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Fuzzy Logic Controller Based Power Management of Micro-grid with Hybrid Storage System

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Abstract: Continuously increasing demand of microgrid with high penetration of distributed energy generators, specially focused on renewable energy sources is modifying the traditional structure of the electric distribution grid. In addition, DC micro grids diverted the attention of researchers and power electronics industry in recent years to stimulate renewable energy technologies (RETs) and distributed energy resources (DERs) deployment and encouraging technological innovation to reduce green house gas (GHG) emission and achieve energy security and independence to meet the growing electricity demand. So for many studies have been done on successful integration of RETs and DERs, operation and control, protection and stability issues, simultaneously and satisfactorily implemented during feasible operation of microgrid. Studies show that DC transmittable power can increase the system efficiency up as compared to AC. But still DC bus voltage fluctuation, power quality and flow during the transition between grid connected mode to islanded mode or transient load insertion which intend to DC microgrid instability are the problems which need to be investigated and resolved for the effective use of DC microgrid generation. In this concept DC microgrid voltage, power flow, power quality and energy management different controls and techniques are reviewed. The Fuzzy logic controller is set of rules or logics, the control rules are indicated with error and change in error having membership functions of input and output Variables are triangular and has seven fuzzy subsets then seven fuzzy subsets are considered for membership functions of the output variable. It will improves the system reliability & stability of the response of the system.

Keywords: DC Microgrid, Bus Voltage, Energy Storage System.

I. INTRODUCTION

Nowadays, the problem of energy crisis has been increasingly tense, while low carbon energy need to be developed. In this context, distributed renewable energy has been paid more attention and developed greatly, especially wind power and photovoltaic (PV) generation, due to their abundant availability and less impact on the environment. But theory and practice have proved that these distributed renewable energy have some inherent problems, such as its intermittency, which has some negative impact on the security, reliability and power quality of utility grid [1]. On this basis, the concept of microgrid presented by Robert Lasseter and other scholars is considered to be a feasible scheme to solve the problem. The microgrid is a local energy network that includes renewable energy sources and storage systems. It can be connected to the mains grid or works isolated when there is a blackout at the main grid, and continues to supply their local loads in "islanded mode" [2-3]. A microgrid can be designed to support alternating current (AC) or direct current (DC). Compared with AC forms, DC microgrid can avoid the consideration of reactive power and frequency synchronization [4]. At the same time, some DC sources and DC loads, such as photovoltaic, super-capacitor, EV and LED, provide opportunities for DC microgrid. Also, DC microgrid will have the capability to increase the overall system efficiency compared to AC system. On the other hand, storage systems are usually installed to alleviate system power mismatch between generation and consumption in DC microgrid, and they can improve the stability, power quality, reliability of supply and overall performance of microgrid.

Storage systems can be characterized based on power density, energy density, ramp rate, life cycle and so on, but none of the storage systems fulfill all expected features. The typical energy storage in practical engineering is lead acid batteries, which possess high energy density but low power density, low charge/discharge rates and life span of less than 1000 full cycle. So batteries can't respond immediately under frequent load fluctuations. Compared to battery, super-capacitor has high power density but low energy density, high charge/discharge rates and life span of around 500,000 cycles. Therefore, super-capacitor can be used to match the quick load fluctuations [5-6]. The combination of the two types is crucial for diverse energy storage needs of both fast and slow fluctuating power and it has become a research hotspot, and the structure of two-types storage systems have been the subject of more research programs, such as the combination of batteries and super-capacitors. Authors in [7-8] demonstrated the hybrid energy storage systems lowers the battery cost and improves the overall system efficiency.

The system integration of PV array, batteries, and super-capacitors has been studied in several literatures, but this system still has some shortcomings [9-11]. Firstly, when it is an islanding mode, electricity shortages occur at times. Secondly, photovoltaic redundant energy will be wasted when storage systems have been fully charged. From the above, we consider how the DC microgrid based on PV array with a hybrid storage system connected with utility grid works. We present a novel power management of DC microgrid to realize system stability, low voltage regulation and equal load sharing in each unit. It is confirmed that the steady state and transient state conversion of different operation mode through MATLAB/SIMULINK simulation platform. The paper is organized as follows. In section Ⅱ, system configuration of this microgrid and its modeling are discussed. Section Ⅲ describes the control strategy and operation modes of this microgrid. The simulation results of the proposed system are given in Section Ⅳ. Finally, the conclusions of the paper are summarized in section Ⅴ.

