 33]. The operating temperature of NiMH batteries ranges from -30 °C to +70 °C. However, the optimal performance is obtained when operated at temperature between 0 and 40 °C [32]. The rated voltage of NiMH batteries is around 1.2 V [26].

The NiMH batteries are environment-friendly, and require less maintenance. They have less memory effect and have wide operating temperature range. The NiMH batteries usually generate heat during the operation and require complex charging technology for safe operation. This will increase the cost of operation on a larger scale [34].

2.1.3 Nickel Cadmium Batteries

The nickel-cadmium (NiCd) battery is the well-established battery technology developed around 1950 A.D [25]. The negative and positive electrodes of the NiCd batteries are made of nickel species active materials and cadmium species active materials respectively. The aqueous alkali solutions are generally used as an electrolyte in NiCd batteries. NiCd and NiMH batteries are popular for applications in EVs as they have high cycle life; have high energy density and can be discharged to low SOC [34].

The cycle life of NiCd batteries ranges from 2,000-2,500 cycles [35]. The cycle life of NiCd batteries depends on the DOD. It can provide the cycle life of more than 50,000 if operated at DOD of 10% [25]. It has average efficiency ranges from 60% to 70%. It has the energy density ranges from 70-110 Wh/kg. The power density of NiCd batteries ranges from 150-300 W/kg [22, 32]. Its operating temperature ranges from -40 °C to 60 °C. It has rated voltage of 1.2 V and a cut-off voltage of 1 V [36].

The advantages of the NiCd batteries are less degradation when used with high charging and discharging current. It has high specific energy. However, NiCd batteries have memory effect, higher price, low system efficiency and is toxic in nature [25, 26, 34]. The self discharge rate of NiCd is also high compared to those of the lead-acid batteries [25, 26, 34].

2.1.4 Nickel Zinc Batteries

Like the other battery technologies which use nickel as an electrode, nickel zinc (NiZn) batteries also use the nickel as the positive electrode. In NiZn batteries, the zinc hydroxide is used as the negative electrode. In NiZn batteries, an aqueous solution of potassium peroxide is used as an electrolyte [26].

The cycle life of the NiZn batteries is between 100-300 cycles [34]. The average efficiency of the NiZn battery is around 75%. It has the energy density ranges from 60-65 Wh/kg. The power density of NiZn batteries ranges from 150 W/kg to 300 W/kg [34]. Its operating temperature ranges from -10 °C to 50 °C. The rated operating voltage of NiZn batteries is 1.65 V [26].

The advantages of NiZn batteries are high specific energy, no effect from deep charge and discharge cycles and the ability to handle a high peak power demand [32]. The energy density of the NiZn batteries is generally higher compared to the lead-acid batteries. The drawbacks of the NiZn batteries are the fast growth of the dendrites which reduce the operating lifetime and high operational cost compared to those of other battery technologies [28].

2.1.5 Lithium-Ion Batteries

The lithium-ion battery technology was introduced around 40 years ago [35]. The first commercial lithium-ion battery was developed in 1991 by Sony based on graphite and lithium cobalt oxide [34]. Since then, it is quite popular in the consumer electronics like tablets, mobile phones, laptop and EV applications. The positive electrodes of the lithium-ion batteries are generally composed of lithium metal oxides. The commonly used lithium metal oxides are lithium metal dioxide powder, lithium cobalt oxide, lithium titanate, lithium nickel cobalt aluminium oxide etc [34]. The negative electrode of lithium-ion batteries is generally made of lithiated graphite carbon. The electrolyte of the lithium ion batteries includes the lithium salts.

The lithium-ion batteries have a life cycle ranges from 1,000-10,000 cycles depending upon the DOD [26, 35]. It has an average cycle efficiency higher than 95%. The energy density of lithium-ion batteries range from 80-150 Wh/kg and the power density range from 50-2000 W/kg [25, 34–36]. It has the self-discharge rate of $< 5\%$ per month of its nominal capacity under normal operating condition [25]. Its operating temperature ranges from $-20\text{ }^{\circ}\text{C}$ to $60\text{ }^{\circ}\text{C}$ [37]. Its rated operating voltage ranges from 3.6-3.7 V [37].

The important features of the lithium-ion batteries are longer lifetime, no memory effect, high energy and high power density [36]. The lithium-ion batteries lifetime is sensitive to the temperature variations and deep charge and discharge of the battery. It requires a cell balancing and the battery management circuits to maintain the battery into safe operating regions during a high power applications [35]. The lithium-ion batteries are the attractive solution for the renewable and EV applications. However, the cost of lithium-ion batteries are higher compared to other energy storage devices. Research

efforts are found in these areas to build the low cost lithium-ion materials and battery management systems [25,37].

2.1.6 Hydrogen Storage and Fuel Cell

Hydrogen ESSs include two different procedures for generating and storing the electrical energy. The common way is the use of a water electrolysis unit to produce hydrogen. The fuel cell unit is used to generate electrical energy from the stored hydrogen. Thus fuel cell is the key technology for hydrogen ESS [36].

Fuel cell (FC) is a popular technology that generates the energy through an electrochemical reaction. It converts the chemical energy from the fuel to the electrical energy [28]. It contains an alkaline fuel in the anode. In cathode it contains an oxidant. The electrolyte separates the anode and the cathode. FC devices are categorized into different types based on the fuel type, electrolyte and operating condition. They are alkaline FC, phosphoric acid FC and hydrogen FC. Among these FC types, hydrogen-based FC is the most popular one [34]. The hydrogen-based FC only produces water as its by-product after cell reactions and it is one of the environment friendly storage technologies.

Hydrogen FC has the cycle life greater than 1,000 cycles at 100% DOD. It has an average efficiency of 20-35% [38]. It has energy density ranges from 800-10,000 Wh/kg and power density more than 500 W/kg [39].

The advantages of the FC over other energy storage technologies are as follows: it has i) high fuel to electricity conversion efficiency, ii) less noise during operation, iii) lower carbon emission, iv) easy to recover the waste heat energy, vi) longer operational lifetime, and vii) reliability [28]. However, the FC efficiency depends on the power extracted from it. The overall system efficiency decreases if high power is drawn from the FC. It is relatively expensive compared to other energy storage technologies. It has relatively slower response time compared to the lead-acid battery and SC [38].

2.1.7 Vanadium Redox Flow Batteries

A vanadium redox flow battery (VRB) was first made at the University of New South Wales, Australia in 1986 [40,41]. It is an electrochemical battery containing two reaction

cells for stationary electricity storage. These reaction cells are separated by a thin membrane. In VRB, the reaction occurs between the two electrolytes instead of electrolyte and electrode, which is the main difference between the VRB and other conventional batteries. In VRB, the electrolytes are stored in the storage tanks and are injected in the stacks with the help of the pumping mechanism [40].

VRB has the cycle life greater than 10,000 cycles at 100% DOD [39]. It has an average efficiency of 60-75% and energy density ranges from 10-30 Wh/kg [39].

The SOC of VRB can be calculated accurately and easily. This is the distinct feature of VRB compared to other energy storage technologies [42]. It is easily scalable to achieve the higher power rating which is effective for the bulk power storage system. It can also supply a step load change or a step power variation in a short duration. The cost of the VRB is equivalent to or lower than the currently available energy storage devices [40]. The major complication is the circulation of the electrolyte when operated below 20% of its rated power capacity. This results in the decrease of overall efficiency of the system. [42].

2.1.8 Supercapacitors

SCs are electrical energy storage devices which can provide high power density with less change in its internal chemical structure. It also has extremely high cycling capacity. Recent development in technologies has made SCs an interesting option to solve the transient power variations in the RESs and EV applications [34]. The thermal and electrical property of the SC is determined by the types of electrolyte and electrode used.

The theoretical life cycle of SCs is very high as no chemical reactions occur inside it. The electrochemical cells in SCs have fewer degradation issues even when operated at 100% DOD continuously. However, the ageing process inside the cells limits their lifespan around 20 years [39]. It has energy density ranges from 2.5-15 Wh/kg. The power density ranges from 500-5,000 W/kg [39] and round-trip efficiency greater than 90%.

The main drawback of SCs is its high self-discharge rates (more than 20% per day) which limit its application to short-term power solutions. The cost of SCs is relatively

high compared to the other energy storage technologies. The SC system requires an additional voltage balance circuit during its series connection. The additional circuit ensures the voltage equalization among the SC cells. The voltage equalization of the SC cells is of utmost importance for the high voltage applications. This also limits its use in the industrial applications which require very high voltage [25].

2.1.9 Comparison of Different Types of Energy Storage Devices

The Ragone chart shows the characteristics of various energy storage devices in a single graph as shown in Figure 2.1 [43]. It also contains the information about the charge and discharge time for the different types of energy storage devices. The detail information regarding the Ragone chart can be found in [44]. This graph helps us to determine the energy storage combinations to build a HESS. As per the requirement of the system, different combinations of energy storage devices can be utilized to form a HESS. The characteristics of various types of energy storage devices described in the above sections are tabulated in Table 2.1 for easy comparisons. Different energy storage devices have their own unique features and disadvantages as well. The SC has highest cycle life $> 500,000$ and highest power density. The efficiency of the lithium ion is higher compared to other energy storage devices. The energy density of the FC is higher compared to that of other energy storage devices. The NiMH batteries have wide operating temperature range compared to that of other energy storage devices.

Figure 2.1: Ragone chart.

The choice of ESSs depends on the system requirements. Generally, the high energy and

Table 2.1: Comparison of different ESSs

	Cycle life (cycles)	Efficiency (%)	Energy density (Wh/kg)	Power density (W/kg)	Operating temp (°C)
Lead-acid	1,200 - 1,800	85 - 90	30 - 50	75 - 300	-30 to +40
NiMH	> 1,000	65 - 70	70 - 110	150 - 300	-30 to +70
NiCd	2,000 - 2,500	60 - 70	70 - 110	150 - 300	-40 to +60
NiZn	100 - 300	75	60 - 65	150 - 300	-10 to +50
Lithium ion	1,000 - 10,000	> 95	80 - 150	50 - 2,000	-20 to +60
Hydrogen FC	1,000	25 - 35	800 - 10,000	500	-
VRB	10,000	60 - 75	10 - 30	-	-
SC	> 500,000	> 90	2.5 - 15	500 - 5,000	-

high power density requirement may not fulfill by using a single energy storage type. For example, the lead-acid battery has high energy density and can store the energy for a longer time period. While SC has high power density and can supply the power faster than the lead-acid battery but cannot sustain the same power output for a longer time period. The cycle life of the lead-acid battery is quite low compared that of to the SC. In opposite to the lead-acid battery, SC has a high cycle life. They have complementary characteristics. In general, the combinations of ESSs are used to obtain an ideal energy storage behaviour in the system. With the hybridization of the ESSs, the requirement of the high energy density and high power density can be easily fulfilled. The performance of the individual energy storage device can be improved with the hybridization of ESSs. The operational lifetime of the lead-acid battery can be enhanced when operated in combination with the SC system.

2.2 Configurations of HESS in DC Microgrids

The HESS can be operated with the DC microgrid or AC microgrid depending upon the system requirements. The common practice is the integration of HESS in the DC microgrid. It has several advantages such as (i) it reduces the number of converters required for ESSs to connect to AC microgrid and (ii) it is easy to integrate the ESSs in the DC microgrid as it does not require any synchronization mechanism [43]. The integration of the HESS in the DC microgrid is the cost effective and efficient solution. The possible configurations of the HESS in the DC microgrids and EV applications are shown in Figure 2.2 [45]. The choice of the HESS configuration depends on the power level of the system and its application. There are three basic types of HESS

Figure 2.2: Configurations of HESS in DC microgrids. (a) and (b) are passive HESS configurations. (c) and (d) are semi-active HESS configurations. (e), (f), (g) and (h) are active HESS configurations.

configuration used in the DC microgrids. They are passive HESS configuration, semi-active HESS configuration and full-active HESS configuration [46].

2.2.1 Passive HESS Configurations

Among different HESS configurations, the passive HESS configuration is the simplest and the cost effective one. The possible passive HESS configurations are presented in Figure 2.2 as configuration (a) and configuration (b) respectively. In these configurations, energy storage devices are directly joined to the DC microgrid without control over their power flow. It has been shown that these configurations are effective to re-

duce the peak current demand in the system. These configurations are also effective for the smooth transition of the battery current. These configurations are also effective to support the peak power demand in the system from HESS [47].

In configuration (a), the HESS and load are connected in parallel to the DC microgrid. This configuration is simple to implement. However, it has several limitations such as uncontrolled battery and SC current, less flexibility to choose the battery and SC voltage, and unregulated DC link voltage [48]. In this configuration, the response from the battery and SC entirely depends on their internal resistance values, SOC, voltage levels and individual charge/discharge characteristics.

In configuration (b), the DC link voltage is maintained constant by the DC-DC converter. The DC-DC converter regulates the DC link voltage. However, the battery and SC currents are uncontrolled. The voltage level of the battery and SC should be same to use this configuration.

In order to operate the energy storage devices at different voltage level one or both of them should be controllable. In configurations (a) and (b), power allocation to the energy storage devices is based on their internal resistance values and is uncontrolled. This results in a poor transient response in the system during the generation and load variation [47].

2.2.2 Semi-active HESS Configurations

In the semi-active HESS configurations, one of the energy storage devices is controllable. This allows the battery and SC to operate at different voltage levels as one of the ESS is controllable. This allows us to optimally utilize the different characteristics of ESSs in the HESS. The semi-active HESS configurations are represented in Figure 2.2 (c) and (d) as configuration (c) and configuration (d) respectively.

In configuration (c), the battery is linked to the DC microgrid with the bi-directional DC-DC converter. However, the SC is uncontrollable and connected to DC microgrid directly. In this configuration, the dynamic performance of the battery can be improved. However, the power-sharing between the battery and SC is not fully controlled [49,50]. In this configuration, the battery can be operated at wide voltage range. This configuration

is feasible for EV technologies which require high power.

In configuration (d), the bi-directional DC-DC converter is used to connected the SC to the DC microgrid. In this configuration, the battery is uncontrolled and connected directly to the DC link. The DC-DC converter allows the SC to be operated at wide voltage range. This will increase the utilization ratio of the SC. However, the battery discharge current can be high if the voltage of SC drops below the battery voltage level [51, 52]. The connection of the battery to the DC microgrid without any DC-DC converter increases the stress on the battery during high current fluctuations which have a negative impact on its lifetime.

2.2.3 Full-active HESS Configurations

In full-active HESS configurations, the power from the HESS are effectively controlled with the bi-directional DC-DC converters. The control flexibility in these configurations allows the efficient utilization of the HESS. The full-active HESS configurations are presented in Figure 2.2 as configuration (e), (f), (g) and (h).

The configuration (e) is the most adopted topology for the systems which require high power. It is also used in grid-connected operation of the ESSs. In configuration (e), the battery and SC can be controlled over wide voltage ranges. This will increase the volumetric efficiency of the HESS. The configurations (f) and (g) provide a similar control flexibility as configurations (c) and (d). However, an additional DC-DC converter is required to control the load power in configuration (c) and (d) [51, 52]. The additional DC-DC converter increases the cost and size of the system. In configuration (h), the multiple-input single-output (MISO) DC-DC converter is used to integrate the HESS to a common DC microgrid. The advantages of the MISO converter are lesser components and smaller size. However, the control algorithms for the MISO converter are generally complex and difficult to implement in the practical controller platforms. In configuration (h), the battery and SC are operated in complementary fashion.

In this thesis, the configuration (e) is adopted for the integration of HESS in the DC microgrid and implementation of the various control strategies. In configuration (e), both the battery and SC are connected to DC microgrid with the bi-directional DC-DC

converter. This provides the freedom to control the power from an individual energy storage system. The main features of configuration (e) are: i) provide flexibility to choose the different voltage levels for the energy storage devices; (ii) the battery and SC currents can be controlled independently; (iii) the DC link voltage can be controlled; and (iv) minimizes the requirement of additional DC-DC converter to supply constant load demand.

Table 2.2: Comparison of HESS configurations

Configuration	a [47, 48]	b [47]	c [49, 50]	d [51, 52]	e [45]	f [53]	g [52]	h [54]
No of converters	0	1	1	1	2	2	2	1
Controlled DC link voltage	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Controlled battery current	No	No	Yes	No	Yes	Yes	Yes	Yes
Controlled SC current	No	No	No	Yes	Yes	Yes	Yes	Yes
DC link voltage swing	less	less	High	less	High	High	High	High

The characteristics of the different configurations of the HESS in the DC microgrid applications are summarized in Table 2.2. The comparisons are made based on the HESS current control, voltage control and the number of converters used.

2.3 Power Decomposition Method for HESS

The power allocation methods for HESS determine the effective utilization and performance of the overall HESS. The main objectives of all the power decomposition methods are to share the steady and transient power requirement to the battery and SC respectively. The efficient and optimal power decomposition methods are of crucial importance to maximize the utilization of HESS. The power decomposition method also affects the sizing of the HESS and has been a subject of intensive research. The few power decomposition methods which are used in HESS control are summarised in the following sub-sections.

2.3.1 LPF/HPF Based Power Decomposition Method

The LPF or high pass filter (HPF) based power decomposition method is one of the popular and easiest ones to implement in the HESS. In this method, the total current demand is passed through the LPF/HPF and the current references for the battery

Figure 2.3: (a) Block diagram representation of LPF based power decomposition method, (b) Rate-limit based power decomposition method, (c) MPC based power decomposition method, and (d) FLC based power decomposition method.

and SC are generated. The total current demand is calculated based on the total load demand and renewable generation. The cut-off frequency of LPF/HPF is designed based on the dynamic response characteristics of the energy storage devices. In general, the cut-off frequency of the LPF depends on the dynamic response characteristics of the energy storage device with the slower response time. The general architecture of LPF based power decomposition method is presented in Figure 2.3(a) [55] [56]. The current references generated after the LPF are then fed to the respective current controllers.

2.3.2 Rate-limit Based Power Decomposition Method

The general block diagram representation of the rate-limit based power decomposition method is presented in Figure 2.3(b). In this method, the total current demand is passed through a rate-limiter block. The rate-limiter block regulates the ramp rate of the total current demand. The slower ramp current is fed as a current reference for the battery current controller. The SC current controller then handles the fast transient current. In [57], a two-stage rate-limit control method for HESS has been presented. In the proposed method, the current references are calculated based on the SOC of the battery and load demand. The generated current references are then fed to the PI-based current

controllers that handle the battery and SC current. The proposed method reduces the rate of charge and discharge current from the battery system. Thus, improves the battery cycle life.

2.3.3 MPC Based Power Decomposition Method

The block diagram representation of MPC based power decomposition method for the HESS control is shown in Figure 2.3(c) [58]. In the MPC method, the optimal switching states are calculated in the defined control horizon. The system constraints and cost functions are used to calculate the switching states. The cost function and the system constraints in the MPC algorithms determine the optimal power sharing between the ESSs. In the MPC method, different weighting values can be assigned to the system parameters to be controlled. This provides the flexibility to independently control and monitor the parameters of the system. However, the MPC method requires larger computational resources compared to those of the conventional power decomposition methods.

2.3.4 Fuzzy Logic Control Power Decomposition Method

The architecture of the power decomposition method based on FLC is presented in Figure 2.3(d) [59, 60]. FLC method is an effective intelligent control technique in order to control the complicated systems. In the FLC based power decomposition method, the fuzzy rules are defined based on the characteristics of the energy storage devices. The transient power is allocated to the storage units like SC which can handle the transient power fluctuations and the slow varying current demand is allocated to the battery system. In general, the FLC generates the power-sharing ratios $Ratio_b$ and $Ratio_{sc}$ for the battery and SC. The fuzzy rules determine the $Ratio_b$ and $Ratio_{sc}$ value based on the load demand and SOC of the energy storage devices.

2.3.5 Haar Wavelet Based Power Decomposition Method

The effective power decomposition method which provides an optimal solution is of crucial importance to maximize the utilization of the HESS. The haar wavelet (HWT)

based power decomposition method provides a promising solution to distribute the total current demand between the different energy storage devices. In HWT, the original current signals are analysed and decomposed into various portions based on the different frequency parameters [61]. The total current demand can be effectively separated to low-frequency and high-frequency current demand through HWT. The battery controller handles the low-frequency current demand and the SC controller handles the high-frequency current demand.

2.3.6 ANN-Based Power Decomposition Method

The optimal operation of the adaptive neural network (ANN) based power decomposition method large number of datasets. It depends on the amount of datasets used to train it. The ANN method also requires large computational resources to generate the optimal power decomposition in the HESS. The ANN calculates the effective current references for a given load condition based on the various datasets used during the training process [62]. The most efficient current references are determined maintaining the system constraints such as the rate of charge/discharge of the battery and SOC limits of SC. The main drawbacks of ANN-based power decomposition method are: (i) it depends on large computational resources to obtain the required solution; and (ii) the performance of ANN depends on the numbers of data sets used to train it.

2.4 Control Strategies for HESS

Different types of control strategies for HESS have been proposed in the literature, which includes FLC [59, 60], ANN [62–64], PI control [55, 56, 65–67] and MPC [45, 58]. These control methods have been applied in the PV power system [55, 56, 65, 66], wind power system [60, 68], EVs [69–73] and UPS applications [74].

In [59], Feng *et.al* presented a multi-mode FLC method for HESS. The proposed method is composed of three different modes of operation controlled by two sets of fuzzy rules. The system operates in mode I, if both the SOC of the battery (SOC_b) and SOC of the SC (SOC_{sc}) are under safe operating region. The mode II and mode III are

developed to maintain the SOC_{sc} in the predefined safe limits and protects the SC from over discharge and charge problems. The proposed method is effective in maintaining the SOC_b and SOC_{sc} within the safe operating region. The study also presents the short-term and long-term performance analysis of the proposed method. The authors also presented the comparisons of the proposed method with the LPF and HWT based control methods. The reduction in the charge/discharge cycles are observed with the multi-mode FLC method. The results obtained exhibit that the multi-mode fuzzy logic control can enhance the battery life compared to other methods. The multi-mode fuzzy logic control also solves the issues in the HWT control method. In general, the impact of the SOC is neglected in most cases in HWT control method. However, the practical implementation of the multi-mode FLC method is problematic as it is sensitive to system parameter variations.

In [60], an adaptive fuzzy logic control technique has been implemented for the HESS in the HEV system. The adaptive fuzzy logic method is used to calculate power references for the battery and SC to handle the overall power balance. The on-line tuning of the membership function is done in the proposed method. Thus, the prior information about the driving cycle is not required to generate power references for the HESS. The proposed method reduce the battery current ripple and maintains the SOC_{sc} within safe operating limits.

In [62], the ANN control technique has been implemented for HESS in EV applications. In the proposed method, the ANN control is trained with various datasets to calculate the optimal HESS current references for the given load condition. However, the performance of ANN control depends on the number of datasets used to train the ANN and requires large computational resources. In [63], the ANN control for the hybrid AC/DC microgrid has been presented. In the proposed method the ANN control is used to track the MPP condition from the RESs and to exchange the power with the microgrid. The method is based on the online trained neural network controller which is complex to model and requires large computational resources to get the optimal control parameters.

In [64], the novel hierarchical controller has been implemented for a operation of the PV

based hybrid power system (HPS). The hierarchical control method consists of three different layers. The first layer is composed of ANN which ensures the operation of PV at its MPP. The second layer is composed of the FLC method which generates the power references for the different energy storage devices depending upon their SOC limits. The third layer consists of a local controller which regulates the power from the energy storage devices. The proposed method shows better dynamic response compared to that of the PI based control method. However, the FLC in the secondary layer is sensitive towards the system condition variation which makes it difficult to apply in the practical applications.

In [55, 56], PI-based control methods for HESS have been presented for the DC grid applications. In these methods, the current references for the HESS are regulated using the PI compensators. In the PI-based control methods, the PI compensator gains should be calculated and selected carefully considering the battery and SC dynamics to obtain the good controller performance. In [65], a modified PI control method for HESS in the DC grid application has been presented. In the proposed method, the battery error term is used as a feed-forward term to the SC current controller. The proposed method provides better dynamic performance compared to the conventional control methods [55, 56]. In [66], the new control method for HESS has been presented for the dynamic energy management of the HESS. In the proposed method, a high gain PV converter is used to reduce the size of the overall PV system. In the proposed method, the voltage loop PI compensator and LPF are used to generate current references for the HESS. The current references are then handled based on the dynamic converter equations. The advantage of this method is the use of weighting factor in the dynamic converter equations. This provides the flexibility to control the power from the battery and SC based on the weight values. The weight values can be controlled based on the ratings of the ESSs. In [67], the extended droop control (EDC) method has been used to generate current references for HESS. The EDC method is the extension of virtual resistance droop control to the virtual capacitance droop control. The current references are then regulated using a PI based control method. The EDC method is applied for the decentralized dynamic power sharing between the ESSs in the autonomous DC microgrids.

In [75, 76] sliding mode control (SMC) techniques have been used to control the HESS. The proposed methods are supported by detailed experimental results. However, the control approaches mentioned are complex to design and their performance depends on system parameter variation. In [68], a generalization of the PI controller has been used to design and implement the SMC technique for HESS. This ensures the easy implementation and simple design of the SMC. In [77], a single sliding mode strategy has been applied to control the HESS connected bi-directional DC-DC converter over the entire operating range. This approach simplifies the design and implementation of the SMC. The authors have also presented the detail stability analysis of the sliding mode control. The presented sliding mode control method is suitable for implementation in the digital signal processor (DSP) commonly used in power electronics converter control.

In [45], the MPC method has been used to obtain an optimal control signal for HESS for EV applications. The proposed method uses a probability-weighted Markov process. The probability-weighted Markov process predicts the future load demand value. In this method, the power sharing between the ESSs are determined in real-time which depends on the probabilities of state trajectories and the prediction algorithm. However, the performance of the MPC method is sensitive to change in the parameters used to define the model and the optimization time.

2.5 Model Predictive Control

The MPC method is quite advanced control technique for the process control applications. The MPC method is also popular for the control of the power electronics converters. The MPC method predicts the future states of the system with the mathematical model of the system. The MPC methods have been applied for the DC-DC converter [78–83], single-input multiple-output (SIMO) converter, multiple-input multiple-output (MIMO) DC-DC converter, inverter [84–88] and rectifier [89–92]. The detailed review of the MPC methods applied for the power electronic converters has been presented in [93, 94]. Generally, the finite control sets MPC (FS-MPC) is applied for the power electronics converter control as it requires less computational resources and can be used in DSP control boards.

A control architecture of the FS-MPC method for the power converter control is presented in Figure 2.4. The FS-MPC requires state-space model of the system for its

Figure 2.4: Control architecture of FS-MPC for power converters.

implementation. The state-space model is used to predict all the possible control variables. The prediction of the control variables is done by the receding horizon approach. The optimal control variables are selected based on the optimization algorithm and the cost function. The optimization algorithm determines the control variable sequence that optimizes the system performance over the control horizon. However, the first element from the control variable sequence is used for control action. The rest of the control elements are discarded and the process is repeated. After the execution of the control variable, the process is repeated with new measured data over a new prediction horizon. The advantages of FS-MPC over traditional controller are highlighted as follows: (i) simple to design, (ii) control of different converters parameters without modulator or cascaded control loops, (iii) low complexity, (iv) powerful and easy to integrate constraints and (v) provides variable switching frequency. In [93], the applications of FS-MPC for power electronic converters are discussed in detail. In [94], the FS-MPC has been used for the operation of the three-phase inverter. The authors have compared the proposed method with the conventional linear control methods. The results obtained show the aforementioned advantages of FS-MPC. The implementation of the linear control method in the DSP boards requires an additional discretization step while the FS-MPC algorithm can be directly implemented in the DSP boards.

In [78, 79], the cascaded control methods combining SMC and MPC have been implemented for boost converter control. In the proposed methods, the inner control loop is SMC and the outer voltage control is designed based on the MPC. The SMC observer is used to calculate the unknown system parameters. The proposed control methods

provide a better dynamic response with less overshoot and current spikes during a step change in voltage reference. In [80], the EMPC has been implemented as a current regulator for the boost converter. The EMPC requires less computational power compared to the conventional MPC based control methods and use relatively few prediction steps. The EMPC based current control provides a better dynamic performance and robustness to the parameters variations. However, it exhibits a moderate computational complexity to implement in the DSP boards. In [81], an EMPC has been implemented to balance the output DC link voltage of the boost converter. The EMPC method is effective and does not require any current controller to stabilize the DC link voltage. The optimal control variables in EMPC are obtained by solving the cost function using an enumeration technique. This makes it simple to design and implement in the DSP boards. The EMPC provides better dynamic response and robustness to the step change in voltage reference and load variation.

In [82], the authors have presented a model predictive voltage control (MPVC) method to solve the cross regulation problem in multi-output DC-DC converter. The MPVC method is applied for the SIMO DC-DC converter which significantly reduces the cross regulation. In general, quadratic programming methods are used to determine the best control sequences for a defined cost function in MPC. However, quadratic programming methods are complex to implement in the DSP boards and it takes larger computational time to obtain an optimal solution. So in the proposed method, the authors have used an enumeration-based method to generates an optimal control sequences. This makes the control simple to design and implement. The simulation and experimental case studies for the MPVC method show the reduction in cross-regulation and tight DC link voltage regulation with less ripple.

In [83], a stabilizing MPC has applied in boost converter. The boost converter is used to regulate the DC link voltage. In the proposed method, the PI and MPC method are cascaded. The authors have presented the detail stability analysis and mathematical formulation of the stabilizing MPC. The results obtained show a better steady state and dynamic performance compared to those of the classical cascaded PI-based voltage control methods. The output capacitor voltage and input inductor current are well regulated with the input constraints considered in the MPC algorithm.

In [84], the authors have presented a modulated MPC method to control the multi-level cascaded converter system. The modulated MPC performs better than the conventional MPC. In the proposed control method, a new modulation technique is used as the cost minimization technique. The results obtained show a better steady state and dynamic performance compared to those of the conventional MPC and deadbeat control method. The results exhibit that the modulated MPC reduce the ripple content in the load current and also enhance the total harmonic distortion (THD). Moreover, the proposed method can also be used to deal with the multi-objective control problems. The proposed method generates a constant switching frequency which reduces the complexity to design the parameters of the filter for the multi-level cascaded converter system.

In [85], the model predictive direct power control (MPDPC) has been applied to AC/DC converter control. In this method, the authors manipulate the duty cycle with MPDPC. The proposed method improves the overall controller dynamics. The MPDPC is used a single cost function to regulate the active and reactive power from the AC/DC converter. In general, the separate cost functions are used to handle the active and reactive power. The problem with using two cost functions is the mutual interference between them. The problem is significant when there is a large power variation in one control target. This concentrates the control weight to only one side. The concentration of control weight to only one side of cost function deteriorates the dynamics of the overall control system. This problems are addressed with the proposed control method. The experimental results show the improved dynamic performance of the system. Thus, it effectively handles the active and reactive power variation from the AC/DC converter.

The LC filters are commonly used to smoothen the output of the AC/DC converter. The LC filters reduce the THD and provide sinusoidal voltage and current. However, the control design is difficult with the use of LC filters. In [86], the MPC method has been used for the AC/DC converter control. The proposed method uses the system model to predict the possible switching states in each time step. The output voltage profiles are predicted on each sample period and optimal switching states are generated. In the proposed method, an observer is also used which estimates the varying load current and improves the stability of the system. The observer helps to decrease the total sum of current sensors requirement in the system. The authors have implemented the proposed

control method in the 5.5 kW hardware prototype in order to validate its feasibility in practical applications. The results obtained show the better performance than the linear PI control methods under both the linear and non-linear loading condition.

In [87], the authors have presented an optimized MPC method for the multilevel converter system. As the multilevel converters have a larger number of switches, it generally generates a large number of voltage vectors. Thus to obtain optimal switching signals, the MPC requires considerable computational resources. This hinders its implementation in standard DSP boards. To solve these issues the authors have presented a voltage vector selection technique. The voltage vectors selection technique calculates only few voltage vectors out of the entire possible voltage vectors in each sampling time. This significantly reduces the computational time and complexity and makes the proposed method suitable for practical applications. In [88], the MPC method is used to regulate the grid-tie four-level diode clamp inverter. In the proposed method, the multi-objective control feature of the MPC method is investigated. The cost function includes several system parameters such as output voltage balancing, voltage ripple, reactive power control and minimization of switching frequency. The single cost function implementation reduces the mutual interference problem which improves the dynamics of the control system.

In [89], the MPC method has been used to control the rectifier. It provides a good controller response compared to other control methods with better dynamic response. In [90], the improved MPDPC has been implemented for the PWM rectifier control. In the conventional MPC method for PWM rectifiers, the sampling frequency should be very high to have better control action. In two-level rectifier the number of voltage vectors are limited making it difficult to control. In this method, the time step is divided into two sections. The first section is used to determine the non-zero voltage vectors and the second part is used to calculate the zero voltage vectors. The power minimization algorithm is used to calculate the time period for the non-zero and zero voltage vectors. The results obtained show the reduction in switching ripple and THD with the improved MPDPC compared to the existing MPC methods.

As mentioned above the MPDPC requires a high sampling frequency for better control

response in the PWM rectifier control. The problem with MPDPC is the distortion of grid current when subjected to unbalanced grid conditions. In [91], the authors have presented a new MPDPC concept to control the PWM rectifier in both the balanced and unbalanced grid conditions. In the proposed method, the reactive power is defined in cost function which results in sinusoidal grid current even in unbalanced grid conditions. The proposed method also eliminates the second order grid frequency components in the grid current.

In [92], the EMPC method has been presented to regulate the power from the cascaded H-bridge multi-level rectifier. The proposed EMPC method provides a sinusoidal grid current in balanced as well as unbalanced grid condition. It is obtained by direct manipulation of the control signals for the cascaded H-bridge multi-level rectifier. In the EMPC method, the short prediction horizon is used which improves the stability and robustness of the control system.

Beside the application of MPC in power converters, some theoretical aspects of MPC have also been explored in [95–99]. These studies are focused on exploring the MPC for power converters and reducing the computational burden. The ability of MPC to incorporate both the input and output constraints are explored in [95, 96]. These can provide more flexibility and protection during the practical implementation of MPC. In addition, the researchers have applied an off-line computation method in [97–99] to reduce the computational burden in MPC. This helps to further decrease the amount of computational resources required to implement MPC. The lookup table methods for MPC have been implemented in [97–99]. The lookup tables are based on the classification of the control law into different operating regions. Moreover, these control methods can provide a huge boost for the implemented of MPC in the practical systems.

2.6 Energy Management System

The EMS for HESS is to maximize the utilization ratio of the HESS in both standalone and grid-connected mode of operation. The EMS should maintain a stable, reliable, robust and high quality power supply in the microgrid. The load demand should be fulfilled all the time even during the varying RESs generation. It should maintain the

HESS into the safe operating region and also extend its operational time. The EMS should provide a cost effective solution in the system considering the economic aspects of the different ESSs. In the microgrid, the EMS for HESS is divided into two categories depending upon the operation of the HESS, they are (i) EMS for the standalone mode of operation of HESS in DC microgrids and (ii) EMS for the grid-connected mode of operation of HESS. The detailed explanation of the EMS for the standalone and grid-connected mode of operation of HESS is given below in following sub-sections.

2.6.1 EMS for Standalone DC Microgrid with HESS

The architecture of the EMS for standalone mode of operation of the DC microgrid with HESS is presented in Figure 2.5. The EMS can be divided into two sub-controls, they

Figure 2.5: Typical architecture of the EMS for standalone DC microgrid with HESS.

are (i) the primary level control and (ii) secondary level control. The current references which maintain power balance among the RESs and ESSs is generated by secondary level control. The primary level control regulates the current references generated from the secondary level control to obtain the power balance in the microgrid. The dynamic response of ESSs to the load and generation variations on the performance of the primary level control. The system stability is highly dependent on the primary level control. The primary level control can be PI-based control, MPC, SMC etc., as explained in the Section 2.4. The secondary level control in the EMS consists of the algorithms which generate the optimal power references for various units in the system. The secondary

level control incorporates the various information from the system such as generation forecast, load prediction, SOC estimation, cost of HESS etc and provides an optimal current reference. This maximizes the utilization ratio and efficiency of the overall microgrid.

The objectives of the EMS for the standalone mode of operation of HESS in the DC microgrid can be divided into three groups: (i) optimizing the performance of HESS, (ii) system reliability and (iii) economic feasibility. The optimizing performance includes increasing HESS efficiency, improving power quality and maintaining microgrid stability. The microgrid reliability includes the ESSs lifespan extension, maintaining SOC of the HESS in the safe operating region and HESS protection. The economic feasibility includes the cost effective operation of HESS and scheduling generation and the load demand [46]. The EMS algorithms which are implemented in the secondary level control include deterministic rule based strategy [72], FLC [100–102], dynamic programming, genetic algorithms [103], supervised machine learning approach, particle swarm optimization [104–106] etc. The EMS algorithms are chosen based on the requirement of the system and the computational capability of the control units.

2.6.2 EMS for grid-connected HESS

The architecture of the EMS for grid-connected HESS is presented in Figure 2.6. Similar

Figure 2.6: Typical architecture of the EMS for the grid-connected HESS with PV system.

to the EMS for the standalone mode of operation of HESS, the EMS for grid-connected operation can also be divided into the primary level control and secondary level control. In grid-connected mode, the primary level controls include the RESs control, HESS control and inverter control. The secondary level control generates the power references for different units in the system depending upon the system constraints. The EMS also helps the system to switch between grid-connected and standalone mode depending upon the grid availability.

2.7 Summary

The ESSs are the inevitable part of the microgrid. ESSs help to balance the power flow in the system during the generation and demand mismatch. To have an effective operation of the system the choice of converter configurations of ESSs and their control play a vital role. In this Chapter, the detail literature review of the available ESSs has been presented. The possible converter configurations have been discussed. The states of art power sharing methods and control methods have been analyzed. The EMS for the standalone and grid-connected operation of the DC microgrid with HESS has also been presented.

Chapter 3

Faster Joint Control Strategy

In this chapter, the faster joint control strategy for the integration of the HESS in the DC link is studied. The faster joint control strategy utilizes the uncompensated power from the battery system to improve the performance of the overall HESS. The system modelling, controller parameter selection, stability analysis and experimental validation are presented in this chapter. The main contributions of this study are theoretical evaluation of the faster joint control strategy, controller design, experimental validation and comparisons of the joint control strategy with the existing control methods for HESS in the DC microgrid applications. The advantages of the joint control method are increasing the battery lifetime, improving the DC link regulation and reducing the stress on the battery system.

3.1 Modelling of Components of DC Grid

3.1.1 Modelling of PV Panel

The PV panel can directly change light energy into electrical energy. The prime unit of the PV panel is a PV cell. The series and parallel combinations of the PV cells form a PV panel. The PV panels are further arranged in series and parallel combinations to design a PV array. The PV array is designed based on the voltage and current level requirements. The PV panel can be directly used to feed the light loads like led light, calculator, led display etc. However, the PV array requires a power electronics converter

to effectively connect to the microgrid systems. The power electronics converter gives an extra degree of freedom to extract the power from the PV system. The PV system is generally operated at the MPP condition to harvest the maximum available power. The mathematical model of the PV cell is required to design and evaluate the effective control methods for the entire PV system.

Figure 3.1: Equivalent circuit representation. (a) PV array, (b) Lead-acid battery and (c) SC

The equivalent circuit representation of the PV array is presented in Figure 3.1(a) [107]. The characteristic equation of the PV array shown in Figure 3.1(a) is presented in (3.1) [108]. The characteristic equation presented here is based on the single diode model representation of PV array. This approach provides a true representation of the PV array and is easy to design. Sophisticated model representations that provide more accurate results can also be found in the literature [109, 110]. In general, the current and voltage (I-V) characteristics of the PV cell exhibits a non-linear behaviour. The characteristic equation of the PV array is given below,

$$i_{pv} = N_p I_{ph} - N_p I_{rs} \left(e^{\frac{q \left(\frac{V_{pv}}{N_s} + \frac{i_{pv} R_s}{N_p} \right)}{AKT}} - 1 \right) - \frac{\frac{N_p V_{pv}}{N_s} + i_{pv} R_s}{R_{sh}}, \quad (3.1)$$

where N_p represents the total number of parallel connected PV cells. N_s represents the total number series connected PV cells. I_{ph} is the total photo-current generated from the PV array. I_{ph} is depends on the incident solar irradiation (s). I_{rs} represents the reverse saturation or the leakage current of the diode. R_s and R_{sh} represent the series and shunt resistance. A is the diode ideal factor; T is cell's working temperature measured in Kelvin and K is the Boltzmann's constant ($1.38 * 10^{-23} J/K$). v_{pv} and i_{pv} represent the PV array terminal voltage and current. The detail parameter calculations and modelling of the PV arrays for the system study and simulation study are presented

in [111, 112].

3.1.2 Modelling of Battery

There are three basic types of battery models presented in the literature [113, 114]. They are the experimental battery model [113, 114], electrochemical battery model [115] and electric circuit-based battery model [116, 117]. The simple electric circuit-based battery model is presented in Figure 3.1(b). In electric circuit-based battery model, the voltage source and resistance are connected in series. In this model, the no-load terminal voltage is defined by non-linear equation presented in (3.2). The battery terminal voltage depends on its actual SOC value. In the electric circuit-based battery model, the same characteristics equation is used to define both the charging and discharging mode of operation. In this model, the battery internal resistance (R) is supposed to be constant. The battery internal resistance is assumed to be independent of the magnitude of charge and discharge current [117]. The characteristics equations that define the battery behaviour are given in (3.2), (3.4).

$$E = E_o - K \frac{Q}{(Q - i_t)} + Ae^{-Bi_t}, \quad (3.2)$$

$$i_t = \int_0^t i_b dt, \quad (3.3)$$

$$v_b = E - Ri_b, \quad (3.4)$$

where E and E_o represent the no-load voltage and nominal voltage. K and Q represent the polarization voltage and the ampere-hour capacity of the battery. i_b and v_b are the current and terminal voltage of the battery. R is the battery internal resistance. A represents the exponential zone amplitude. B represents the exponential zone time constant inverse of the battery. The remaining parameters mentioned in (3.2) can be determined from specifications given in [117].

3.1.3 Modelling of SC

There is increasing use of SC in the various applications where high power in short time period is necessary. With the increasing utilization of SC in various applications, an accurate SC model is imperative. There are three basic electrical circuit models of SC. They are the series RC model [118], parallel RC model [118, 119] and series-parallel RC model [120, 121]. Among the different electric circuit models of SC, the simplest one is the series RC model. The series RC model of SC uses a resistor and capacitor in series. The resistance and capacitor determine the dynamic behaviour of the SC. In general, the series resistance is termed as equivalent series resistance (ESR). It represents the losses in SC during charging/discharging process. In the series RC model, the series capacitance shows the behaviour of the SC during the charging and discharging process. During the charging mode of SC, if the charging current is suddenly dropped to zero the SC voltage drops gradually and takes some time to reach the steady state condition [119]. This behaviour of SC is not fully addressed by the series RC model. This problem is somewhat addressed by the parallel RC circuit model of SC. The parallel RC model uses a parallel combination of two or more RC series circuits. The different RC branches have different time constant value. Thus, each RC branch in the parallel RC model behaves differently in charge and discharge mode of operation. This results in an accurate representation of the dynamic response of SC. The parallel RC model represents the dynamic behaviour of SC accurately compared to that of the series RC model.