II. SYSTEM CONFIGURATION

A grid-connected DC microgrid investigated in this paper is shown in Fig.1. It consists of PV-panel, hybrid storage unit, utility grid, DC/DC converters, DC/AC converter and DC load. The PV panel is connected to the DC bus through a boost DC/DC converter which extracts the maximum power from PV panel using maximum power point tracking (MPPT) algorithm. The hybrid energy storage unit is composed of lead-acid batteries and super-capacitors. The batteries and the super-capacitors are connected with the DC bus through two bi-directional half-bridge DC/DC converters. The utility grid is connected to the DC bus through a three-phase bi-directional full-bridge AC/DC converter.

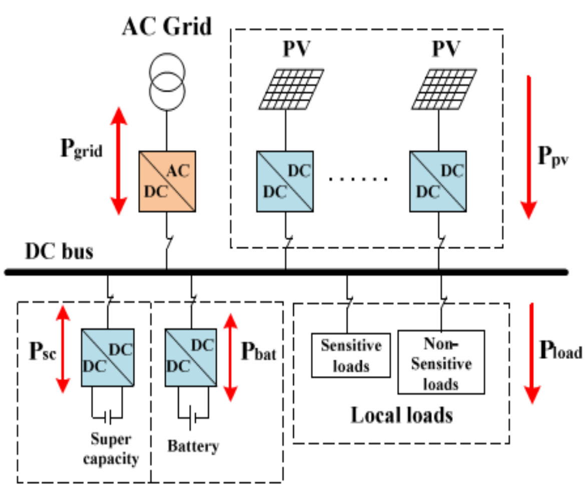

Fig.1. DC microgrid with hybrid storage system.

A. MPPT Control of PV Module

The photovoltaic (PV) cells are connected in series to form a module that gives a standard dc voltage. Modules are connected into an array to produce sufficient current and voltage to meet a demand for a grid-connected application [12]. Normally, the PV modules are first connected in series into strings and then in parallel into an array. The PV model can be described by detailed equation. The power produced by a PV array is dependent on the irradiance and temperature. There is a maximum power point (MPP) which should be tracked in the power-voltage (P-V) curve. It can be accomplished through DC/DC converter linking the PV array to the DC bus as shown in Fig.2. Typical MPPT control strategies include open-circuit voltage method, short-current circuit current method, perturb and observe method (P&Q) and incremental conductance method (INC). In general, P&Q method and INC method are the widely used approaches for MPPT control. However, those conventional MPPT algorithms have disadvantages such as instability, poor adaptability to external environment. Sometimes they may fail to track the MPP when the atmospheric conditions change rapidly. The step size is automatically tuned according to the inherent PV array characteristics. If the operating point is far from MPP, it increases the step size which enables a fast tracking ability. If the operating point is near to the MPP, the step size becomes very small that the oscillation is well reduced contributing to a higher efficiency. The flow chart of the variable step size INC MPPT algorithm is shown in fig.3 and the variable step size &V is automatically tuned.

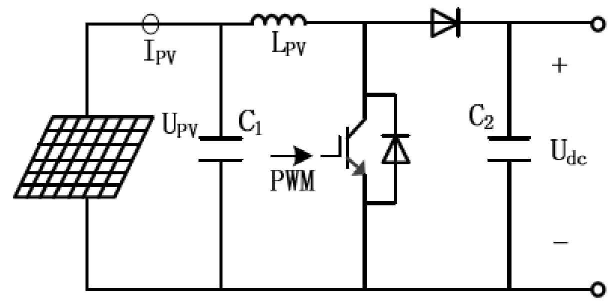

Fig.2 DC/DC converter of PV module with MPPT function.