The series-parallel branch model is used in our study and is presented here in Figure 3.1(c). ESR in Figure 3.1(c) represents the series resistance which is responsible for the ohmic losses during the charge and discharge mode of operation of SC. In Figure 3.1(c), R_p and C_p represent the parallel resistance and parallel capacitance respectively. The R_p and C_p combination defines the dynamic response from the SC. C_1 represents the actual storage capacitance of the SC. R_1 represents the self-discharge rate of the SC. v_{sc} and i_{sc} are the terminal voltage of SC and output current from the SC respectively. The procedure to calculate the model parameters are discussed in detail in [121].

Figure 3.2: Switching model. (a) Bi-directional DC-DC converter, (b) Boost converter, (c) Boost converter when s_1 is closed and (d) Boost converter when s_1 is open.

3.2 Bidirectional DC-DC Converter

The non-isolated bi-directional DC-DC converters are used in our study to integrate the HESS to the DC microgrid. The switching model of the bi-directional DC-DC converter is presented in Figure 3.2(a). The main components in the bi-directional DC-DC converter are the control switches, input filter inductor (L) and output filter capacitance (C). In Figure 3.2(a), s_1 and s_2 represent the control switches. R_L , v_c and i_{dcl} represent the total DC load, voltage across capacitor and load current in the system.

3.2.1 Topology of DC-DC converter

The filter parameters of the bi-directional DC-DC converters are designed as given in [122]. The bi-directional DC-DC converters are assumed to be operated in continuous current conduction mode (CCM) for the design of filter parameters. Thus, the inductor value (L) is obtained as follows,

$$L = \frac{V_i D_i}{2 \Delta i_{in} f_{sw}}, \quad (3.5)$$

$$D_i = 1 - \frac{V_i}{V_{dc}}, \quad (3.6)$$

where I_l , V_i , D_i and V_{dc} , represent the DC steady-state value of inductor current, input

voltage, duty cycle and output DC link voltage. These values are used for the controller parameter selection. f_{sw} represents the switching frequency of the bi-directional DC-DC converter. Δi_{in} represents the inductor current ripple percentage of the bi-directional DC-DC converter. The larger value of the inductor will contribute to a lesser input current ripple. However, a larger value of the inductor will increase the converter size, system cost and loss in the system. Thus, the input current ripple (Δi_{in}) is limited to 3% for both the battery and SC converters in our study.

The output filter capacitor value (C) for the bi-directional DC-DC converter is obtained as follows,

$$C = \frac{V_{dc} D_i}{2 \Delta v_{dc} R_L f_{sw}}. \quad (3.7)$$

The output capacitor reduces the output voltage ripple. The output voltage ripple (Δv_{dc}) percentage depends on the capacitor value. A larger value of the capacitance will contribute to a lesser output voltage ripple. Thus, the output voltage ripple is maintained at 1% of the DC link voltage for both the battery and SC converters.

3.2.2 Small Signal Analysis and Feedback Control

The small signal analysis of the power electronics converter provides information about the effect of various factors in the system response. The system transfer functions obtained from the small signal analysis are important to calculate the controller parameters for the bi-directional DC-DC converter control.

The operation of the bi-directional DC-DC converter depends on the nature of control signal applied to the control switches. The control switches s_1 and s_2 in Figure 3.2(a) operates in complementary fashion in the bi-directional DC-DC converter. Thus, it shares the same transfer function during the buck and boost mode. The boost mode operation refers to the flow of current from lower voltage level to the higher voltage level. The buck mode operation refers to the power flow from the DC microgrid to the input voltage source. The boost mode operation is discussed here to make the analysis clear and concise. The switching model representation of the boost converter is presented in Figure 3.2(b). The operational mode of the boost converter when the switch s_1 is on

and off are given in Figure 3.2(c) and Figure 3.2(d) receptively.

The average DC-DC converter state equations over a period of one switching cycle are shown below in (3.8) and (3.9).

$$L \frac{di_l(t)}{dt} = v_i(t) - (1 - \delta_i(t))v_{dc}(t), \quad (3.8)$$

$$C \frac{dv_{dc}(t)}{dt} = (1 - \delta_i(t))i_l(t) - \frac{v_{dc}(t)}{R_L}, \quad (3.9)$$

where i_l , v_i , δ_i and v_{dc} are the inductor current, input voltage, duty cycle and output DC link voltage during normal operation. The design of the feedback control method for the DC-DC converter requires linearised state equations. Thus, the state equations of the system are linearised in the defined DC bias point with small-signal perturbations in the system. Thus, the state parameters with the small signal perturbations can be represented as follows:

$$v_{dc}(t) = V_{dc} + \hat{v}_{dc}(t), \quad i_l(t) = I_l + \hat{i}_l(t), \quad v_i(t) = V_i + \hat{v}_i(t), \quad \delta_i(t) = D_i + \hat{\delta}_i(t), \quad (3.10)$$

where $\hat{i}_l(t)$, $\hat{v}_i(t)$, $\hat{\delta}_i(t)$ and $\hat{v}_{dc}(t)$, are the small-signal perturbation in inductor current, input voltage, duty cycle and output DC link voltage. With the introduction of the small-signal perturbation in the system, the state equations in (3.8) and (3.9) can be represented as follows:

$$L \frac{d(I_l + \hat{i}_l(t))}{dt} = V_i + \hat{v}_i(t) - (1 - D_i - \hat{\delta}_i(t))(V_{dc} + \hat{v}_{dc}(t)), \quad (3.11)$$

$$C \frac{d(V_{dc} + \hat{v}_{dc}(t))}{dt} = (1 - D_i - \hat{\delta}_i(t))(I_l + \hat{i}_l(t)) - \frac{V_{dc} + \hat{v}_{dc}(t)}{R_L}. \quad (3.12)$$

The DC steady-state quantities and small-signal quantities in (3.11) and (3.12) are equated and the small-signal quantities are analysed. In our study, the effect of the second order small signal quantities in the system are neglected. Thus, the average state equations with the small-signal quantities are given as follows:

$$L \frac{d\hat{i}_l(t)}{dt} \approx \hat{v}_i(t) - (1 - D_i)\hat{v}_{dc}(t) + V_{dc}\hat{\delta}_i(t), \quad (3.13)$$

$$C \frac{d\hat{v}_{dc}(t)}{dt} \approx (1 - D_i)\hat{i}_l(t) - I_l\hat{\delta}_i(t) - \frac{\hat{v}_{dc}(t)}{R_L}. \quad (3.14)$$

The time-domain equations (3.13) and (3.14) are transformed into the frequency domain equations by using a Laplace transformation to make the analysis simple. The representation of the small-signal model of the boost converter is presented in Figure 3.3(a). The time domain equations (3.13) and (3.14) after the Laplace transformation are given

Figure 3.3: (a) Small signal model of boost converter and (b) Representation of current and voltage control loop for boost converter.

in (3.15) and (3.16).

$$sL\hat{i}_l(s) = \hat{v}_i(s) - (1 - D_i)\hat{v}_{dc}(s) + V_{dc}\hat{\delta}_i(s) \quad (3.15)$$

$$sC\hat{v}_{dc}(s) = (1 - D_i)\hat{i}_l(s) - I_l\hat{\delta}_i(s) - \frac{\hat{v}_{dc}(s)}{R_L} \quad (3.16)$$

Rearranging (3.15) and (3.16), the expression for boost DC-DC converter system transfer functions are obtained as shown below:

$$G_{vd} = \frac{\hat{v}_{dc}(s)}{\hat{\delta}_i(s)} = \frac{(1 - D_i)V_{dc} - LI_s}{LCs^2 + \frac{L}{R_L}s + (1 - D_i)^2} \quad (3.17)$$

$$G_{id_c} = \frac{\hat{i}_l(s)}{\hat{\delta}_i(s)} = \frac{CV_{dc} + 2(1 - D_i)I_l}{LCs^2 + \frac{L}{R_L}s + (1 - D_i)^2} \quad (3.18)$$

$$G_{vi_v} = \frac{\hat{v}_{dc}(s)}{\hat{i}_l(s)} = \frac{(1 - D_i)V_{dc} - LI_s}{CV_{dc}s + 2(1 - D_i)I_l} \quad (3.19)$$

where G_{vd} , G_{id_c} and G_{vi_v} are the duty cycle to the output voltage transfer function, duty cycle to the inductor current transfer function and the inductor current to output voltage transfer function respectively. These transfer functions are used to calculate

Figure 3.4: Architecture of HESS with PV system in standalone DC microgrid.

the voltage controller (G_{pi_v}) gain values and current controller (G_{pi_c}) gain values to regulate the voltage and current from the boost converter. The block diagram representation of the voltage and current control loop for the boost converter is presented in Figure 3.3(b). In Figure 3.3(b), H_c and H_v are the current loop and voltage loop feedback gains.

3.3 Architecture of HESS in DC Microgrid

The system architecture for the HESS with a PV system in the standalone DC microgrid is presented in Figure 3.4. The PV system is the main RPS. The RPS is linked to the DC link with a boost converter. The bi-directional DC-DC converters are used to connect the HESS to the DC link. The bi-directional DC-DC converter controls the output power from the HESS which maintains the constant DC link voltage. In Figure 3.4, L_{pv} , L_b and L_{sc} are the filter inductors for the PV, battery and SC connected converters. C_{dc} and R_{dc} represent the total filter capacitance and the total load demand of the system. v_{pv} , v_b and v_{sc} are the input voltage of the PV, battery and SC connected converters. i_{pv} , i_b and i_{sc} are the average currents flowing through the filter inductors of the DC-DC converters. i_{dcl} , $i_{pv,d}$, $i_{b,d}$, $i_{sc,d}$ are the average DC load current, PV current, battery and SC current at DC link. v_{dc} represents the nominal DC link voltage. q_{pv} , q_b , q'_b , q_{sc} and q'_{sc} are the control signals for the DC-DC converters. The switching signals q_b and

Figure 3.5: (a) Representation of the conventional control method and (b) the joint control strategy.

q'_b for the battery connected converter are complementary to each other. The switching signals q_{sc} and q'_{sc} for the SC connected converter are also complementary to each other. The switching signals “1” and “0” represent on and off of the corresponding switches.

3.4 Conventional Control Method

The representation of the conventional control method used for the HESS control is shown in Figure 3.5(a). In the conventional control method, dual loop voltage control technique is applied to handle the DC link voltage. The dual loop voltage control method contains the inner control loop and outer control loop. The inner control loop regulates the current from the HESS. The outer control loop is used to obtain the current reference for the current control loop [65]. The total current reference is generated such that the overall power flow in the DC link is balanced during the load and generation variations.

In conventional method shown in Figure 3.5(a), the DC link voltage (v_{dc}) is compared with the DC link voltage reference value (v_{ref}). The error voltage obtained after the comparison is fed to the voltage control loop. The voltage loop PI compensator generates the total current reference (i_{tot}) to be supplied/absorbed by the HESS. i_{tot} is then divided into the average current demand and the transient current demand using a LPF as shown in Figure 3.5(a). The average current (i_{avg}) and transient current (i_{tran}) are used as current references for the battery and SC respectively. The controller bandwidth of the voltage and current PI compensator must be carefully selected to avoid the converter controller’s conflict problem. Moreover, these controllers are designed to operate at

certain operating points and their performance degrades if the operating points are changed. The conventional control method generally neglects the battery error current produced by the battery controller and slow battery dynamics.

3.5 Joint Control Strategy

The joint control strategy address the aforementioned issues in the conventional control method. The primary objectives of the joint control strategy are (i) to improve the battery lifetime, (ii) enhance the DC link voltage regulation and (iii) reduce stress on the battery system. The representation of the joint control strategy is shown in Figure 3.5(b). It is applied for the control of HESS with a PV system in the standalone DC microgrid application. Alike the conventional control methods [55, 56, 123], the power required to balance the overall power flow in the DC link during the load and generation variations are categorized into two components, (i) average power component (P_{avg}), and (ii) transient power component (P_{tran}). Thus, the power balance equation can be obtained as follows,

$$P_{dcl}(t) - P_{ren}(t) = P_b(t) + P_{sc}(t) = P_{avg}(t) + P_{tran}(t), \quad (3.20)$$

where $P_{dcl}(t)$, $P_{ren}(t)$, $P_b(t)$ and $P_{sc}(t)$ are the DC load, RES generation, battery and SC power respectively. The HESS handles the net power demand to ensure that the DC link voltage remains at a predefined limit. The battery and SC power are given in (3.21).

$$P_b(t) + P_{sc}(t) = P_{avg}(t) + P_{tran}(t) = v_{dc} i_{tot}(t), \quad (3.21)$$

The HESS handles the total current demand which regulates the DC link voltage is represented as follows,

$$i_{tot}(t) = \frac{P_{avg}(t)}{v_{dc}} + \frac{P_{tran}(t)}{v_{dc}} = i_{avg}(t) + i_{tran}(t), \quad (3.22)$$

The voltage control loop calculates the total current ($i_{tot}(t)$) and it is shown in (3.23),

$$i_{tot}(t) = i_{avg}(t) + i_{tran}(t) = k_{p_v} v_{er} + k_{i_v} \int v_{er} dt, \quad (3.23)$$

where k_{p_v} and k_{i_v} are the proportional and the integral gains of the voltage control loop. v_{er} represents the error voltage. v_{ref} represents the DC link voltage reference. The effective sharing of i_{tot} is essential for achieving a quick DC link voltage restoration and better performance of the joint control strategy. As in the conventional control strategy, LPF is employed to extract an average current component from i_{tot} . The average current (i_{avg}) is given by (3.24),

$$i_{bref}(s) = i_{avg}(s) = \frac{\omega_c}{s + \omega_c} i_{tot}(s), \quad (3.24)$$

where ω_c represents the cut-off frequency of the LPF. $i_{bref}(s)$ represents the current reference for the battery current controller. The cut-off frequency of LPF is chosen to be $2\pi \cdot 5$ rad/sec, as presented in [124]. The average current is handled by the battery system. The uncompensated power is observed in the system due to the slow response of the battery system. This includes dynamics of the battery, battery controller and the bi-directional DC-DC converter response. The uncompensated power from the battery system is given as

$$P_{b_uncomp}(s) = (i_{bref}(s) - i_b(s)) v_b(s), \quad (3.25)$$

where $P_{b_uncomp}(s)$ is the uncompensated power from the battery system. In the joint control strategy, the $P_{b_uncomp}(s)$ is utilized to enhance the performance of the SC. The transient current component (i_{tran}) and $P_{b_uncomp}(s)$ are supported by the SC. The current reference for SC ($i_{scref}(s)$) is thus obtained by (3.27),

$$i_{tran}(s) = \left(1 - \frac{\omega_c}{s + \omega_c}\right) i_{tot}(s), \quad (3.26)$$

$$i_{scref}(s) = i_{tran}(s) + (i_{bref}(s) - i_b(s)) \frac{v_b(s)}{v_{sc}(s)}. \quad (3.27)$$

The generated battery and SC current references are then compared to their actual current measurements. The error current obtained after comparisons are fed to the PI current compensator. It calculates the duty cycle to follow the respective current

Table 3.1: Nominal battery and SC connected bi-directional DC-DC converter parameters

v_b	L_b	C_{dc}	R_{dc}	V_{dc}	D_b	I_b
24 V	6.3 mH	440 μ F	60 Ω	48 V	0.5	1.6 A
v_{sc}	L_{sc}	C_{dc}	R_{dc}	V_{dc}	D_{sc}	I_{sc}
30 V	5 mH	440 μ F	60 Ω	48 V	0.375	1.25 A

Table 3.2: Control bandwidth selection for controller gain calculation

Control loop	Cut-off frequency (krad/s)
SC current control loop	$2\pi f_{sw}/6 = 16.75$
Battery current control loop	$2\pi f_{sw}/10 = 10.05$
Overall voltage control loop	$2\pi f_{sw}/40 = 2.51$

references. In Figure 3.5(a) and Figure 3.5(b), δ_b and δ_{sc} are the duty cycle for the battery converter control and duty cycle for the SC converter control respectively.

3.6 Stability Analysis of Joint Control Strategy

The main objective of the joint control strategy is to enhance the voltage regulation while maintaining the proper power flow balance in the DC link. The nominal system parameters required for selection of the controller gains are shown in Table 3.1. The dynamic response in the system during supply and demand mismatch mainly depends on the SC, battery and PV current response to DC link voltage change. The deviation in the DC link voltage can be represented as follows,

$$\Delta v_{dc} = G_b \Delta i'_b + G_{sc} \Delta i'_{sc} + G_{pv} \Delta i'_{pv}, \quad (3.28)$$

where Δv_{dc} is a small deviation in the DC link voltage. G_b , G_{sc} and G_{pv} represent the small signal impedance of the battery, SC and PV converter respectively. $\Delta i'_b$, $\Delta i'_{sc}$ and $\Delta i'_{pv}$ are the changes in the battery, SC and PV current respectively. The converter parameters and control bandwidths determine the response of the battery, SC and PV to the DC link voltage variations. The SC dynamic response is faster compared to the battery. Thus, the controller parameters are basically selected based on the SC system [125]. To ensure the overall system stability, the following bandwidths for the different control loops are selected as shown in Table 3.2. In Table 3.2, f_{sw} is the

Table 3.3: Transfer functions for control of the PV system with HESS

Duty Cycle to inductor current transfer function for SC	
$G_{id_sc}(s) = \frac{\hat{i}_{sc}}{\hat{\delta}_{sc}} = \frac{C_{sc}V_{dc}s + 2(1 - D_{sc})I_{sc}}{L_{sc}C_{sc}s^2 + \frac{L_{sc}}{R_{dc}}s + (1 - D_{sc})^2}$	
Inductor current to output voltage transfer function for SC	
$G_{vi_sc}(s) = \frac{\hat{v}_{dc}}{\hat{i}_{sc}} = \frac{(1 - D_{sc})V_{dc} - L_{sc}I_{sc}s}{C_{sc}V_{dc}s + 2(1 - D_{sc})I_{sc}}$	
Duty Cycle to inductor current transfer function for battery	
$G_{id_b}(s) = \frac{\hat{i}_b}{\hat{\delta}_b} = \frac{C_bV_{dc}s + 2(1 - D_b)I_b}{L_bC_bs^2 + \frac{L_b}{R_{dc}}s + (1 - D_b)^2}$	
Transfer function of SC current control loop compensator	
$G_{pi_sc}(s) = k_{p_sc} + \frac{k_{i_sc}}{s}$	
Transfer function of battery current control loop compensator	
$G_{pi_b}(s) = k_{p_b} + \frac{k_{i_b}}{s}$	
Transfer function of voltage control loop compensator	
$G_{pi_v}(s) = k_{p_v} + \frac{k_{i_v}}{s}$	

switching frequency of the DC-DC converters. f_{sw} for the DC-DC converters is selected as 16 kHz for our study. If the margin between the different control bandwidths is not selected properly the converter control conflict may arise in the system. This makes the overall system unstable.

3.6.1 SC Current Control Loop Design

The transfer functions for the calculation of the current compensator parameters for the SC current control loop are given in Table 3.3. In Table 3.3, V_{dc} , I_b , I_{sc} , D_b and D_{sc} are the nominal DC link voltage, battery current, SC current, nominal duty cycle for the battery current control and nominal duty cycle of the SC current control. The transfer functions G_{id_sc} and G_{pi_sc} are used to determine the current compensator parameters. In Table 3.3, k_{p_sc} and k_{i_sc} are the proportional and integral gains for the SC current compensator. The current compensator parameters are selected such that it obtains a phase margin of 60° at a bandwidth of 16.75 krad/s . The SISO toolbox in MATLAB [126] is used to compute the desired current compensator parameters and the value obtained are, $k_{p_sc} = 0.301$ and $k_{i_sc} = 2,900$.

The open loop transfer function (G_{ol_sc}) and closed loop transfer function (G_{cl_sc}) of

Figure 3.6: (a) Open loop Bode plot of overall voltage control loop, (b) open loop Bode plot of SC current control loop and (c) open loop Bode plot of battery current control loop.

the SC current control loop are analysed to determine the stability of the overall system.

Thus, G_{ol_sc} and G_{cl_sc} of the SC current control loop are given below,

$$G_{ol_sc} = G_{pi_sc} G_{id_sc} H_{sc} \quad (3.29)$$

$$G_{cl_sc} = \frac{G_{pi_sc} G_{id_sc}}{1 + G_{pi_sc} G_{id_sc} H_{sc}} \quad (3.30)$$

In (3.29), H_{sc} represents the feedback gain for the SC current control loop. The Bode plots of the open loop transfer function for SC current control loop with PI compensator and without PI compensator are shown in Figure 3.6(b). The Bode plots show that the designed controller is stable at the desired operating point with sufficient phase margin and gain margin.

3.6.2 Battery Current Control Loop Design

The transfer functions for the calculation of the inner current compensator parameters for the battery current control loop are given in Table 3.3. The transfer functions G_{id_b} and G_{pi_b} are used to determine the current compensator parameters. In Table 3.3, k_{p_b} and k_{i_b} are the proportional and integral gains for the battery current compensator respectively. The proportional and integral gains are selected such that it obtains a phase margin of 60° at a bandwidth of 10.05 krad/s. The calculated compensator parameters are $k_{p_b} = 0.18$ and $k_{i_b} = 1030$. The open loop transfer function (G_{ol_b}) of the battery

current control loop is given below,

$$G_{ol_b} = G_{pi_b} G_{id_b} H_b \quad (3.31)$$

In (3.31), H_b represents the feedback gain for the battery current control loop. The Bode plots of the open loop transfer function for the battery current control loop with PI compensator and without PI compensator are shown in Figure 3.6(c). It shows that the designed controller is stable at the desired operating point with sufficient phase margin and a gain margin.

Figure 3.7: Open loop Bode plot of voltage control loop. (a) Cut-off frequency at 2.51 krad/s and (b) Cut-off frequency at 5 krad/s

3.6.3 Overall Voltage Control Loop Design

The current compensator values for the battery and SC system are used to design the voltage control loop. The voltage controller parameters are calculated such that it obtains a phase margin of 60° at a bandwidth 2.51 krad/s. The controller parameters

obtained are $k_{p_v} = 1.42$ and $k_{i_v} = 1720$. The open loop transfer function (G_{ol_vdc}) of the voltage control loop is calculated as follows,

$$G_{ol_vdc} = G_{pi_v} G_{cl_sc} G_{vi_sc} H_{vdc} \quad (3.32)$$

G_{ol_vdc} is used to determine the stability of the system. In (3.32), H_{vdc} represents the feedback gain for the overall voltage control loop. The Bode plot response of the open loop transfer function for the voltage control loop is shown in Figure 3.6(a). The Bode plots response show that the system is stable at the desired operating point with a required phase margin and gain margin. The design ensures the overall stability of the system.

The coupling effect on the stability of the overall voltage control loop is analysed and compared based on the Bode response shown in Figure 3.7(a) and Figure 3.7(b). The Bode of the voltage control loop responses are analysed for the cut-off frequency of 2.51 krad/s and 5 krad/s with and without the coupling of battery error components in the system. The Bode plots show that there is a change in the gain margin which is less than 1 db with the coupling of the battery error components to the SC system. However, it does not affect the overall system stability. The limitation of the proposed control method is that both the battery and SC system should be closed to each other.

3.7 Experimental Results

The picture of the experimental setup for the HESS with a PV system in the DC microgrid application is presented in Figure 3.8. For the experimental setup, 3 kW bi-directional DC-DC converters for the PV, battery and SC are built. Semikron SKM 75GB128D IGBTs are used as power switches. The LEM current transducer LA 55-P is used for current measurements. The voltage transducer LV 25-P is used for voltage measurements in the experimental setup. The current from the regulated power supply is controlled to generate different PV current profiles during the experimental study. The proposed control method is implemented in real-time in the dSPACE 1103 controller platform. The comparative performance evaluation of the proposed and the conventional control methods [55, 56, 123] under the short-term and long-term scenario is carried out.

Figure 3.8: Experimental setup for HESS.

Table 3.4: System parameters for experimental study

PV array simulator	Values
Open circuit voltage (v_{pvo})	30.2 V
Short circuit current (i_{pvo})	5 A
Mppt voltage (V_{mppt})	29 V
Mppt current (I_{mppt})	4.8 A
Mppt power (P_{mppt})	140 W
Lead-acid battery specifications	Values
Ah capacity	17 Ah
Terminal Voltage (v_b)	12 V
Number of batteries in series	2
Maxwell BM0D0058 E015 B01 SC specifications	Values
Terminal voltage (v_{sc})	15 V
Capacitance (C_{scint})	58 F
Number of SC in series	2
DC-DC converters parameters	$L_{pv} = 10 \text{ mH}$, $L_b = 6.3 \text{ mH}$, $L_{sc} = 5 \text{ mH}$ $C_{dc} = 440 \text{ }\mu\text{F}$,
Nominal load resistance (R_{dc})	60 Ω
Nominal load power (P_{dcl})	38.4 W

The nominal system parameters for experimental study are presented in Table 3.4.

3.7.1 Performance under Short-term Operation Scenario

The short-term power variation tests are performed to show the competence of the joint control method to deal with sudden changes in the load demand and the generation. During the short-term performance analysis, the SOC of the battery and SC are maintained within their respective safe operating regions as per the instructions provided by the manufacturer in their datasheets. The four different operating conditions are

Figure 3.9: Experimental result for a step increase in PV generation: (a) conventional control method and (b) proposed control method. Experimental result for a step decrease in PV generation: (c) conventional control method and (d) proposed control method. $v_{dc} \sim 5 \text{ V/div}$, $i_{pv} \sim 2 \text{ A/div}$, $i_{dcl}, i_b, i_{sc} \sim 1 \text{ A/div}$, $time \sim 200 \text{ ms/div}$.

studied as presented in the following subsections.

Case I. Step increase in PV generation

The experimental results for the conventional control method is shown here in Figure 3.9(a). The experimental results for the proposed control method is shown here in Figure 3.9(b). In both cases, the PV generation is suddenly increased from 2 A to 4 A at time instant t_1 . The step change in PV generation is obtained by changing the current reference for the PV converter control. In this condition, the load is maintained constant with load resistance of $R_{dc} = 60 \Omega$. As observed in the results, before the step increase in PV generation at t_1 , the steady-state value of $v_{dc} = 48 \text{ V}$, $i_{pv} = 2 \text{ A}$, $i_{dcl} = 0.8 \text{ A}$, $i_b = -0.2 \text{ A}$ and $i_{sc} = 0.01 \text{ A}$. At time instant t_1 , due to a sudden increase in the PV generation, the DC link voltage tends to increase. To restore the DC link to its nominal value, the HESS should deal with the power mismatch between PV generation and load. The results obtained show the settling time of 630 ms for the conventional control method and settling time of 260 ms for the proposed control method. It is observed from the results that with the diversion of error current components from the battery system

to the SC controller, the faster DC link voltage restoration can be achieved. The reason behind the better dynamic performance is the faster response of SC in the proposed control method.

Case II. Step decrease in PV generation

The experimental results for the conventional control method and proposed control method for a step decrease in PV generation is presented in Figure 3.9(c) and Figure 3.9(d) respectively. The PV generation is decreased suddenly by changing the current reference for the PV DC-DC converter at time instant t_1 . During the experiment, the load resistance (R_{dc}) is kept constant at 60Ω with $i_{dcl} = 0.8 A$.

At time instant t_1 , the PV generation is intentionally decreased from $4 A$ to $2 A$. Due to a sudden decrease in PV generation, the DC link voltage tends to decrease. The sudden power fluctuation in the system is handled by the HESS. The results for conventional control method shows the settling time of around $590 ms$. The proposed control method shows two times faster response compared to the conventional one with the response time of $250ms$, as shown in Figure 3.9(d). It is observed from the results that the dynamic performance of the proposed control method is better compared to that of the existing control method.

Case III. Step increase in load demand

The results obtained for the conventional control method and the proposed control method are presented in Figure 3.10(a) and Figure 3.10(b) respectively. At time t_1 , R_{dc} is decreased from 60Ω to 30Ω . This increases the i_{dcl} from $0.8 A$ to $1.6 A$. During this experiment, the i_{pv} is kept constant at $4 A$.

Before time t_1 , the steady-state value of $v_{dc} = 48 V$, $i_{pv} = 4 A$, $i_{dcl} = 0.8 A$, $i_b = -1.8 A$ and $i_{sc} = 0.01 A$. At time t_1 , the PV generation remains constant and load demand increase to $i_{dcl} = 1.6 A$. This creates a power imbalance in the system. The HESS control balance the overall power with SC dealing with transient power demand and battery with average power demand. The v_{dc} is restored in $450 ms$ as shown in Figure 3.10(a) for the conventional control strategy. v_{dc} is restored at $210 ms$ as shown in Figure

Figure 3.10: Experimental result for a step increase in load demand : (a) conventional control method and (b) proposed control method. Experimental result for a step decrease in load demand : (a) conventional control method and (b) proposed control method. $v_{dc} \sim 5$ V/div, $i_{pv} \sim 2$ A/div, $i_{dcl}, i_b, i_{sc} \sim 1$ A/div, time ~ 200 ms/div.

3.10(b) for the proposed control method. The results show with the proposed method we can obtain a better dynamic performance in the system.

Case IV. Step decrease in load demand

The experimental results presented in Figure 3.10(c) and Figure 3.10(d) shows the step decrease in the load demand at time t_l . i_{dcl} is decreased by $0.8A$ with change in a load resistance from $(R_{dc}) = 30\Omega$ to $(R_{dc}) = 60\Omega$. The step change in i_{dcl} influence the DC link voltage.

The sudden power fluctuation in the system is handled by the HESS. The slow average power demand is handled by the battery system and fast-changing transient power demand is handled by the SC in both the conventional and proposed control method, as presented in Figure 3.10(c) and Figure 3.10(d). With the conventional control method, the DC link voltage is restored in $460ms$. The obtained experimental result shows that with the implementation of the proposed control we can consistently achieve two times faster voltage restoration with less overshoot in the DC link compared to the existing control method. The total time taken by the proposed control method to restore the

Figure 3.11: Experimental result for a long-term PV power variation scenario: (a) Input irradiance pattern, $time \sim 30 \text{ min/div}$. (b) PV change with constant load demand and (c) PV change with change in load demand. $v_{dc} \sim 20\text{V/div}$, $i_{pv}, i_b, i_{dcl}, i_{sc} \sim 500\text{mA/div}$, $time \sim 2\text{s/div}$.

v_{dc} is 240 ms .

3.7.2 Performance under Long-term Operation Scenario

The PV irradiation data were recorded from 10:00 to 16:00 hr in a 1 minute interval. The data were recorded on April 10th, 2011 in Singapore. The PV irradiation graph is presented in Figure 3.11(a). The irradiation data are scaled down for our application. The respective i_{pv} waveform is presented in Figure 3.11(b). To study the realistic operating condition, the load change is done along with the PV generation variations. In this experiment, the HESS SOC is maintained at safe operating region defined by manufacturer.

From the experiment results, it can be observed that the proposed controller is effective in managing the intermittent PV power (represented by i_{pv} current), by effectively controlling the slow base power fluctuations from the battery (represented by i_b), and the faster transient power fluctuations from the SC system (represented by i_{sc}). The v_{dc} is sustained roughly at a constant v_{ref} value. The experimental results for the simultaneous variation in the PV power generation and the load variation are shown in Figure 3.11(c). At t_1 and t_3 , the PV generation is varying as shown in the Figure 3.11(c), and simultaneously a step increase in i_{del} is applied by changing $R_{dc} = 60\ \Omega$ to $30\ \Omega$. During this condition, the transient power fluctuations are dealt by the SC and the average power demand is gradually handled by the battery. The smooth transition of the battery current can be observed with a faster v_{dc} regulation. At time t_2 , R_{dc} is increased from $30\ \Omega$ to $60\ \Omega$ as shown in Figure 3.11(c). The PV generation is varied based on the respective irradiation pattern. The v_{dc} is stable and restored quickly in this condition. The fast transient and slow base power are seamlessly handled by HESS. The experiment results show that the joint control strategy can provide faster DC link voltage restoration under varying renewable generation and varying load demand condition.

3.7.3 Performance Evaluation

The overshoot and the response time to restore the v_{dc} during a change in the load and generation are considered for the performance evaluation of the proposed control method. During a step increase and decrease in the load demand and the generation, the overshoot percentage in the system (M_p) is calculated as (3.33) below,

$$M_p = \frac{|v_{ref} - v_{max}|}{v_{ref}} \times 100 \quad (3.33)$$

The graphical representation of the performance comparison of the conventional and proposed control method is given in Figure 3.12. The results demonstrate the advantages of the joint control strategy over the conventional controller method. The proposed controller shows two times faster response compared to conventional controller [55, 56, 123] in all the case studies. The overshoot in the system is also reduced by 1% in all four case studies. The proposed control method is designed such that the SC supports

Figure 3.12: Graphical representation of performance comparison between conventional control method and proposed control method. (a) Response time and (b) voltage overshoot

the HESS until the battery comes to the steady-state condition. This results in faster v_{dc} regulation with robust performance.

3.8 Summary

A faster joint control strategy for the HESS with a PV system in the DC microgrid applications has been presented in this chapter. The detail HESS modelling, bi-directional converter design, controller design, stability analysis and experimental verification have been presented. The comparisons of the proposed control method with that of the conventional control method have been illustrated.

The basic idea behind the conventional control strategies is that the battery supports

the average power fluctuation while the SC supports the dynamic high-frequency power fluctuations. However, the current tracking error is observed in the battery system. The error due to the dynamics of the battery, battery controller, and the DC-DC converter is not addressed in the conventional control strategies. To address the aforesaid issues, a new joint control method has been proposed, which provides faster DC link voltage restoration compared to the conventional control method [55, 56]. The proposed control method overcomes the slow dynamics of the battery system with utilization of battery error current. The proposed control method enhance the battery lifetime with less stress on it. The features of the proposed control approach are summarised as follows: (i) faster DC link voltage restoration with the utilization of uncompensated power from the battery system, (ii) less stress in primary energy storage system during a step change in load and generation and (iii) the ability to suppress the overshoot in DC link voltage. The experimental test cases show that the proposed control method can provide two times faster voltage regulation with less overshoot compared to the conventional control method.

Chapter 4

Enumeration-based Model Predictive Current Control

4.1 Introduction

The MPC method has been intensively studied for the industrial process control for more than four decades. In last decade, the MPC method is implemented in many power electronics converter topologies, such as boost converters [80, 81, 127], bi-directional DC-DC converters [128] and single-inductor multi-port converters [82, 129].

There are very few works done for the implementation of MPC for HESS in DC microgrid applications. In [58], Herdzak *et. al* presented a MPC method for the HESS control in the DC microgrid. The prime objective of the proposed scheme is to maintain the SOC of the battery and SC within their prescribed SOC limits with an active power sharing between them. However, the design of the MPC parameters follow the classical MPC method which depends on the discrete mathematical model of the HESS. This requires larger computational resources. In the proposed method, the cost function is solved using a quadratic programming method which requires a long computational time to obtain optimal control parameters. Moreover, the MPC generates a duty cycle for the battery and SC converter control, so the PWM modulator is required to generate switching signals which result in a fixed switching frequency.

In our study, we proposed EMPCC method for the HESS. The main contributions of this study are a theoretical evaluation of EMPCC, EMPCC design, experimental validation and comparison of the EMPCC method with the existing control methods for HESS in the DC microgrid applications. The advantages of the EMPCC method over the traditional MPC method [58] for HESS are: (i) less computational complexity, (ii) simpler controller design and (iii) direct manipulation of control signals without PWM modulator, and (iv) faster dynamic response.

The representation of the EMPCC method is shown in Figure 4.1. The outer PI compensator generates the total current reference (i_{tot}) to be handled by the HESS. The total current reference (i_{tot}) is split into low-frequency current reference (i_{bref}) and high-frequency current reference (i_{scref}) using a LPF. The cut-off frequency of LPF is determined based on the battery dynamics. The i_{bref} and i_{scref} are used as current references of EMPCC for the battery and SC system. The EMPCC generates optimal switching signals which maintain the battery and SC current according to their current references. The detailed design of the EMPCC method for HESS in DC microgrid applications is presented in following sections.

4.2 EMPCC Design for Inner Control Loop

The system architecture for the design of EMPCC is similar to that presented in Chapter 3, Figure 3.4. To make the analysis simple, the battery system is discussed here for the

Figure 4.1: Block diagram representation of EMPCC for HESS.

design of the EMPCC algorithm which controls the battery current. The similar method is implemented to design the EMPCC algorithm for the SC system. The charging (buck-

mode) and discharging (boost-mode) operation depends on the PWM signal applied to the switches. The control switches q_b and q_b' operates in fashion. Thus, it shares same transfer function during charging and discharging mode. In such cases, the unified controller design approach is acceptable [130]. The boost-mode operation is discussed here to design the EMPCC for battery current control. The same method is implemented to design the EMPCC algorithm for the SC system.

4.2.1 State-space Model for Battery Converter

The state-space model of the bi-directional DC-DC converters for HESS is analysed for the design of the EMPCC. The boost mode operation of the battery connected converter is only discussed here to make the analysis simple and easy to understand. The CCM equations for the battery connected DC-DC converter are presented in (4.1) and (4.2),

$$L_b \frac{di_b(t)}{dt} = v_b - (1 - q_b)v_{dc}(t), \quad (4.1)$$

$$C_{dc} \frac{dv_{dc}(t)}{dt} = (1 - q_b)i_b(t) - i_{dcl} + i_{pv,d} + i_{sc,d}. \quad (4.2)$$

The forward Euler method is used to discretized the continuous-time equations in (4.1) and (4.2) considering the switching states of q_b . The discrete-time equations of the battery connected DC-DC converter are given below in (4.3) and (4.4),

$$i_b(k+1) = \begin{cases} \frac{t_s}{L_b} v_b + i_b(k), q_b(k) = 1 \\ \frac{t_s}{L_b} (v_b - v_{dc}(k)) + i_b(k), q_b(k) = 0, \end{cases} \quad (4.3)$$

$$v_{dc}(k+1) = \begin{cases} -\frac{t_s}{C_{dc}} (i_{dcl}(k) - i_{pv,d}(k) - i_{sc,d}(k)) + v_{dc}(k), q_b(k) = 1 \\ \frac{t_s}{C_{dc}} (i_b(k) - i_{dcl}(k) + i_{pv,d}(k) + i_{sc,d}(k)) + v_{dc}(k), q_b(k) = 0, \end{cases} \quad (4.4)$$

As i_{dcl} , $i_{pv,d}$ and $i_{sc,d}$ in (4.2), (4.4) are sampled at high frequency, they can be considered

as a constant [131]. Thus, the i_{dcl} , $i_{pv,d}$ and $i_{sc,d}$ can be expressed as (4.5), (4.6) and (4.7).

$$\frac{di_{dcl}(t)}{dt} = 0, \quad (4.5)$$

$$\frac{di_{pv,d}(t)}{dt} = 0, \quad (4.6)$$

$$\frac{di_{sc,d}(t)}{dt} = 0. \quad (4.7)$$

The discrete-time equations of (4.5), (4.6) and (4.7) are shown below in (4.8), (4.9) and (4.10),

$$i_{dcl}(k+1) = i_{dcl}(k), \quad (4.8)$$

$$i_{pv,d}(k+1) = i_{pv}(k), \quad (4.9)$$

$$i_{sc,d}(k+1) = i_{pv}(k). \quad (4.10)$$

Combining equations (4.3), (4.4), (4.8), (4.9) and (4.10) the discrete-time state-space model of the battery system can be described as follows,

$$\begin{aligned} x(k+1) &= [A + Bq_b(k)]x(k) + Cv_b \\ y(k) &= Dx(k) \end{aligned} \quad (4.11)$$

where $x(k) = [i_b(k) \ v_{dc}(k) \ i_{dcl}(k) \ i_{pv,d}(k) \ i_{sc,d}(k)]^T$, and $y(k) = i_b(k)$. In (4.11), A, B, C and D are the coefficient matrices whose values are determined as follows:

$$A = \begin{bmatrix} 1 & -t_s/L_b & 0 & 0 & 0 \\ t_s/C_{dc} & 1 & -t_s/C_{dc} & t_s/C_{dc} & t_s/C_{dc} \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix},$$

$$B = \begin{bmatrix} 0 & t_s/L_b & 0 & 0 & 0 \\ -t_s/C_{dc} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix},$$

$$C = \begin{bmatrix} t_s/L_b & 0 & 0 & 0 & 0 \end{bmatrix}^T,$$

and

$$D = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \end{bmatrix}.$$

4.2.2 EMPCC Objectives

The prime objective of the EMPCC is to find the optimal control signals that regulate the battery current according to its current reference. The state-space model is used to predict all possible future battery current values. Among the group of the expected battery current values, the one which minimises the cost function in (4.13) is chosen, and the corresponding set of control signals is the optimal set.

The function that calculate the difference in the battery reference and actual current is presented below in (4.12)

$$l[i_{bref}(k), i_b(k+i)] = [i_{bref} - i_b(k+i)]^2, \quad (4.12)$$

The objective function (J) is defined and presented below in (4.13),

$$J = \sum_{i=1}^{N_c} l[i_{bref}(k), i_b(k+i)] \quad (4.13)$$

The first control signal in the optimal set is used to control the battery bi-directional DC-DC converter to regulate the battery current. The other elements of the optimal set are discarded and the process is repeated in each execution time with the new measured data in the receding horizon technique [94].

4.2.3 Enumeration Technique

The optimal control signals are calculated by solving the objective function over a finite control horizon. The quadratic programming algorithm is the popular method to solve these optimization problems [82]. However, it is computationally complex and requires large computational resources to solve the optimization problem. This make it difficult to use in the digital signal processor (DSP) platform.

In the proposed method, the enumerated technique is used to calculate the optimal switching sequence. The enumeration technique includes three basic steps. They are (i) calculation and assemble of all the possible combinations of q_b and q'_b over N_c , (ii) prediction and evaluation of 2^{N_c} sequence of the battery current trajectory and (iii) selection of the switching sequence with the smallest associated objective function value. The sequence of switching states over the prediction horizon is represented as follows,

$$Q_b(k) = \begin{bmatrix} q_b(k) & q_b(k+1) & \dots & q_b(k+N_c) \end{bmatrix}^T \quad (4.14)$$

Conventional MPC involves lots of matrix calculations which are complex to implement in the commonly used DSP. With the enumeration technique the large matrix calculation requirement is reduced which makes it compatible for implementation in the commonly used DSP.

4.2.4 Move Blocking Prediction Technique

The boost mode operation of the DC-DC converter exhibits the non-minimal phase behaviour in the system. Thus, it requires a long prediction interval to assure the closed-loop control stability [81]. In conventional MPC, t_s is fixed as T_s , so it requires a high computational resource to obtain long prediction horizon. T_s is execution time determined by the DSP controller.

To solve this issue, the moving block technique (MBT) is implemented. The MBT provides a sufficiently long prediction interval with a low computational requirement. In MBT, t_s varies as $n_j T_s$ in each prediction step. The relation of n_j is given below in (4.15),

Figure 4.2: Representation of EMPCC with MBT.

$$n_1 < n_2 < \dots n_j < \dots < n_{N_c}, n_j \in N^+ \quad (4.15)$$

The binomial tree representation of EMPCC with MBT is presented in Figure 4.2 with the control horizon of N_c steps in the future. It can be observed that the total number of possible sets of the control sequences is 2^{N_c} . It also shows that with MBT, t_s varies in each prediction step. Without the MBT, the $2^{(n_1+n_2+\dots+n_{N_c})}$ numbers of switching sequences need to be investigated. This will require a large computational resources to generate an optimal control action. The inherent computational complexity is the most prominent drawback of MPC and the computational power required increases exponentially as the prediction horizon is extended. The MBT does not provide the global optimal control solution as the conventional MPC. However, it significantly reduces the computations required and facilitates the real-time implementation of the controller.

4.2.5 EMPCC Control Algorithm

The implementation of the EMPCC in the MATLAB and dSPACE 1103 controller board is summarized in **Algorithm 1**. The input parameters are the measurements

from the DC microgrids and the output parameters are the control signals for the DC-DC converters. The initialization parameters are the fixed nominal system parameters and control parameters.