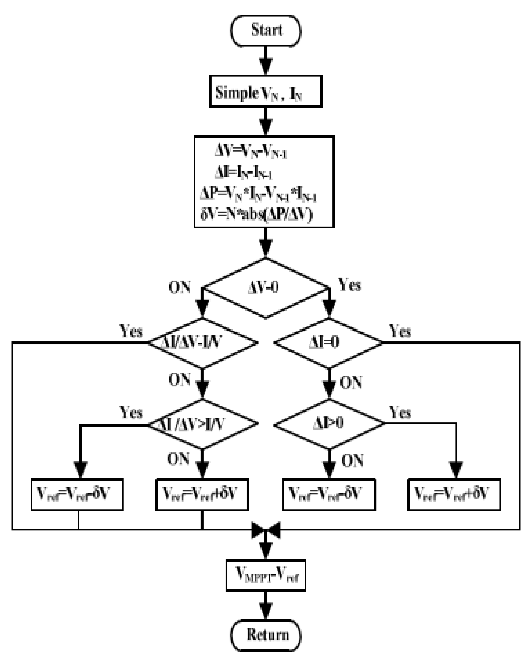

Fig.3 Flowchart of the variable step size INC MPPT algorithm.

B. Control of Bi-Directional DC/DC Converter for Hybrid Energy-Storage

Battery has high energy density whereas it has relatively slow charging and discharging speed. On the other hand, super-capacitor has high power density and fast response. The super-capacitor as a short-term energy storage device is utilized to compensate for fast changes in the output power, while the battery as a long-term energy storage device is applied to meet the energy demand [14]. The battery is modeled using a simple controlled voltage source in series with a constant resistance. The SC is modeled as a regular capacitor in series with a constant resistance. The bi-directional buck/boost converter is used in the paper to link the SC or battery with the DC bus. The structure of the two converters is a parallel connection. This converter works as a boost converter during storage unit discharge mode and a buck converter during charge mode. The control method is a conventional double loop, including an inner current loop and an outer voltage loop, which is shown in Fig.4.

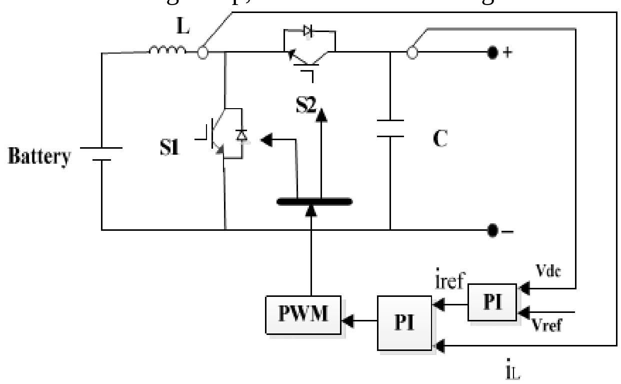

Fig.4 Control strategy of the bi-directional DC/DC converter.

C. The Control of Three Phase Bi-Directional AC/DC Converter

The utility grid is connected to the DC bus through a three-phase bi-directional full-bridge AC/DC converter. The control strategy is a direct quadrature (DQ) current controller together with an outer voltage control loop as illustrated in fig.5. When utility grid works normally, the DC bus will be connected to utility grid through the bi-directional converter and the power will be transmitted mutually; otherwise it will be disconnected with utility grid to avoid faults.

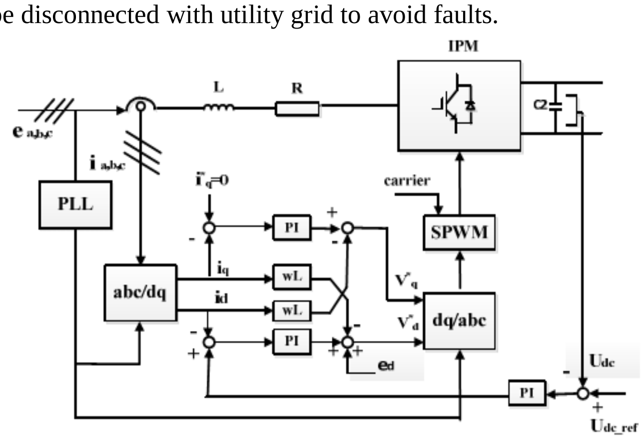

Fig.5. Control strategy of the bi-directional DC/AC converter.