Algorithm 1 EMPCC algorithm for battery converter

```

1: Input:  $v_b, i_b, v_{dc}, i_{dcl}, i_{bref}, v_{ref}$ 
2: Output:  $q_b, q'_b$ 
3: Initialize:  $q_b, q'_b, L_b, C_{dc}, T_s, N_c, n = [n_1, n_2, n_3, \dots, n_{N_c}]$ 
4: global variables
5:    $J \leftarrow []$  ▷ Empty array
6: end global variables
7: procedure EMPCC: ( $J = P_{r\_c}(v_{dc}, i_b, J, J_p, P_{r\_l})$ )
8:   for  $q_b = 0, 1$  do
9:      $next\ i_b \leftarrow i_b(k+1)$  ▷ eqn. (4.3)
10:     $next\ v_{dc} \leftarrow v_{dc}(k+1)$  ▷ eqn. (4.4)
11:     $J_p \leftarrow J_p + l(i_{bref}, next\ i_b)$  ▷ eqn. (4.12)
12:    if  $P_{r\_l} < N_c$  then
13:       $next\ J \leftarrow P_{r\_c}(next\ v_{dc}, next\ i_b, J, J_p, P_{r\_l} + 1)$ 
14:    else
15:       $next\ J \leftarrow J_p$ 
16:    end if
17:  end for
18:   $J = [J, nextJ]$ 
19:  Return  $J$ 
20: end procedure
21: procedure MAIN:
22:    $J \leftarrow P_{r\_c}(v_{dc}, i_b, J, 0, 0)$  // EMPCC:
23:    $pos \leftarrow \underset{i}{\operatorname{argmin}} (J(i))$ 
24:   if  $pos < 2^{N_c-1}$  then
25:      $q_b \leftarrow 0, q'_b \leftarrow 1$ 
26:   else
27:      $q_b \leftarrow 1, q'_b \leftarrow 0$ 
28:   end if
29: end procedure

```

The program flow of the Algorithm 1 are explained below:

1. Firstly, the input and output parameters are defined as shown in line 1 and 2 in Algorithm 1. Then the initial values of the parameters are initialized.
2. The program is executed with the MAIN loop and function $J = P_{r_c}(v_{dc}, i_b, J, J_p, P_{r_l})$. The J function is executed with input variables such as the measured DC link voltage, battery current, $J[]$ array, $J_p = 0$ and $P_{r_l} = 0$. $J_p = 0$ is the initialization value for the first element of J . $P_{r_l} = 0$ is the initialization of the variable used to count the execution of the function.

3. In function J from line 7 to 20 in Algorithm 1 the following tasks are performed:
 - 3.1 The future value of the i_b and v_{dc} are calculated in each prediction step for $q_b = 0$ and $q_b = 1$.
 - 3.2 The future value of i_b and v_{dc} is compared with the actual i_b and the values are stored in array J .
 - 3.3 The process 3.1 and 3.2 are repeated based on the value of N_c as represented in Figure 4.2.
 - 3.4 After the completion of the function J , the stored values in $J[]$ are returned to the MAIN loop.
 - 3.5 Based on the N_c value the function returns $J[] = [J_1 J_2 \dots J_{2(N_c)}]$. For example, if $N_c = 3$, the function returns $J[] = [J_1 J_2 \dots J_8]$.
 - 3.6 The elements of $J[]$ are arranged such that the first $2^{N_c} - 1$ elements are obtained when $q_b = 0$ and the rest are obtained when $q_b = 1$.
4. From $J[] = [J_1 J_2 \dots J_8]$, the position of the element which minimizes the error between the predicted battery current and reference battery current is calculated.
5. If the calculated position lies in the first 2^{N_c-1} elements of $J[]$, then $q_b = 0$ else $q_b = 1$.
6. The respective switching signals are used to control the converters and the process is repeated with new measured data.

The process is repeated again after the execution of control signals.

4.3 Voltage Control Loop Design

The EMPCC is used to control the battery current. Thus, it is acceptable to consider that the EMPCC is faster than the PI-based voltage control loop. As shown in Figure 4.1, the total current demand ($i_{tot}(t)$) is the output from the outer voltage control loop. i_{tot} should be handled by HESS to ensure the constant DC link voltage. Thus, the expression for the calculation of $i_{tot}(t)$ is as follows,

$$i_{tot}(t) = k_{p_v}(v_{ref} - v_{dc}(t)) + k_{i_v} \int (v_{ref} - v_{dc}(t)) dt, \quad (4.16)$$

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4.3. VOLTAGE CONTROL LOOP DESIGN

where k_{p_v} and k_{i_v} are the PI compensator gains of the voltage control loop. In (4.16), v_{ref} is the DC link voltage reference. The i_{tot} is split into i_{bref} and i_{scref} using a LPF and are given in (4.16) and (4.17),

$$i_{bref}(s) = \frac{\omega_c}{s + \omega_c} i_{tot}(s), \quad (4.17)$$

$$i_{scref}(s) = \left(1 - \frac{\omega_c}{s + \omega_c}\right) i_{tot}(s), \quad (4.18)$$

where ω_c represents the LPF cut-off frequency. For the selection of the k_{p_v} and k_{i_v} , the SISO toolbox in the MATLAB is used. In the SISO toolbox, the transfer function of the system and controller are used for the PI controller gains calculation. The transfer function representation of the voltage control loop, LPF and EMPCC loop are shown in Figure 4.3(a). The voltage loop PI compensator transfer function ($G_{pi_v}(s)$), LPF

Figure 4.3: (a) Representation of voltage control loop design and (b) Voltage control loop Bode response.

transfer function ($G_{lf}(s)$), and inductor current to output voltage transfer function for SC ($G_{vi_sc}(s)$) and open loop voltage control transfer function ($G_{ol_vdc}(s)$) are given below in (4.19), (4.20), (4.21) and (4.22) respectively. In Figure 4.3(a), the $G_{cl_b}(s)$ and $G_{cl_sc}(s)$ are the battery and SC closed loop gain respectively. Their values are assumed to be unity as the MPC controller is much faster compared to the voltage control loop.

$$G_{pi_v}(s) = k_{p_v} + \frac{k_{i_v}}{s}, \quad (4.19)$$

$$G_{lf}(s) = \frac{\omega_c}{s + \omega_c}, \quad (4.20)$$

$$G_{vi_sc}(s) = \frac{\hat{v}_{dc}}{\hat{i}_{sc}} = \frac{(1 - D_{sc})V_{dc} - L_{sc}I_{sc}s}{C_{dc}V_{dc}s + 2(1 - D_{sc})I_{sc}}, \quad (4.21)$$

$$G_{ol_vdc}(s) = G_{pi_v}(s) \left(G_{lf}(s)G_{cl_b}(s) + (1 - G_{lf}(s))G_{cl_sc}(s) \right) G_{vi_sc}. \quad (4.22)$$

The system architecture is shown in Chapter 3, Figure 3.4. The nominal system parameters for the controller design are given in Table 4.1. D_b and D_{sc} are the nominal duty cycle for the battery and SC converter control. The LPF cut-off frequency is 31.416 rad/s. The voltage loop PI compensator gains are designed such that the control loop has a phase margin of 60° at a cut-off frequency of 300 rad/s. The calculated proportional and integral gains for the voltage loop PI compensator are $k_{p_v} = 0.931$ and $k_{i_v} = 148$. The open loop Bode plots with and without the PI compensator in the voltage control loop are presented in the Figure 4.3(b) to study the system stability. The Bode plots show that the proposed control method is stable with sufficient gain and phase margin at a cut-off frequency of 300 rad/s. The design ensures the stability of the control system.

Table 4.1: Nominal converter parameters

v_b	L_b	C_{dc}	R_{dc}	V_{dc}	D_b	I_b
24 V	6.3 mH	2200 μ F	48 Ω	48 V	0.5	2 A
v_{sc}	L_{sc}	C_{dc}	R_{dc}	V_{dc}	D_{sc}	I_{sc}
30 V	6.3 mH	2200 μ F	48 Ω	48 V	0.375	1.6 A

Figure 4.4: Experimental setup

4.4 Experimental Results

The picture of experimental setup is presented in Figure 4.4. The Semikron SKM 75GB12T4 IGBTs are used as the power switches to built the 3 kW bi-directional DC-DC converter. SKYPER 32R IGBT gate drivers are used to control the IGBT switches. The LEM current transducer and voltage transducer are used to measure the current and the voltage in the experimental setup. The current from the regulated power supply is controlled to generate different PV current profiles during the experimental study. The two 12 V, 17 Ah lead-acid batteries are used as battery system. The two 15 V Maxwell BMOD0058 E015 B01 SCs are used to form a SC system. The proposed control method is implemented in real-time in the dSPACE 1103 controller platform. During the experimental study, the SOC limit of the battery and SC are kept within safe operating region as per the instructions given by manufacturer in their datasheets.

For the performance analysis of the EMPCC method, the transient behaviour during the step change in the load demand and generation are analysed. During the step increase and decrease in the load demand and generation, the overshoot percentage in the system (M_p) is calculated as (4.23) below,

$$M_p = \frac{|v_{ref} - v_{max}|}{v_{ref}} \times 100 = \frac{\Delta V}{v_{ref}} \times 100 \quad (4.23)$$

The time required (t_{ss}) by the controller to stabilize the system to its nominal condition

is also measured. The execution time (T_s) is the time required by the controller to provide an optimal solution. T_s value depends on the nature and complexity of the method used. If the control method is very complex, T_s should be large to implement on the dSPACE 1103 controller platform. M_p , t_{ss} and T_s of the EMPCC method are compared with those of the existing control methods. The nominal system parameters used during experiment are presented in Table 4.2.

Table 4.2: Nominal system parameters for experimental study

PV array parameters	Values
Open circuit voltage (v_{pvo})	30.2 V
Short circuit current (i_{pvo})	5 A
Lead-acid Battery specifications	Values
Terminal voltage (v_b)	12 V
Ampere-hour capacity	17 Ah
Number of batteries in series connection	2
BMOD0058 E015 B01 SC specifications	Values
Terminal voltage (v_{sc})	15 V
Internal capacitance (C_{sc})	58 F
Number of SCs in series connection	2
dSPACE 1103 controller parameters	Values
Execution time (T_s)	30 μs
EMPCC parameters	$N_c = 3, n_1 = 1, n_2 = 5, n_3 = 9$

4.4.1 Load Step Change

In the first case study, a step change in load is studied. Figure 4.5(a) shows the experimental results for a step increase in load demand. The load resistance R_{dc} is decreased from 50Ω to 25Ω which increases the load current (i_{dcl}) from $0.96 A$ to $1.92 A$. The current from PV (i_{pv}) is kept constant during the step change in the load demand. During this scenario, the SC handles the transient power and the battery system handles the average power demand. The calculated parameters are as follows: $\Delta V = 1.4 V$, $M_p = 2.9\%$ and $t_{ss} = 25 ms$ in this scenario.

The results for a step decrease in i_{dcl} are shown in Figure 4.5(b). In this scenario, R_{dc} is increased from 25Ω to 50Ω . The current from the PV (i_{pv}) is kept constant at $2 A$. The excess power due to a step decrease in i_{dcl} while the PV generation is constant is absorbed by HESS. The calculated parameters from the proposed method are as follows: $\Delta V = 1.3 V$, $M_p = 2.7\%$, $t_{ss} = 24 ms$ and $T_s = 30 \mu s$.

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Figure 4.5: (a) Step increase in load demand and (b) Step decrease in load demand. $v_{dc} \sim 500mV/div$, i_{pv} , i_b , $i_{sc} \sim 1A/div$, $i_{dcl} \sim 500mA/div$, time $\sim 50ms/div$.

4.4.2 PV Power Step Change

In this case study, a step change in i_{pv} is done. The DC link voltage overshoot (M_p), settling time (t_{ss}) and execution time (T_s) during the step change in PV power are analysed. In this scenario, the load is kept constant at $R_{dc} = 50\Omega$. The step change is applied to the stable steady state system by changing the current references for the PV converter control.

The experimental results for a step increase and step decrease in PV power are presented in Figure 4.6(a) and Figure 4.6(b). In both the cases, the high-frequency current component is handled by the SC and the average slow varying power demand is supplied by the battery system. This reduces the stress in the battery system. The ΔV values for a step increase and step decrease in PV power are $1.3V$ and $1.4V$ respectively. The calculated M_p values for a step increase and decrease in PV power are 2.7% and 2.9% respectively. The t_{ss} values for a step increase and decrease in PV generation are $20ms$ and $22ms$ respectively. This shows the i_{pv} variations are effectively handled by the

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Figure 4.6: (a) Step increase in PV generation and (b) Step decrease in PV generation. $v_{dc} \sim 500 \text{ mV/div}$, i_{pv} , i_b , $i_{sc} \sim 1 \text{ A/div}$, $i_{dcl} \sim 500 \text{ mA/div}$, $\text{time} \sim 50 \text{ ms/div}$.

proposed control method. The execution time $T_s = 30 \mu\text{s}$ is used for this case study.

4.4.3 Random PV Power and Load Fluctuations

In the third case study, a realistic PV pattern is generated and the load change is also applied to the system. The PV irradiation data were obtained from the irradiation data recorded every one min from 10:00-15:30 hr in Singapore on April 10th, 2011. The PV current pattern is obtained by changing the current reference for the PV current controller. The load changes are also applied at $\text{time} = 8 \text{ s}$ by changing the R_{dc} from 50Ω to 25Ω and at $\text{time} = 10.3 \text{ s}$ by changing R_{dc} from 25Ω to 50Ω . This makes the case study similar to the practical application where the generation and load are varied simultaneously.

The experimental results for random PV generation and load fluctuations are given in Figure 4.7. It is observed that the proposed controller is effective in handling the DC link voltage at its reference value during random PV generation and load fluctuations.

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Figure 4.7: Random PV generation and load fluctuations. $v_{dc} \sim 10 \text{ V/div}$, i_{pv} , i_b , i_{sc} , $i_{dcl} \sim 1 \text{ A/div}$, $time \sim 5 \text{ s/div}$.

The SC system balances the transient current demand and the battery system balances the average current demand in the system. During the step load change at $time = 8 \text{ s}$ and $time = 10.3 \text{ s}$, the transient current is supplied by SC and the battery current slowly rises as shown in the experimental results of Figure 4.7. This reduces the stress in the battery system and allows the battery to have a smooth transition. The controller maintains v_{dc} at v_{ref} during the entire period of operation. The zoomed view of Figure 4.7 at time 8s is presented in Figure 4.8. It shows the battery and SC response during the PV and DC load variation. The v_{dc} is restored to v_{ref} in less than 50 ms during the random PV and load variation.

4.4.4 Performance Evaluation

The transient response of the EMPCC method and the counterpart in [132] for a step change in load and PV generation is tabulated in Table 4.3. The overshoot percentage in the DC link voltage (M_p), settling time (t_{ss}) and execution time (T_s) values during

Figure 4.8: Zoomed view of Figure 4.7 at time 8 s. $time \sim 300 ms/div$.

Table 4.3: Performance of the proposed control method

Conditions	Performance Parameters	[58]	[132]	Proposed
Load Change	M_p	-	5.3%	$\sim 2.8\%$
	t_{ss}	-	0.25 s	$\sim 25 ms$
	T_s	0.01 s	75 μs	30 μs
PV Change	M_p	-	5.3%	$\sim 2.8\%$
	t_{ss}	-	0.25 s	$\sim 22 ms$
	T_s	0.01 s	75 μs	30 μs

the step change in load and generation are evaluated. The average M_p for the conventional control method during load change and PV change is around 5.3%. The average M_p for the proposed method is around 2.8%. The settling time for the conventional control method is around 0.25 s while that of the proposed control method is around 25 ms. The execution time (T_s) for the conventional method is around 75 μs and for the EMPCC method is around 30 μs . Thus, The EMPCC method shows a better transient performance compared to the pure PI-based method [132] for controlling the HESS.

The proposed control method is also compared with the conventional MPC method [58]. The execution time (T_s) for conventional MPC method is around 0.01 s. The execution time depends on the complexity of the control method. This includes a system model, a prediction approach and the optimization technique. Thus, the T_s value for the proposed control method is around 30 μs as it uses a simple converter model, MBT for prediction and enumeration technique for optimization. This shows that the EMPCC method results in faster dynamic response with less computational resources.

4.5 Summary

The implementation of EMPCC for the HESS in DC microgrid applications has been presented in this Chapter. The state-space model of the DC-DC converter for the EMPCC method has been presented. The EMPCC method for the battery converter has been designed and discussed in detail. The MBT technique for the prediction of the control sequences in the future has been discussed. The enumeration based optimization technique has been examined. The EMPCC algorithm for the implementation in the dSAPCE 1103 real-time controller has been presented. The stability analysis and control design of the EMPCC method has been explored. Moreover, the features of the EMPCC method over the conventional MPC and PI-based control method have been compared with experimental results.

Experimental test cases such as (i) load step change, (ii) PV power step change and (iii) random PV power and load fluctuations have been illustrated to evaluate the EMPCC method performance. The results validate that the EMPCC method can provide a better dynamic performance to load change and generation variation compared to other control methods. The proposed method uses a simple converter model, the MBT prediction technique and enumeration based optimization technique to obtain the optimal control parameters. Thus, the T_s of the EMPCC method is less compared to that of existing control methods. In the proposed method, the functionality of the MPC method can be used with less controller complexity and computational burden in the controller platform.

Chapter 5

Dynamic Evolution Control Method for HESS

5.1 Introduction

There is always a need for the good controller design to perform a better system response under a high fluctuating RES generation and load demand. The proportional-integral-derivative (PID) controller design methods are the most applied in the field of power electronics converter control. These methods use a simple linear controller to regulate the states of the system. The main disadvantage of the PID-based control methods is their performance degrades as it moves away from its designed operating point. As the power electronics converters exhibits a non-linear behaviour, the controller should provide a stable operation even in the non-linear region. The DEC method addresses the above issues as it includes the time-varying and non-linearity of the system during controller design. Thus, the DEC method provides a better dynamic performance even under high power fluctuations and changes in the operating point.

There are few implementations of DEC in power electronics converter control. In [133], the DEC method has been implemented in EV system powered by SC and fuel cell. The SC is used as an auxillary power source in the EV system. The power output from the SC is controlled by the DEC method during start-up and transient condition to improve the dynamics of the HESS. It shows a better dynamic performance than

the traditional PI control methods. In [134], the DEC method has been used for a synchronous DC-DC buck converter control. The detail theoretical analysis, controller design and implementation are also presented in the paper. In [135], the DEC has been applied for boost power factor correction converter control. The DEC method improves the dynamic performance of the overall system. The experimental results demonstrate the reduction in THD under heavy and light load operation of the system.

In this chapter, the DEC method is studied for the HESS in the DC grid applications. The new power sharing method is also proposed for the HESS. The new power sharing method calculates the power reference for the battery and SC in the system. The DEC method regulates the power from the HESS based on the calculated power reference and maintains the constant DC link voltage. The DEC design includes following steps: (i) evolution path selection, (ii) dynamic evolution function formulation, (iii) analysis of the power electronics converter dynamics, (iv) formulation of the duty cycle equation for power electronics converter control and (v) PWM generation. The DEC method uses a converter dynamic equation to formulate the duty cycle equation for converter control which makes it simple to design. Moreover, the duty cycle equation contains the predictive term and feed-forward term which calculate the duty cycle for a converter in each time step. This results in better dynamic performance with less computational time.

5.1.1 DEC Evolution Path

In the closed loop control system, the controller tries to reduce the difference between the system output and its reference value in all conditions. The variation of the system output to its reference value is denoted as an error state. The error state should be reduced to zero in all circumstances irrespective of the disturbance present in the system. The evolution path is the trajectory in which the system follows to make the error state to zero. The suitable evolution path can be determined based on the system dynamic response and error trajectory. The dynamic response exhibited by the second-order controlled system to a step reference change is presented in Figure 5.1(a). The corresponding error state trajectory is presented in Figure 5.1(b). The step change

produces overshoot and oscillations in the second order system as presented in Figure 5.1(a). However, it is observed that the error state magnitude slowly reaches to zero with the increase of time as shown in Figure 5.1(b). The error trajectory has an initial error state with a positive value and its magnitude eventually decreases to zero. The error state magnitude can be guided to zero with a defined ideal error trajectory controlling the output response as presented in Figure 5.1(b). From these observations, the suitable evolution paths are defined for the DEC design.

Figure 5.1: (a) Step response of a controlled second order system, (b) Error trajectory of second order system, (c) Representation of the linear evolution path and (d) Representation of the exponential evolution path.

There are two commonly used evolution paths in the DEC design. They are linear and exponential evolution path. The graphical representation of the linear and exponential evolution path are presented here in Figure 5.1(c) and Figure 5.1(d) respectively. The equations that define the linear evolution trajectory are given in (5.1).

$$\begin{aligned} Y_0 &= 0, \\ Y_1 &= c - mt, \\ Y_2 &= c + mt, \end{aligned} \tag{5.1}$$

where Y_1 is the evolution path if the initial error state value is positive. Y_2 is the

evolution path if the initial error state value is negative. c and m represents the initial error state value and the slope of the evolution path which determines the speed at which the error state moves to zero. The linear evolution path guides the error state value to zero using a linear path. The rate at which the error state moves to zero is defined by a magnitude of the slope of the evolution path. The high value of m of the evolution path will result in faster controller response to minimize the disturbance in the system.

The equation for the exponential evolution path is given below in (5.2).

$$Y = ce^{-mt}, \quad (5.2)$$

where Y represents the exponential evolution path. The convergence of error state to zero depends on the magnitude of m . The magnitude of the m is chosen to obtained a desired system response. In the exponential evolution path, the same equation in (5.2), can be used for both the negative and positive initial error state.

5.2 Controller Design

The representation of the conventional control method used for HESS control is presented in Figure 5.2(a). The operation of the conventional control method [56, 65, 132] is discussed in Section 3.4. The conventional control method uses a dual loop control strategy to handle the system states. In these methods, the controller bandwidth of different PI based control loops must be carefully selected to avoid the controller conflict problem in the system. Moreover, these controllers are designed to operate at certain operating points and their performance degrades if the operating points are changed.

The DEC method addresses the aforementioned issues. The block diagram representation of the DEC method is presented in Figure 5.2(b). In the proposed control method, a simple power balance equation is applied which generates the total power reference (P_{tot}) for HESS. The total power reference is then separated into the average power reference (P_{avg}) and transient power reference (P_{tran}) using a LPF as presented in Figure 5.2(b). The current reference for the battery converter control is obtained after division

5.2.1 Reference Current Generation

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Table 5.1: Nominal DC-DC converter parameters

Symbols	v_{pv}	v_b	v_{sc}	R_{dc}	C_{dc}	f_{sw}
Values	32 V	24 V	30 V	48 Ω	2200 μ F	10 kHz
Symbols	D_{pv}	D_b	D_{sc}	L_{pv}	L_b	L_{sc}
Values	0.34	0.5	0.375	3.6 mH	5 mH	5.7 mH

than the PV generation and vice versa. Hence, the DC link power balance equation is given as follows in (5.3),

$$P_{tot} = P_{dcl} - P_{pv}, \quad (5.3)$$

where P_{tot} , P_{dcl} and P_{pv} are the HESS power, DC link load power and PV generation power respectively. The DC link voltage tends to fluctuate depending upon the system condition. To respond to a change in the DC link voltage, a voltage balance condition is calculated as follows,

$$v'_{dc} = \begin{cases} v_{ref}, & \text{if } (v_{dc} < v_{ref}) \\ v_{dc}, & \text{otherwise} \end{cases} \quad (5.4)$$

From (5.3) and (5.4), the P_{tot} for the proposed control method is calculated and is given in (5.5).

$$P_{tot} = \frac{i_{dcl} v'_{dc}}{v_{dc}} v'_{dc} - i_{pv} v_{pv} \quad (5.5)$$

As presented in Figure 5.2(b), the LPF generates the p_{avg} and p_{tran} to be supplied/absorbed by the HESS. The $H_{lpf}()$ represents the function of first-order LPF. The LPF cut-off frequency is $2\pi 5$ rad/s. p_{avg} is supplied by the battery system and the p_{tran} is supplied by the SC system. Thus, the p_{avg} is divided by the v_b to generate a current reference for the battery current controller as shown in (5.6). In similar way, the p_{tran} is divided by the SC terminal voltage to calculate a current reference for the SC current controller as shown in (5.7).

$$i_{bref}(t) = \frac{H_{lpf.}(P_{tot})}{v_b}, \quad (5.6)$$

$$i_{scref}(t) = \frac{1 - H_{lpf.}(P_{tot})}{v_{sc}} + \frac{v_b}{v_{sc}} \Delta i_b + \beta v_e, \quad (5.7)$$

$$\Delta i_b = i_{bref} - i_b, \quad (5.8)$$

$$v_e = v'_{dc} - v_{dc}, \quad (5.9)$$

where i_{bref} and i_{scref} represent the battery and SC current references. $H_{lpf.}(P_{tot})$ represents the output power from LPF. Here, β is the compensation factor for the DC link variation. The value for β is 5. The battery error current is also diverted to the SC system to avoid the large voltage sag or swell due to slow dynamics of the battery system. This ensures a faster DC link voltage regulation in spite of the slow battery dynamics. Thus, the SC current reference contains transient current, DC link voltage error and battery current error term.

5.2.2 SC Controller Design

The SC current control plays a significant part for acquiring a faster DC link voltage restoration. The dynamics of the SC current control also affect the stress level on the battery system. Figure 5.3 (a) shows the switching model of the SC system required for SC controller design. The switching signals q_{sc} and q'_{sc} for the SC converter are complementary to each other. So it is reasonable to consider the boost mode of operation for a controller design. Assuming that the SC connected converter operates in CCM, the voltage and current dynamics during the boost mode of operation are presented in (5.10) and (5.11).

Figure 5.3: (a) Switching model of the SC system and (b) Switching model of the battery system

$$v_{sc} = L_{sc} \frac{di_{sc}(t)}{dt} + v_{dc} (1 - \delta_{sc}(t)). \quad (5.10)$$

$$\frac{di_{sc}(t)}{dt} = \frac{v_{sc}}{L_{sc}}\delta_{sc}(t) - \frac{(v_{dc} - v_{sc})}{L_{sc}}(1 - \delta_{sc}(t)). \quad (5.11)$$

The current reference for SC consists of the transient current reference, uncompensated power from the battery and the voltage error term. The DEC for SC regulates the SC current and DC link voltage together. The main advantage of the DEC is it controls the system dynamic characteristics to operate on the target equation [134]. The basic concept of the DEC method is to lead a state error to zero using a specific evolution path. Thus, an exponential evolution path is chosen as shown in Figure 5.4 and the corresponding equation is given as

Figure 5.4: Dynamic evolution path for a voltage error control

$$v_e^*(t) = v_{eo} \cdot e^{-mt}, \quad (5.12)$$

where v_e^* and v_{eo} represents the dynamic characteristic of the system. m is the rate at which the system responds to minimize the voltage error and v_{eo} is the initial value of the voltage error. Thus, the dynamic evolution function of the proposed evolution path is given as follows,

$$\frac{dv_e^*(t)}{dt} + m v_e^*(t) = 0, \quad m > 0. \quad (5.13)$$

In order to ensure the voltage error term moves to zero with the proposed evolution path, the synthesis process is conducted. In the power electronic application, the state error function is need to be defined to derive a control equation. The function can be either of error current or error voltage. The linear function of the error voltage is selected for

our application and is given as follow,

$$v_e^*(t) = kv_e(t), \quad k > 0 \quad (5.14)$$

where k is the positive coefficient. Combining (5.14) and (5.13), the dynamic evolution function can be obtained as follows,

$$k \frac{dv_e(t)}{dt} + mkv_e(t) = 0, \quad (5.15)$$

Subtracting $v_e(t)$ to both sides in (5.15) the relation between the v_{dc} and error function is obtained. The corresponding equation is given in (5.16).

$$k \frac{dv_e(t)}{dt} + (mk - 1)v_e(t) + v'_{dc} = v_{dc}. \quad (5.16)$$

By combining (5.10) and (5.16), a relationship between the SC voltage, SC current, voltage error term and duty cycle to control the SC converter is obtained. The corresponding equation is presented below,

$$v_{sc} = L_{sc} \frac{di_{sc}(t)}{dt} + k \frac{dv_e(t)}{dt} + (mk - 1)v_e(t) + v'_{dc} - v_{dc}\delta_{sc}(t). \quad (5.17)$$

Rearranging (5.17) the expression for the duty cycle is obtained for the control of the SC system. The expression for δ_{sc} is given below,

$$\delta_{sc}(t) = \frac{v'_{dc} - v_{sc}}{v_{dc}} + \frac{(m.k - 1)}{v_{dc}} v_e(t) + \frac{k}{v_{dc}} \frac{dv_e(t)}{dt} + \frac{L_{sc}}{v_{dc}} \frac{di_{sc}(t)}{dt}. \quad (5.18)$$

The duty cycle equation in (5.18) forces the linear function of error voltage to satisfy the exponential evolution path given in (5.12). The duty cycle equation expressed in (5.18) consists of four parts. The effect of SC voltage variation in the DC link voltage is compensated by the first part. The remaining three are the proportional and derivative terms, and their coefficients value changes with the DC link voltage. Thus, this results in a faster control action to DC link voltage variation. The duty cycle equation for SC shows that it compensates the input voltage variation, DC link voltage variation and the inductor current variation in the system. In the proposed control method, PI compensator are not used which further simplifies the its design.

5.2.3 Battery Controller Design

The switching model of the battery system is presented in Figure 5.3 (b). The duty cycle equation for the battery system is derived based on its CCM of operation [66]. The CCM equations for the buck and boost mode operation of the battery system are given below in (5.19) and (5.20),

$$\frac{di_b(t)}{dt} = \frac{(v_{dc} - v_b)}{L_b} \delta_b(t) - \frac{v_{dc}}{L_b} (1 - \delta_b(t)), \quad (5.19)$$

$$\frac{di_b(t)}{dt} = \frac{v_b}{L_b} \delta_b(t) - \frac{(v_{dc} - v_b)}{L_b} (1 - \delta_b(t)). \quad (5.20)$$

Equations (5.19) and (5.20) show the dynamics of the inductor current of the battery system. In the unified controller, the switches q_b and q'_b of the battery system are operated in complementary fashion. So the buck and boost mode operation of the battery system shares the similar transfer function. Therefore, it is sufficient to analyse the boost mode operation to design a controller for the battery converter [130]. The duty cycle equation for the battery connected bi-directional DC-DC converter control is obtained by simplifying (5.20) and is given as follows,

$$\delta_b(t) = \frac{v_{dc} - v_b}{v_{dc}} + \frac{L_b}{v_{dc}} \frac{di_b(t)}{dt}. \quad (5.21)$$

The duty cycle equation in (5.21) consists of two terms. The v_{dc} regulation with respect to the v_b change is handled by first term. The second term is the predictive term which regulates the battery current reference. The coefficient of the second term depends on v_{dc} and it changes in each time-step. This results in a faster dynamic response to changes in the v_{dc} . The main improvement with this method is that the battery current is regulated without any PI controller so it is easy to design and implement.

5.3 DEC Controller Parameters Selection

The block diagram representation of the implementation of DEC method in Matlab/Simulink is presented in Figure 5.5. In the DEC method, the controller gains k and m are tuned such that the faster transient response is achieved in the system. The transient response

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Figure 5.5: Block diagram representation of DEC method for HESS in Matlab/Simulink.

Figure 5.6: Simulation result for a step change in voltage reference from 48V to 60V with different m values. (a) controller response to a step change in voltage reference, (b) error voltage response to a step change in voltage reference. $R_{dc} = 48\Omega$, $i_{pv} = 2A$, $\beta = 2e^{-4}$, $k = 0.0315$, $m_1 = 2e^4$, $m_2 = 5e^4$, $m_3 = 1e^5$, $m_4 = 2e^5$ and $m_5 = 2.85e^5$.

of the system depends mostly on the m value. The controller responses faster with the increased m value. However, the high overshoot in the system is observed when the m value is increased above certain limits. In general, the best m value is the maximum value before the overshoot appears in the system [133–135]. The similar procedure is applied to calculate the controller gains for the HESS. The step change in voltage reference is applied to different m values and the responses are observed. The m value which

Table 5.2: System parameters for simulation and experimental study

PV array parameters	Values
Open circuit voltage (v_{pvo})	30.2 V
Short circuit current (I_{pvo})	5 A
Mppt voltage (V_{mppt})	29V
Mppt current (I_{mppt})	4.8 A
Mppt power (P_{mppt})	140 W
Lead-acid Battery specifications	Values
Ah capacity	17 Ah
Terminal Voltage (v_b)	12 V
Number of batteries in series	2
SC specifications	Values
Terminal voltage (v_{sc})	30V
Internal capacitance (C_{sc})	29F
Switching frequency (f_{sw})	10 kHz
m, k	31.74, 0.0315

satisfies the system requirement before the overshoot occurs in the system is selected. The step response of the voltage controller and the voltage error with different m values are shown in Figure 5.6(a) and Figure 5.6(b). The simulation results show that the increase in m value improves the performance of the overall system. In the simulation study, the m values are $m_1 < m_2 < m_3 < m_4 < m_5$. Thus, the controller response is better with the m_5 value and the error voltage converges faster.

In our proposed method, the SC current reference also contains the voltage error compensation factor β . Thus, the β and m values are tuned to get the desired transient response in the system. These parameters minimize the voltage error in the system. In the proposed control method, only two parameters are required to obtain the desired system response compared to six parameters to be tuned in PI based control methods [56, 132]. Thus, the proposed method is simple to design and also provides better dynamic performance.

5.4 Simulation Results

The simulation studies are done to validate the performance of the proposed control method. The nominal simulation parameters are given in Table 5.2. The SOC limits of the battery and SC are kept under the safe operating region in the simulation studies.

The execution time (T_s) is chosen to be 30 us and the communication delay time (T_{cd}) is chosen to be 1 us .

5.4.1 Performance under Step Change in Load Demand and Generation

In the first case study, a step change in the load and PV generation are done to observe the short-term power management capability of the proposed control method. The simulation results are presented in Figure 5.7. From time 0 s to 1 s , the PV generation is kept constant at 60 W and the load demand at 48 W . In this condition, the load demand is lower than the PV generation. The excess power in the system is handled by the battery system for steady-state operation.

Figure 5.7: Results for the proposed control method in a step change in the PV generation and load disturbances. (a) v_{dc} (b) i_{sc} and i_b and (c) PV power (P_{pv}), DC link load power (P_{dc}), SC power (P_{sc}) and battery power (P_b).

At time 1 s , the load resistance is decreased from $R_{dc} = 48\text{ }\Omega$ to $R_{dc} = 24\text{ }\Omega$. The step change in a DC load resistance creates a power deficit situation in the DC link. The variation in the load demand is handled by the HESS to make the system stable. The SC responds to a fast-changing variation and the battery current slowly rises to make the system stable as presented in Figure 5.7(b). v_{dc} is stable during this condition with

an overshoot less than 1% as shown in Figure 5.7(a).

Similarly, at time 2s, a step decrease in load is done by increasing the R_{dc} from $24\ \Omega$ to $48\ \Omega$. In this condition, the system performance is stable with SC taking the transient power demand and the battery taking the average power demand. The overshoot in the DC link is less than 1% in this case as well.

At time 3s, the load power is kept constant at 48W and a step change in a PV generation is made by increasing the PV output from 60W to 120W. In this situation, P_b is lower than the P_{pv} and the excess power is stored in the HESS. The PV generation, DC link, SC and battery powers in the system are shown in Figure 5.7(c).

From time 1s to 2s the system operates at deficit power condition as the load demand increases. From time 3s to 4s the system operate at excess power condition with a step increase in the PV generation at 3s. The HESS power moves from discharging to charging and vice-versa to complement the various operating scenarios. Thus, the v_{dc} is well maintained during a step change in the load demand and generation.

5.4.2 Performance under Long-Term Generation Variation

The evaluation of the proposed control method for the long-term power variation scenarios are presented in Figure 5.8. The PV irradiation data were recorded every one minute on April 10th, 2011 in Singapore from 10:00 to 16:30 hr as shown in Figure 5.8(a). The study shows the effectiveness of the proposed control method to deal with the real PV power variations. The PV irradiation data is scaled down to suit for our application. During the long-term PV generation variation scenarios, the SOC limits of the battery and SC are kept under the safe operating region.

The PV generation power is varied as shown in Figure 5.8(d) for 60s to observe the performance of the DEC method. The p_{pv} is varied as presented in Figure 5.8(d). The step change in the load demand is also done at time t_1 and t_2 along with the PV power variation to study the practical scenario where the load and generation are varied simultaneously. i_{sc} and i_b current profiles which meet the long-term power variation are shown in Figure 5.8(c). The high-frequency power demand is diverted to the SC system while the average power demand is handled by the battery system. As given in

Figure 5.8: Performance of proposed control method under a long-term PV generation variation. (a) PV irradiance pattern, (b) v_{dc} (c) i_{sc} and i_b and (d) P_{pv} , P_{dc} , P_{sc} and P_b .

Figure 5.8(b), the DC link voltage is well maintained at 48 V during random generation power variation. The voltage deviation is less than 1% during study. This shows that the proposed control method is stable and effective in maintaining the v_{dc} at a constant value with an effective power sharing between energy storage devices.

5.5 Experimental Results

The same experimental setup explained in Chapter IV, in Section 4.4 is used to implement the DEC method. The DEC method is implemented using the dSPACE 1103 real-time controller platform. The SOC limit of the HESS is kept under the safe operating region during the experiment as per the instructions given in manufacturer datasheets.

Figure 5.9: (a) Performance of conventional control method under a step change in the load demand and (b) Performance of proposed control method under a step change in the load demand. $v_{dc} \sim 20 \text{ V/div}$, i_{pv} , i_b , i_{sc} , $i_{dcl} \sim 2 \text{ A/div}$, $time \sim 1 \text{ s/div}$.

The simulation parameters and experimental parameters are similar as tabulated in Table 5.2. The DEC method is compared with the conventional control method presented in [132] in the following experimental test cases. The effectiveness of the DEC method over the conventional control method is analysed based on the voltage overshoot (M_p) and settling time (t_{ss}) in the system during the load regulation and generation variation.

5.5.1 Load Regulation

Figure 5.9 shows the results for the load regulation. The performance of conventional control method is given in Figure 5.9 (a). The performance of the DEC method is presented in Figure 5.9 (b). In this study, i_{pv} is kept constant at 4 A. At time t_1 , the R_{dc} is decreased from 48Ω to 24Ω , and i_{dcl} is increased from 0.96 A to 1.96 A correspondingly. The 100% load increment is done to observe the performance of the proposed control method. In this condition, the power variation due to the change in i_{dcl}

Figure 5.10: (a) Performance of conventional control method under a step change in the PV generation and (b) Performance of proposed control method under a step change in the PV generation. $v_{dc} \sim 20 \text{ V/div}$, i_{pv} , i_b , i_{sc} , $i_{dcl} \sim 2 \text{ A/div}$, $time \sim 1 \text{ s/div}$.

is handled by HESS. i_{sc} supplies the transient current demand and i_b slowly increases from -2.2 A to -0.4 A . From the experimental results, it can be examined that the deviation in (Δv_{dc}) is 2.5 V in the conventional control method with settling time (t_{ss}) of 0.3 s . With the DEC method, the Δv_{dc} is less than 0.5 V and the settling time (t_{ss}) is less than 0.02 s . The results show that the proposed control method responds fast and provides a good dynamic response compared to that of the conventional control method.

5.5.2 PV Generation Variation Regulation

Figure 5.10 shows the results for the PV generation regulation. The results of the conventional control method and the proposed control method are presented in Figure 5.10(a) and Figure 5.10(b) respectively. During the experiment, the DC load resistance R_{dc} is kept constant at 48Ω . The PV generation is changed from 4 A to 2 A as given in Figure 5.10. The variation in i_{pv} is handled by HESS to maintain the system stability.

Figure 5.11: Performance of proposed control method under a random PV generation variation. $v_{dc} \sim 20 \text{ V/div}$, i_{pv} , i_b , i_{sc} , $i_{dcl} \sim 2 \text{ A/div}$, $time \sim 1 \text{ s/div}$.

i_{sc} supplies the transient current demand and i_b slowly increases from -2.2 A to -0.25 A to compensate the average power fluctuations.

The experimental results show that with the conventional control method the calculated M_p is about 5.3% and t_{ss} is 0.35 s. With the implementation of the DEC method, a better v_{dc} regulation is achieved. M_p with proposed control is less than 1.1% and t_{ss} is less than 0.02 s. The results show a better performance with the DEC method compared to that of the conventional control method.

The experimental study of the random variation in the PV generation is also done. i_{pv} is varied as shown in Figure 5.11 by changing the current reference for the PV converter control. Figure 5.11 shows that v_{dc} is well maintained in all conditions with M_p less than 1.1% and t_{ss} less than 0.02 s. During the random PV generation variation, p_{avg} is supplied by the battery and p_{tran} is handled by the SC system. The results obtained show that the DEC method is able to handle the sharp changing random PV generations effectively.

5.5.3 Response to Change in Voltage Reference

The results for the change in the v_{ref} are presented in Figure 5.12. The v_{ref} is step changed from 48 V to 60 V. In this condition, the R_{dc} is kept constant at 48Ω. The PV generation is kept constant at 4 A. The smooth transition in the output voltage is observed. The required power to maintain the system stability is supplied by the HESS. i_b slowly increases from -2.2 A to -1.8 A to compensate the average power fluctuations.

Figure 5.12: Performance of proposed control method under a step change in voltage reference. $v_{dc} \sim 20 V/div$, i_{pv} , i_b , i_{sc} , $i_{dcl} \sim 2 A/div$, $time \sim 1 s/div$.

i_{sc} supports the transient current demand. i_{dcl} increases from $0.96 A$ to $1.25 A$ with the increase in the v_{dc} . The results show that the DEC method effectively handles the step v_{ref} change.

5.5.4 Performance Evaluation

The performance comparisons between the DEC method and conventional control method are summarised in Table 5.3. The voltage overshoot (M_p) and settling time (t_{ss}) during the step change in the load demand and generation are studied based on the experimental results presented in Figure 5.10 and Figure 5.11. During a step change in the i_{dcl} the average M_p is 1.04% and t_{ss} is around $0.02 s$ for the DEC method. With the same test case, an average M_p and t_{ss} is around 5.3% and $0.3 s$ for the conventional control method. For a step change in PV power, M_p with the proposed method is 1.10% with T_{ss} of $0.02 s$. In the same test case, M_p with the conventional control method is around 5.3% with T_{ss} of $0.35 s$. The experimental results thus show that the DEC method provides faster v_{dc} restoration with a lesser v_{dc} variation.

5.6 Summary

The new DEC method for a PV system with the HESS in the DC microgrid applications has been presented in this Chapter. In the DEC method, an evolution path is applied to reduce the error state in the system. The duty cycle equations in the DEC method

Table 5.3: Performance comparisons of the proposed control method with the conventional method

Conditions	Performance Parameters	Conventional [132]	Proposed
Load Change	M_p	5.3%	1.04%
	t_{ss}	0.3 s	0.02 s
	T_s	75 μs	20 μs
PV Change	M_p	5.3%	1.10%
	t_{ss}	0.35 s	0.02 s
	T_s	75 μs	20 μs

consist of the predictive term and feed-forward term. These terms control the DC link voltage, battery current and SC current. The DEC method is more robust and simple to design compared to that of the existing control methods and provides faster DC link voltage restoration. The simulation and experimental results for a step change in the load and PV generation have been presented. Finally, the performance of the DEC method has been compared with the conventional control method in terms of M_p and t_{ss} based on the experimental results. The results obtained show a better dynamic response with the proposed control method. In the DEC method, the battery error voltage and the DC link error voltage are compensated by the SC system. This results in lesser ripple contents in the DC link voltage and battery current. The DEC method also provides constant switching frequency for power electronics converter. This reduces the complexity to design the power filter in the system.

Chapter 6

EMS and Control for grid-connected HESS

6.1 Introduction

The EMS and control are of prime importance for HESS when operated in islanded mode or grid-connected mode. The RESs power, HESS power, grid power and load demand should be managed properly in grid-connected mode for its effective operation. The EMS and control for the grid-connected HESS can be evaluated into two parts, (i) the primary level control and (ii) secondary level control. The primary level control consists of instantaneous control methods which regulate the current references generated from the secondary level control. The primary level control is responsible for a short-term power regulation. The dynamic response of the system depends on how fast the primary level control responds to the disturbances in the system. However, the long-term operation depends on the current reference calculated by the secondary level control methods. The secondary level control takes the various system parameters like SOC of the HESS, DC link voltage, system capacity etc., to determine the optimal current references for each unit in the grid-connected HESS. The secondary level control is important for the optimal execution of the system for a long-term power regulation. Our study is mainly focused on two parts (i) development of faster primary level control, which regulates the DC link voltage properly and effectively and (ii) development of secondary level control

for effective participation of the SC and the grid to reduce stress in the battery system.

Several works have been done for the EMS and control of the grid-connected HESS [132, 136–138] and few of them are discussed here. A unified EMS for the grid-connected HESS has been presented in [132]. The unified EMS operates in three different operating modes depending upon the RES power and load power. The proposed method is effective in maintaining the SOC limits of the battery and SC to their predefined values. However, the power-sharing between the grid and the battery during different operating conditions is based on the battery SOC, which results a discrete power-sharing. This approach creates a sharp increase in the battery charge/discharge current during the mode transition which can reduce the battery operating lifetime. In [136], a supervisory EMS for hybrid microgrid application has been presented. The key feature of the supervisory EMS is reduction of the sensors required to implement EMS compared to the conventional approach [132]. It also considers the electricity pricing to determine the optimal current references for the HESS and grid. In the proposed method, the power between the grid and battery is shared following a discrete sharing function. This approach creates a sharp rise and fall of the battery current which affects the lifetime of the battery system. In [137], the grid-adaptive EMS is proposed for islanded and grid-connected operation of HESS. The proposed EMS generates the optimal current references for the HESS. The optimal current references depend on the DC link voltage and frequency of the AC grid. The proposed method also uses the discrete power sharing approach to divide the active power between the battery and grid. In [138], a unified EMS and control for the PV-battery hybrid microgrid for the grid-connected and islanding operation has been presented. In the proposed method, the battery balances the DC microgrid and AC microgrid power in all conditions. This increases the stress in the battery system. It will increase the system cost to meet the peak load demand and also affects the battery cycle life. In [19], a review of the various control methods and EMS for various hybrid AC/DC microgrid configurations has been presented. Various AC/DC microgrid configurations, their practical applications and EMS are also discussed in [139–141].

The new control strategies are studied for the DC microgrid applications with the HESS in the previous Chapters. In this chapter, the grid-connected operations of the HESS

are presented.

6.1.1 Features of Proposed EMS and Control

In this study, the new EMS and control is proposed for the HESS in grid-connected mode of operation. The proposed EMS and control method solves the issue related to the sharp rise and fall of the battery current when the sharing co-efficient between the grid and battery is calculated based on the discrete power-sharing function. The features of the proposed EMS and control method are: (i) faster DC link voltage restoration, (ii) operation of the battery and SC within their SOC limits, (iii) introduction of a new sharing coefficient for effective power-sharing with the battery and the grid which reduces the rate of charge/discharge of the battery during long-term operation and (iv) seamless mode transitions. The design of the proposed EMS and control method are elaborated in following sections.

6.1.2 Architecture of HESS in Grid-connected Operation

The overall system architecture for grid-connected HESS with a PV system is presented in Figure 6.1. It consists of an emulated PV source, HESS and the utility grid. The

Figure 6.1: Architecture for the grid-connected operation of HESS with PV system.

PV system is connected to the DC grid using a boost converter. The bi-directional

DC-DC converters are used to connect the battery and SC to the DC microgrid. The DC microgrid is connected to the AC grid with the VSC which acts as a rectifier or an inverter depending upon the current reference. In Figure 6.1, v_g is the AC grid terminal voltage. L_f and L_s are converter filter inductors for the VSC and grid. C_{dc1} and C_{dc2} are the DC link filter capacitors connected in series. c_{pv} , c_s , c_b are the output filter capacitances of the PV, SC and battery connected DC-DC converter. C_f is the VSC filter capacitor. R_{lc} and R_{nl} are the linear load resistance and non-linear load resistance in the AC grid. L_{lc} and L_{nl} are the linear load inductor and non-linear load inductor respectively. R_f , R_s and R_d represent the internal resistors of the filter inductors. S_a , S'_a , S_b and S'_b are the representation of the control switches used for VSC. i_{vsc} , i_g and i_{nl} represent the inverter, grid and non-linear load current respectively. The other parameters in Figure 6.1 are similar to those explained in Chapter 3, Section 3.3.

6.2 EMS and Control Method

6.2.1 Reference Current Generation

The effective operation of the grid-connected HESS depends on the power sharing among the various RESs and ESSs. The overall power balance should be maintained in the DC microgrid to make the system stable. The control method should support the load in all operating conditions. Thus, the overall power balance equation is as follows,

$$P_l(t) - P_{ren}(t) = P_b(t) + P_{sc}(t) + P_g(t) = P_{avg}(t) + P_{tran}(t), \quad (6.1)$$

where $P_l(t)$, $P_{ren}(t)$, $P_b(t)$, $P_{sc}(t)$ and $P_g(t)$ are the load, RES, battery, SC and grid power respectively. $P_{avg}(t)$ and $P_{tran}(t)$ represent the total average power and transient power demand to be supplied/absorbed from the HESS and the grid. v_{dc} is the reflection of the power balance among various sources and sinks [137]. Thus, the total current $i_{tot}(t)$ to be handled by the HESS and grid is obtained from the voltage control loop. The corresponding equation is given in (6.2),

$$i_{tot}(t) = k_{p-v} (v_{ref} - v_{dc}) + k_{i-v} \int (v_{ref} - v_{dc}) dt, \quad (6.2)$$

where k_{p_v} and k_{i_v} are the PI compensator gains for the voltage control loop. In (6.2), v_{ref} is the DC link reference voltage. The effective sharing of i_{tot} is essential to manage a faster v_{dc} restoration and effective performance of the proposed control method. Alike the existing control methods, the LPF is employed to extract an average current (i_{avg}) of the total current as given below in (6.3),

$$i_{avg}(s) = \frac{\omega_c}{s + \omega_c} i_{tot}(s), \quad (6.3)$$

$$i_{b,r}(s) = \gamma i_{avg}(s), \quad i_{g,r}(s) = (1 - \gamma) i_{avg}(s), \quad (6.4)$$

where ω_c , $i_{b,r}(s)$, $i_{g,r}(s)$ and γ are the LPF cut-off frequency, the current reference for the battery converter control and the current reference for the grid and sharing coefficient. The cut-off frequency of the LPF is chosen to be 31.416 rad/s. Taking into account the v_b and battery SOC, it is important to select the appropriate sharing coefficient. As i_{avg} is shared between the battery and the grid supply the proper sharing coefficient is necessary. The discrete power sharing approach is presented in the literature [132, 136, 137]. The discrete power-sharing approach creates a sharp rate of change of battery current ($\frac{di_b}{dt}$) during a sudden power fluctuation and during normal operation of charge/discharge when the SOC limit of the battery reaches a certain level. Thus, the new sharing coefficient is proposed. The graphical representation of the sharing coefficients are shown in Figure 6.2. The main purpose of the sharing coefficient is to decrease

Figure 6.2: Sharing coefficient (γ) for the proposed energy management scheme for deficit power mode.

the ($\frac{di_b}{dt}$) during sudden power fluctuations. It also maintains the battery SOC in the

safe operating region for a longer duration of time. The curve fitting technique from MATLAB is used to obtain a 4th order polynomial equation for the sharing coefficient (γ).

$$\gamma = P_1(SOC_b)^4 + P_2(SOC_b)^3 + P_3(SOC_b)^2 + P_4 SOC_b + P_5, \quad (6.5)$$

where $P_1 = -2.143$, $P_2 = 2.429$, $P_3 = 0.7071$, $P_4 = 0.09286$, and $P_5 = 1.832e-16$ are the coefficients in (6.5). The transient component in the total current reference is given by (6.6),

$$i_{sc,r}(s) = i_{tran}(s) = \left(1 - \frac{\omega_c}{s + \omega_c}\right) i_{tot}(s) + \alpha \Delta i_b, \quad (6.6)$$

In (6.6), $i_{sc,r}$ and Δi_b are the SC reference current and the uncompensated current from the battery system. $\alpha = \frac{v_b}{v_{sc}}$, is the battery error current compensation factor. The diversion of the uncompensated current from the battery system to the SC system contribute to a faster DC link voltage restoration. In 6.3, i_b , i_{sc} and i_g are the actual battery, SC and grid current respectively. The current references are compared to the actual currents and the error currents after comparison are then fed to the PI current controllers. The PI current controllers generate the duty ratios to regulate the HESS and grid current according to their current references. The overall architecture of the proposed EMS and control method is presented in Figure 6.3. The rate limiter (RTL) in Figure 6.3 is to limit the battery charge/discharge current.

Figure 6.3: Block diagram representation of the proposed EMS and control.

6.2.2 Proposed EMS

The flow chart of the proposed EMS is presented in Figure 6.4. It consists of two different

Figure 6.4: Flowchart of the proposed EMS.

modes, (i) excess power mode (EPM) and (ii) deficit power mode (DPM). These two modes are identified based on the RESs availability and the load demand. They are DPM ($P_{hess} > 0$) and EPM ($P_{hess} \leq 0$), where $P_{hess} = P_b + P_{sc} + P_g = P_{dcl} + P_{acl} - P_{ren}$. Based on the condition of P_{hess} , the system operates in different modes as shown in the flowchart shown in Figure 6.4. Under the DPM and EPM modes, four different operating conditions are identified based on the condition of SOC_b and SOC_{sc} as shown in Table 6.1 and Table 6.2. SOC_b and SOC_{sc} represent the battery and SC SOC's respectively. SOC_b and SOC_{sc} are calculated based on coulomb's counting method presented in [142] and the corresponding equations are given below in (6.7) and (6.8),

$$SOC_b = SOC_b^o - \frac{1}{3600C_{nb}} \int i_b dt, \quad (6.7)$$

$$SOC_{sc} = SOC_{sc}^o - \frac{1}{3600C_{nsc}} \int i_{sc} dt, \quad (6.8)$$

where SOC_b^o and SOC_{sc}^o are initial battery and SC SOC. C_{nb} and C_{nsc} represent the nominal capacity of the battery and SC respectively. The proposed EMS meets the

Table 6.1: Deficit power mode

Conditions	Current settings
$SOC_b > L_{bc} \ \& \ SOC_{sc} > L_{scc}$	$i_{bref} = \gamma \cdot i_{avg}, i_{scref} = i_{sc,r} \text{ and } i_{gref} = (1 - \gamma) \cdot i_{avg}$
$SOC_b < L_{bc} \ \& \ SOC_{sc} > L_{scc}$	$i_{bref} = 0, i_{scref} = i_{sc,r} \text{ and } i_{gref} = i_{avg}$
$SOC_b > L_{bc} \ \& \ SOC_{sc} < L_{scc}$	$i_{bref} = \gamma \cdot i_{avg}, i_{scref} = 0 \text{ and } i_{gref} = (1 - \gamma) \cdot i_{avg} + i_{sc,r}$
$SOC_b < L_{bc} \ \& \ SOC_{sc} < L_{scc}$	$i_{bref} = 0, i_{scref} = 0 \text{ and } i_{gref} = i_{avg} + i_{sc,r}$

Table 6.2: Excess power mode

Conditions	Current settings
$SOC_b < H_b \ \& \ SOC_{sc} < H_{sc}$	$i_{bref} = -i_{b,ra}, i_{scref} = -i_{sc,ra} + i_{sc,r} \text{ and } i_{gref} = i_{tot}$
$SOC_b > H_b \ \& \ SOC_{sc} < H_{sc}$	$i_{bref} = 0, i_{scref} = -i_{sc,ra} + i_{sc,r} \text{ and } i_{gref} = i_{tot}$
$SOC_b < H_b \ \& \ SOC_{sc} > H_{sc}$	$i_{bref} = -i_{b,ra}, i_{scref} = 0 \text{ and } i_{gref} = i_{tot} + i_{sc,r}$
$SOC_b > H_b \ \& \ SOC_{sc} > H_{sc}$	$i_{bref} = 0, i_{scref} = 0 \text{ and } i_{gref} = i_{tot} + i_{sc,r}$

following objectives: (i) always maintains the SOC_b and SOC_{sc} within their safe operating region, i.e., higher (H) and lower (L) SOC limits as specified; (ii) limits the rate of charge/discharge of the battery and SC; (iii) achieves seamless mode transition between different modes of operation; (iv) reduces stress on the battery and increase lifespan of the battery system; and (v) it is computationally less intense.

6.2.3 Deficit Power Mode

The four conditions are identified for the DPM operation. In DPM operation, the renewable power generation is operated at MPP in all four conditions. The various operations under the DPM are given in Table 6.1. In Table 6.1, L_{bc} and L_{scc} represent the lowest allowed SOC limits for the battery and SC as mentioned by the manufacturer in their datasheets. The various operating conditions in DPM are explained below.

Condition I: If $SOC_b > L_{bc}$ and $SOC_{sc} > L_{scc}$, then discharge both the battery and SC. The SC handles the transient and oscillatory power demand and the average power is shared between the battery and the grid. The current setting for the battery, SC and grid are as follows.

$$i_{bref} = \gamma i_{avg}, \ i_{scref} = i_{sc,r}, \ i_{gref} = (1 - \gamma) i_{avg} \quad (6.9)$$

The value of γ is changed dynamically based on the SOC_b value which allows the smooth transition of the battery current.

Condition II: If $SOC_b < L_{bc}$ and $SOC_{sc} > L_{sc}$, then the i_{bref} is set to zero. The i_{tran} is supplied by the SC and the i_{avg} is supplied by the grid. The current setting for the battery, SC and grid are as follows.

$$i_{bref} = 0, \quad i_{scref} = i_{sc,r}, \quad i_{gref} = i_{avg} \quad (6.10)$$

Condition III: If $SOC_b > L_{bc}$ and $SOC_{sc} < L_{sc}$, then the battery is discharged until SOC_b reach L_{bc} to support the average power demand and the SC remains idle. In this condition, the transient power demand is handled by the grid. The current setting for the battery, SC and grid are as follows:

$$i_{bref} = \gamma i_{avg}, \quad i_{scref} = 0, \quad i_{gref} = (1 - \gamma) i_{avg} + i_{sc,r} \quad (6.11)$$

Condition IV: If $SOC_b < L_{bc}$ and $SOC_{sc} < L_{sc}$, then both the battery and SC remain idle. The grid supports the power difference between the RES generation and the load demand. The current setting for the battery, SC and grid are as follows:

$$i_{bref} = 0, \quad i_{scref} = 0, \quad i_{gref} = i_{avg} + i_{sc,r} \quad (6.12)$$

In this condition, the average power demand, as well as the transient power demand, is supplied from the grid.

6.2.4 Excess Power Mode

The excess power from the RES is stored in the battery and SC until SOC_b and SOC_{sc} reach their highest SOC limits. The operating conditions in EPM are given in Table 6.2. In Table 6.2, H_b and H_{sc} represent the highest safe operating SOC limits for the battery and SC as provided by the manufacturer. Once the ESS reaches its highest SOC limit, the excess energy is fed to the grid using a VSC. In Table 6.2, $i_{b,ra}$ and $i_{sc,ra}$ are the battery and SC rated charging current.

Condition I: If $SOC_b < H_b$ and $SOC_{sc} < H_{sc}$, then the battery and SC are charged based on the rated charging current. The transient and oscillatory power demand is handled by the SC. The excess power after charging the battery and SC is fed to the grid. The current setting for the battery, SC and grid are as follows.

$$i_{bref} = -i_{b,ra}, \quad i_{scref} = -i_{sc,ra} + i_{sc,r} \quad \text{and} \quad i_{gref} = i_{tot} \quad (6.13)$$

Condition II: If $SOC_b > H_b$ and $SOC_{sc} < H_{sc}$, then the i_{bref} is set to zero. The SC is charged based on its rated charging current. During the sudden power fluctuations, the SC handles the transient and oscillatory current. The overall power balance in the system is handled by the grid in this condition. The current setting for the battery, SC and grid are as follows.

$$i_{bref} = 0, \quad i_{scref} = -i_{sc,ra} + i_{sc,r} \quad \text{and} \quad i_{gref} = i_{tot} \quad (6.14)$$

Condition III: If $SOC_b < H_b$ and $SOC_{sc} > H_{sc}$, then the battery is charged by its rated charging current until SOC_b reaches H_b . The SC remains idle in this condition. The grid handles the i_{tot} and $i_{sc,r}$ and maintains the power balance. The current setting for the battery, SC and grid are as follows.

$$i_{bref} = -i_{b,ra}, \quad i_{scref} = 0 \quad \text{and} \quad i_{gref} = i_{tot} + i_{sc,r} \quad (6.15)$$

Condition IV: If $SOC_b > H_b$ and $SOC_{sc} > H_{sc}$, then both the battery and SC remain idle. The excess power from the RES after supplying the load demand is fed to the grid. The current setting for the battery, SC and grid are as follows.

$$i_{bref} = 0, \quad i_{scref} = 0 \quad \text{and} \quad i_{gref} = i_{tot} + i_{sc,r} \quad (6.16)$$

6.3 Simulation Results

The proposed EMS and control method is evaluated by the detailed simulation and experimental studies. The performance during the DPM operation, EPM operation and the mode transition are studied. In Table 6.3, the nominal parameters used during simulation study are tabulated. In Table , $k_{p_{pv}}$, k_{p_b} , $k_{p_{sc}}$ are the proportional gains of the PV, battery and SC current loop PI controller. $k_{i_{pv}}$, k_{i_b} , $k_{i_{sc}}$ are the integral gains of the PV, battery and SC current loop PI controller.

Table 6.3: System parameters for simulation study

PV array parameters		Values
Open circuit voltage (v_{pv})		40 V
Short circuit current (i_{pv})		20 A
Lead-acid battery specifications		Values
Ah capacity		12 Ah
Terminal Voltage (v_b)		12 V
Number of batteries in series		4
SC specifications		Values
Terminal voltage (v_{sc})		15 V
Capacitance (C_{sc})		58 F
Number of SCs in series		4
Maximum continuous current		20 A
Maximum current in 1sec		80 A
Converters parameters	$L_{pv} = 10$ mH, $c_{pv} = 440$ μ F	
	$L_b = 1.63$ mH, $c_b = 440$ μ F	
	$L_{sc} = 2$ mH, $c_s = 440$ μ F	
	$C_{dc1} = 1600$ μ F, $C_{dc2} = 1600$ μ F	
	$L_f = 5$ mH, $C_f = 15$ μ F	
	$L_s = 5$ mH	
Controller parameters	$k_{p_pv} = 0.1$, $k_{i_pv} = 1$	
	$k_{p_b} = 0.1$, $k_{i_b} = 100$	
	$k_{p_sc} = 0.4$, $k_{i_sc} = 150$	
	$k_{p_v} = 1$, $k_{i_v} = 100$	
	$\alpha = 0.85$	
Load parameters	$R_L = 50$ Ω , $R_{lc} = 20$ Ω	
	$R_{nl} = 30$ Ω , $L_{nl} = 50$ mH	
DC and AC grid parameters	$v_{dc} = 80$ V, $v_g = 50$ V, 50 Hz	

6.3.1 Performance under DPM Operation

The results for the proposed EMS and control method for DPM operation are presented in Figure 6.5. The PV generation is kept constant in this study. At time t_1 , SOC_b and SOC_{sc} are above their lower SOC limit. At the same time instant, the DC load is changed from $R = 50 \Omega$ to $R = 25 \Omega$, which generates a voltage deviation in the DC link. In Figure 6.5(c), the SC responds to deal with the fast-changing transient power demand and the battery current slowly increases. The AC load is kept constant during this condition.

At time t_2 , SOC_b is decreased below L_{bc} while the SOC_{sc} is still above L_{sc} . In this condition, the active power demand is dealt by the grid supply and the transient power is handled by the SC. The battery current moves to zero as the SOC_b falls below the L_{bc} . The DC link voltage remains constant during this condition.

Figure 6.5: Performance under DPM operation: (a) PV current, (b) DC link voltage, (c) SC and battery current, (d) AC load current, (e) grid current and voltage and (f) Powers.

At time t_3 , SOC_b is higher than L_{bc} and SOC_{sc} is below L_{scc} . In this instant, the i_{tran} is dealt by the grid supply. The sharing coefficient in (6.5) is used to share the average power demand. The SC remains idle during this condition. The DC link voltage is also maintained constant during this condition.

At time t_4 , the AC load is increased by decreasing the linear load resistance. At this time, SOC_{sc} is below L_{scc} . Thus, i_{sc} is zero. i_b slowly rises as the grid compensates the deficit of SC in the system.

At time t_5 , SOC_b is below L_{bc} , and SOC_{sc} is below L_{scc} . Thus, both the battery and SC remain idle. In this condition, the grid supplies the required power to stabilize the

DC link voltage. In this condition, if the grid is not available the load shedding control techniques should be used to ensure power balance in the system. In all the DPM operating conditions, the v_{dc} is restored quickly to its reference value and maintained constant.

6.3.2 Performance under EPM Operation

The simulation results for the EPM operation are presented in Figure 6.6. In this mode,

Figure 6.6: Performance under EPM operation: (a) PV current, (b) DC link voltage, (c) SC and battery current, (d) inverter current, (e) AC load current, (f) grid current and (g) Powers.

the generation is made higher than the load demand. The PV current is maintained constant at 12 A during the entire simulation study.

At time t_1 , SOC_b and SOC_{sc} are below their highest SOC limits. At time $t_1 = 2\text{ s}$, the DC load is changed from $R = 50\ \Omega$ to $R = 25\ \Omega$. This creates a voltage deviation in the DC link. In this condition, the battery and SC are charged with their rated charging capacity until their highest SOC limit is achieved. The average power to maintain the constant v_{dc} is handled by the grid and the transient power demand is handled by the SC system.

At time t_2 , SOC_b reaches to H_b so the battery charging current is zero. In this condition, the SC is charged with the rated charging current as the SOC_{sc} is still below H_{sc} . The remaining excess power is fed to the grid as presented in Figure 6.6(g). From time t_2 to t_3 , the excess power is fed to the grid and the grid power is negative.

At time t_3 , SOC_{sc} rises to H_{sc} and the SC charging current is made zero. In this condition, the battery is charged with the rated charging current until H_b is achieved. The grid handles the transient and average power demand to maintain the constant v_{dc} .

At t_4 , the AC load is increased by decreasing the linear load resistance. During this time period, SOC_{sc} is at H_{sc} and SOC_b is below H_b . The battery charging current remains unchanged while the SC supplies the transient power demand.

At time t_5 , SOC_b and SOC_{sc} are made above their highest SOC limits. In this condition, the grid absorbs all the excess power to maintain constant v_{dc} . The entire load demand is supplied by the generation, and the excess power is fed to the grid.

The inverter, AC load and grid currents are presented in Figure 6.6(d)-(f). The results show that the i_{vsc} compensates the non-linear load current to maintain a distortion-free i_g . In all the operating conditions, the i_g and v_g are maintained at the unity power factor.

6.3.3 Seamless Mode Transition

The transition of the system control from one mode to another can create a power imbalance and make the system unstable. The EMS and control method should respond

to the mode transition as fast as possible and restore the system to its nominal operating condition. The simulation results when the system moves from one mode to another are presented in Figure 6.7.

Figure 6.7: Performance under change in various operating modes: (a) PV current, (b) DC link voltage, (c) SC and battery current and (d) grid current.

To realize the mode transition scenarios, the PV generation is varied as presented in Figure 6.7(a). The DC load and AC load are maintained constant in this study. The system operates at DPM till time 4.8 s. At time 4.8 s, the system moves from DPM of operation to the EPM of operation. During the mode transition, the transient power is handled by the SC as given in the Figure 6.7(c). The battery and grid share the average power demand. The i_b and i_g are shown in Figure 6.7(c) and Figure 6.7(d) respectively. The system continues to operate in EPM from time 4.8 s to 13.8 s with the PV generation variations at time 8 s and 11 s. The operation of the system moves from the EPM of operation to the DPM of operation at time 13.8 s. The smooth restoration of the v_{dc} is observed in all operating conditions with a varying i_{pv} and mode transitions. The smooth mode transitions are observed from the simulation study with less variation in the v_{dc} .

6.4 Experimental Results

The hardware setup used for the experimental study of the grid-connected HESS is shown in Figure 6.8. Semikron SKM 75GB12T4 power switches are used to build the

Figure 6.8: Hardware setup for grid-connected HESS.

DC-DC converters and a DC-AC inverter. SKYPER 32R IGBT gate driver modules are used to drive the IGBT switches. The current and voltage in the system are measured using a LEM transducers. The chroma programmable DC power supply 62012P-600-8 is used as a renewable power source (RPS) in the experiment. The current from the RPS is controlled by changing the current reference for the DC-DC boost converter current controller. The different current references are used to generate different PV current profiles during the experimental study. The two series combinations of 17 Ah capacity lead-acid batteries with a terminal voltage of 12 V are used as the battery system. The two series combinations of Maxwell BMOD0058 E015 B01 SCs with a capacity of 58 F at 15 V are used as the SC system. The maximum discharge current for SC in 1 s is 80 A. The dSPACE 1103 real-time controller is used as a control platform. The DC link voltage ($v_{dc} = 48 V$) and AC grid voltage ($v_{ac} = 20 V(rms)$) are chosen for the experimental study. It is highlighted that the experimental setup is the scaled down version of the system used during the simulation study.

6.4.1 Performance under Different Modes of Operation

Figure 6.9 and Figure 6.10 show the experimental results for the DPM and EPM operations. The possible operating conditions during the DPM are shown in Figure 6.9.

Figure 6.9: Experimental result for DPM operation. $v_{dc} \sim 20$ V/div, i_{pv} , i_b , i_{sc} , $i_{dcl} \sim 2$ A/div, i_g , $i_{acl} \sim 10$ A/div, $v_g \sim 100$ V/div, $time \sim 5$ s/div.

Figure 6.10: Experimental result for EPM operation. $v_{dc} \sim 20$ V/div, i_{pv} , $i_{sc} \sim 5$ A/div, i_b , $i_{dcl} \sim 2$ A/div, i_g , $i_{acl} \sim 10$ A/div, $v_g \sim 100$ V/div, $time \sim 5$ s/div.

The four operating conditions are analysed where SOC_b and SOC_{sc} limits are changed intentionally to observe the extreme conditions. The DC load and AC load are also done during condition I. In condition I, the SOC_b and SOC_{sc} are above their lower SOC limits so both the battery and SC participate to stabilize the system. The v_{dc} is well maintained during the load change and the transition from one operating condition to another. It is observed that the battery and SC participate to maintain the system power balance until their SOC is within the safe operating limits.

In Figure 6.10, four operating conditions during EPM are studied. In condition I, the battery and SC are charged with the excess power at its rated charging current ($i_{b,ra}$ and $i_{sc,ra}$) until H_b and H_{sc} are reached. In this case, the v_{dc} is maintained by the grid power supply. In condition II, the battery charging current is set to zero as SOC_b is at H_b . In condition III, i_{sc} charging current is zero most of the time as SOC_{sc} is at H_{sc} . The soft change in the grid current is observed during the transition and a step load change as SC supports the transient power demand. In condition IV, i_b and i_{sc} are

made zero as they reached their maximum SOC limits. In this condition, the available excess power is handled by the grid. During a step load change conditions in different operating modes, the i_{tran} is supported by SC and the i_{avg} is shared between the battery and the grid.

6.4.2 Long-term Performance Analysis

Figure 6.11 shows the operation of the proposed EMS and control method under a general operational case when the PV generation changes in random manners. The irradiation pattern use in the experiment is shown in Figure 6.11(a). In this experiment,

Figure 6.11: Experimental result for a long-term PV change. (a) Irradiance pattern from 10:00 am - 16:30 pm. (b) $v_{dc} \sim 20$ V/div, i_{pv} , i_b , $i_{sc} \sim 1$ A/div, $i_g \sim 5$ A/div, $v_g \sim 50$ V/div, time ~ 5 s/div.

SOC_b and SOC_{sc} are maintained under the safe operating regions. The respective i_{pv} pattern is generated as per the irradiance pattern, presented in Figure 6.11(b). It results show that the proposed EMS and control method are effective in managing the intermittent PV power, by handling the slow base power fluctuations from the battery and grid, and the transient power fluctuations from the SC system. The v_{dc} is regulated at its reference value during the entire experimental period. A step change in DC load is done at time t_1 and t_2 along with the PV generation variation as presented in Figure 6.11(b). At time t_1 , the i_b changes its modes from charging current of -0.8 A

to discharging current of 0.9 A to support the varying load demand. The transient power variations in the system produced by a step load change and the PV generation variations are absorbed by the SC system. This ensures less stress in the battery system during the long-term operation.

6.4.3 Short-term Performance Analysis

The operation of the conventional control method [132] and the proposed EMS during a step change in the load demands are presented in Figure 6.12(a) and Figure 6.12(b) respectively. In this study, the i_{pv} is made constant at 2 A . The DC load change are

Figure 6.12: Experimental result for a step change in load demand. (a) Results for conventional control scheme. (b) Results for proposed controller. (c) zoomed view of Figure 12 (b) at point t_4 . $v_{dc} \sim 20\text{ V/div}$, i_{pv} , i_b , i_{sc} , $i_{dcl} \sim 2\text{ A/div}$, $i_{acl} \sim 10\text{ A/div}$, $i_g \sim 5\text{ A/div}$, $v_g \sim 100\text{ V/div}$, time $\sim 2\text{ s/div}$.

applied at time t_1 and t_4 and AC load change are applied at time t_2 and t_3 . v_{dc} and v_{ac} are maintained constant during the step increase and decrease in the load demand with both the proposed EMS and conventional control method. During a step decrease in the load demand at t_4 , the calculated m_p for the conventional control method is around 5.3% with t_{ss} of 650 ms. While, the calculated m_p for the proposed control method is around 3.4% with t_{ss} of 440 ms. The zoomed view of the step decrease in the load demand at the point t_4 is shown in Figure 6.12(c). It shows the better operation with the proposed control method. The average power shared between the battery and grid can also be observed in the experimental results. Figure 6.12(c) shows the unity factor operation of the system with i_g and v_g in phase with each other. The measured THD in the grid current in Figure 6.12(c) is less than 7%.

6.4.4 Performance Comparison of Proposed Controller with the Existing Method

Figure 6.13 shows the performance comparison of the proposed EMS and control method with the existing method [132], for smoothing the battery power fluctuations. In the experiment, the SOC_b is changed as shown in Figure 6.13(a). As the control schemes in [132] follow the discrete pattern to calculate the current sharing reference, the sharp changes in the battery current are observed as shown in Figure 6.13(c). In the proposed EMS, the current sharing coefficient for the battery and grid are depends on the SOC_b . Thus, the smooth transition of the i_b is observed in the experimental results presented in Figure 6.13(b). The $\frac{di_b}{dt}$ for the proposed method is lower compared to that of the method in [132].

The comparisons of the proposed EMS and method in [132] are presented in Table 6.4. The voltage overshoot (M_p) and settling time (t_{ss}) during a step decrease in the load demand is studied based on the experimental results presented in Figure 6.12(a) and Figure 6.12(b) at time t_4 . The $\frac{dv_{dc}}{dt}$ is compared based on the experimental results given in Figure 6.13. It shows that the proposed EMS and control provides faster v_{dc} restoration with reduced M_p and $\frac{dv_{dc}}{dt}$ ratio. During a step load change the average overshoot in the DC link voltage is 3.4% and the settling time is around 440 ms for the proposed control

method. With the same test case, the average overshoot in the v_{dc} for the conventional control method [132] is higher and is around 5.3%. It requires 650 ms to stabilize the system. The $\frac{di_b}{dt}$ is also reduced for the proposed EMS and control method. The T_s is 30 μs for the proposed EMS, 75 μs for the method in [132] and 0.01 s for the MPC method [58].

Figure 6.13: Experimental result for a dynamic SOC_b change. (a) SOC_b change and sharing coefficient. (b) Results for proposed controller and (c) Results for conventional control scheme. $v_{dc} \sim 20$ V/div, $i_{pv} \sim 2$ A/div, $i_b \sim 1$ A/div, $i_{sc} \sim 0.5$ A/div, $i_g \sim 5$ A/div, $time \sim 5$ s/div.

Table 6.4: Performance comparisons with various control schemes

Performance index	[58]	[132]	Proposed
Peak overshoot (M_p)	-	5.3%	3.4%
Settling time (t_{ss})	-	650 ms	440 ms
$\frac{di_b}{dt}$ ratio (A/s)	-	0.8	0.05
Execution time (T_s)	0.01 s	75 μs	30 μs

6.5 Summary

A new EMS and control method for the grid-connected HESS has been presented in this Chapter. In order to reduce $\frac{di_b}{dt}$, the new sharing coefficient has been developed. The new sharing coefficient allows the effective sharing of average power between the battery and grid. The new sharing coefficient changes dynamically with the change in the SOC_b which helps to reduce the $\frac{di_b}{dt}$. The EMS to maintain the SOC limits of the battery and SC under the safe operating region has been developed and discussed in detail. The EMS generates the current settings for the battery, SC and the grid based on the RESs generation and the load demand in the system.

Several simulations and experimental case studies have been presented to show the advantages of the proposed EMS and control method. The ability to stabilize the system during DPM and EPM have been presented followed by the mode change conditions. The results show that the proposed EMS and control method stabilizes the DC link voltage faster and with less overshoot compared to those of the conventional PI-based control method during the load demand and generation. The results also show the reduction in $\frac{di_b}{dt}$ with the proposed EMS and control method.

Chapter 7

Conclusion

7.1 Summary of the Research Work

The ESSs cannot be seen separately with the RESs in both the islanded and grid-connected operation. The ESSs come integrated with the RESs as it is of utmost importance to provide a smooth supply to the load under random generation variations. The coordination of the RESs, ESSs and load power depends on the effective control method. The simple and robust control methods with faster response and maintain the system stability are of the top priority. In this thesis, various control methods for the implementation of the HESS in the DC microgrid are studied. The study of the proposed control methods includes the theoretical evaluation, controller design, stability analysis, experimental validation and performance comparison with the existing control methods.

Among the different types of control strategies for HESS, the PI-based control method is the most adopted one. With an objective to boost the execution of the PI-based control method for HESS, the new joint control strategy has been developed for HESS in DC microgrid applications. The joint control strategy uses the battery error current to enhance the performance of the HESS. The detail system parameters selection, controller parameter selection and stability analysis for the joint control strategy have been presented in the thesis. The experimental results demonstrated that with the diversion of the error current from the battery system to the SC system, the transient response of

the system can be improved by two times. The DC link voltage is also restored faster with less overshoot during the load and PV generation step change.

The MPC method has several features like on-line optimization, formulation of the cost function with system constraints and a variable switching frequency. However, its application is hindered in many power electronics applications as it requires large computational resources. There are very few works done to implement the MPC method for the HESS. In this thesis, the EMPCC method for the HESS control has been explored for DC microgrid applications. The EMPCC method explores the possibility of the MPC method in the HESS control. The EMPCC method has been implemented to regulate the current references generated for the HESS. The proposed method reduces the overall execution time for HESS control. The execution time depends on the complexity of the control method. This includes a mathematical model, a prediction horizon and the optimization technique used to design the controller. In conventional MPC methods, discrete mathematical system models are used which results in a large system matrix to model the HESS. In the conventional MPC method, normal prediction methods are used which require larger time steps to predict the solutions in the future. A quadratic programming method is employed to obtain the optimal control actions. They require large computational resources. In contrast to this, the proposed EMPCC method uses a simple converter model instead of an overall system model which results in a simpler design. In the proposed method, the MBT is used for the prediction of the control sequences. In this study, the control horizon (N_c) is 3 for the EMPCC method, with $n_1 = 1$, $n_2 = 5$ and $n_3 = 9$. Thus, the total number of control sequences is $2^3 = 8$. In the EMPCC method, the optimal solution is predicted for 3 time steps ahead in the future. In contrast to this, the control horizon (N_c) of the conventional MPC method is 15 which is the sum of n_1 , n_2 and n_3 . The N_c is 15 for the conventional MPC method which means 15 time steps is required to predict the optimal solution. Thus the total number of control sequences is $2^{15} = 32,768$. As a result, the conventional MPC method requires larger computational resources to obtain the faster control actions. This problem is effectively dealt with the proposed EMPCC method. The EMPCC method uses an enumeration based approach to obtain optimal switching actions. The design is simple to implement and requires lesser calculation steps compared to those of the quadratic

programming methods. The EMPCC method shows a better dynamic response compared to that of the existing methods with less computational resources during a change in PV generation and load. The results we obtained show the effectiveness of EMPCC method for both short-term and long-term power variation conditions.

The DEC method that handles the current from the HESS and DC link voltage has been proposed. The DEC method minimizes the state error following a defined evolution path. The DEC theory is used to design the new control method for the HESS. A new power-sharing approach to generate the current references for the HESS has been proposed. The detail controller design, theoretical analysis and implementation of the proposed DEC method have been validated through simulation and experimental studies. The ability to provide faster DC link voltage and current regulation by the proposed DEC method has been confirmed by the simulation and experimental studies. The results obtained show a better dynamic performance to the load and PV generation variation. The main improvement with this method is that the battery current, SC current and DC link voltage are regulated without any PI controller. This makes it easy to design and implement.

Similarly, the grid-connected operation of the HESS with a PV system has been studied. The new EMS and control for an effective power-sharing between the battery and grid have been presented. The proposed EMS operates the system in DPM and EPM depending on the PV power and the load. The operating conditions under DPM and EPM have been discussed in detail. Several simulations and experimental studies for DPM and EPM operation have been conducted. In each mode of operation, the effect of a step change in the load has been analysed. The effects of PV generation variation, SOC_b variation and SOC_{sc} variation have been presented. Additionally, the seamless mode transition with the proposed control method has been verified by the simulation study. The simulation and experimental results have validated all the features of the proposed EMS and control method.

Table 7.1: Performance comparisons with various control schemes

Performance index	Joint control method	EMPCC	DEC	Grid-connected operation
Peak overshoot (M_p)	1.2%	2.8%	1.1%	3.4%
Settling time (t_{ss})	210 ms	25 ms	20 ms	440 ms
Execution time (T_s)	20 μ s	30 μ s	20 μ s	30 μ s

The comparisons between the proposed control methods are presented in Table 7.1. All the control methods are implemented in the dSPACE 1103 and tested in the similar experiment prototype. The performance of the DEC method is better compared to those of the joint control method and EMPCC. However, the detailed stability analysis of the DEC method is still needed to be done. The joint control method is easiest to implement however it requires tedious tuning of the PI controller parameters. The EMPCC method is computationally extensive compared to other control methods but it provides faster response time compared to the PI based control method. In summary, it is observed that the simple, fast and robust control methods for the HESS in the DC microgrid applications are imperative. However, there is always a trade-off between a better control action and the complexity of the control method. In this thesis, various control methods have been developed and discussed with the experimental validation. The control methods presented here are mainly focused to enhance the response of the overall HESS with less computational complexity. The proposed control methods can be implemented for use of HESS in DC microgrids, AC microgrids, EVs and UPS.

7.2 Future Research Directions

The SISO converter topology has been studied to implement different control strategies for the HESS control in this thesis. The design and implementation of new control techniques for the SISO converter topology for HESS in islanded and grid-connected mode of operation have been presented. The proposed methods are robust and perform better compared to those of the conventional control methods when applied to the SISO converter configuration. The few aspects of this work which can be further explored for better performance are presented here.

7.2.1 MIMO Converter Control for HESS

As observed from the study done in this thesis, the SC system only operates for a small portion of time when the transient power is required in the system. In most of the cases, the SC system remains idle in the HESS applications. The RESs such as PV and wind also remain idle when there are no favourable environmental conditions. Thus,

using an individual converter for the RES and HESS makes the system expensive and also underutilized. One of the solutions to this issue is to develop the MIMO power converters which can integrate the RES and HESS together. The advantages of the MIMO converter system over the SISO converter system are (i) reduction in system size, (ii) reduction in converter cost and (iii) better utilization ratio of the HESS.

There are several challenges with the MIMO converters. The complexity of the control system increases when a large number of RESs and ESs are controlled by a single converter. The development of the efficient and effective control method can be explored. The control method should utilize the various characteristics of the RESs and HESS. The other aspect is the reliability of the MIMO converters as the failure of a single converter could lead to the shut down of the overall system. The fault tolerance and clearance aspect can also be investigated for MIMO converters for the HESS with RESs.

7.2.2 Implementation of EMPVC for Overall HESS Control

The EMPCC method for the regulation of current from the HESS has been experimentally verified in this thesis. The proposed EMPCC method regulates the current references generated from the PI-based voltage controller. Thus, the output DC link voltage contains the overshoot during step change in load and PV generation. The PI-based voltage controller can be replaced with the enumeration-based model predictive voltage control (EMPVC) method to get a better controller response in the HESS.

There are several challenges associated with the implementation of the EMPVC method for the HESS control. The EMPVC method should generate the current references for the HESS also regulate the DC link voltage. Thus, the EMPVC method should simultaneously control the current and voltage of the system. The bi-directional DC-DC converter exhibits the non-minimal phase behaviour which may create a controller conflict problem when a single controller is implemented to regulate both current and voltage in the HESS. The use of EMPVC method for overall HESS control will also increase the controller computational time. Thus, the new optimization method can be explored to reduce the computational time.

7.2.3 Economic Aspect in Determination of Power Sharing Coefficient for the Battery and the Grid

In this thesis, the new sharing coefficient for the power sharing between the battery and the grid has been presented for the grid-connected operation of HESS. The sharing coefficient value is calculated based on the SOC_b in the secondary level control. As an extension of this work, the tertiary level control can be implemented which determines the sharing coefficient value based on the market value of the battery and the electricity price. This will help to improve the usage ratio of the battery system. The effect of the sharing coefficient on the peak electricity pricing and off-peak electricity pricing of the grid should be analysed. The inclusion of economic aspect to determine the sharing coefficient will help to determine the optimal size of the HESS. This will further reduce the overall installation and maintenance expenses of the HESS.

7.2.4 Implementation of EMPCC and DEC Method for the Grid-Connected Operation

The EMPCC and DEC method have been studied for the standalone mode of operation of the DC microgrid. The EMPCC and DEC method for the grid-connected operation of HESS is a recommended research area. The performance analysis of the EMPCC and DEC method for the grid-connected operation can be studied as an extension of the work presented here. The implementation of the EMPCC and DEC method for the hybrid AC/DC microgrids control is also a recommended research area. The detail stability analysis of the EMPCC and DEC methods for the grid-connected operation should be done before its implementation.

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. Kollimalla, 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 *International Journal of Electrical Power & Energy Systems*, Elsevier.. (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* Nov, 2018.

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 Micro-grid 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.

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