III. CONTROL STRATEGY

A novel power management strategy of DC microgrid is proposed in this paper. The key point of power management scheme in DC microgrid is to keep the power balance among PV module, storage systems, utility grid and loads all the time, which is manifested by DC bus voltage [15-17]. The super-capacitor is the secondary power supply as auxiliary power of PV power and it works when there are surges or energy bursts in the system. The utility grid is the next place of the power supply priorities when there is bulk energy mismatch over a longer time period. The structure can lower the loss of lifetime of the battery in the conditional microgrid. Finally, when the main grid faults, the accessorial batteries will charge or discharge to keep the DC bus voltage steady.

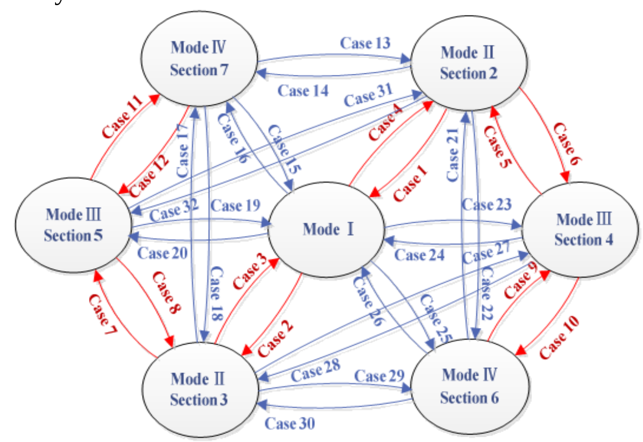

Fig.6 Mode transition mechanism.

TABLE I: Summary of Each Mode and Its Characteristics

Mode Name	Power Characteristic	Bus Voltage Range	Bus Regulation	Power Supply
Mode Ⅰ (section 1)	$P_{pv}=P_{load}$	$U_{low1}<U_{dc}<U_{high1}$	PV Unit	PV
Mode Ⅱ (section 2)	$P_{pv}+P_{sc}=P_{load}$	$U_{low2}<U_{dc}<U_{low1}$	Super-capacitor Unit	PV、Super-capacitor
Mode Ⅱ (section 3)	$P_{pv}-P_{sc}=P_{load}$	$U_{high1}<U_{dc}<U_{high2}$	Super-capacitor Unit	PV、Super-capacitor
Mode Ⅲ (section 4)	$P_{pv}+P_{ac}=P_{load}$	$U_{low3}<U_{dc}<U_{low2}$	Utility Unit	PV、Utility grid
Mode Ⅲ (section 5)	$P_{pv}-P_{ac}=P_{load}$	$U_{high2}<U_{dc}<U_{high3}$	Utility Unit	PV、Utility grid
Mode Ⅳ (section 6)	$P_{pv}+P_{bat}=P_{load}$	$U_{dc}<U_{low3}$	Battery Unit	PV、Battery
ModeⅣ (section 7)	$P_{pv}-P_{bat}=P_{load}$	$U_{high3}<U_{dc}$	Battery Unit	PV、Battery

At the same time, the system also has several abnormal cases drawn by blue arrow lines, as shown in fig.6. These abnormal cases will happen when certain source or certain converter is in trouble. For example, the case 15 and case 16 between mode I and mode Ⅳ will happen in the situation that the utility grid or grid-connected converter breaks down and super-capacitor is full. Actually, it has twenty abnormal cases in unexpected situations. In table I, we have summarized each mode and its characteristic. In general, the switching between different modes and the changes of control methods for converters can be achieved through bus voltage changes without communication links. These modes are analyzed in the following paragraphs:

ModeI: Ulow1<Udc<Uhigh1. In this mode, the DC bus voltage is regulated only by the PV generation, which means the generated PV power just matches the demands. The bus voltage fluctuates at the reference value in a small range. At the same time, the other converters are in the standby state. The power flow is shown in fig.7.

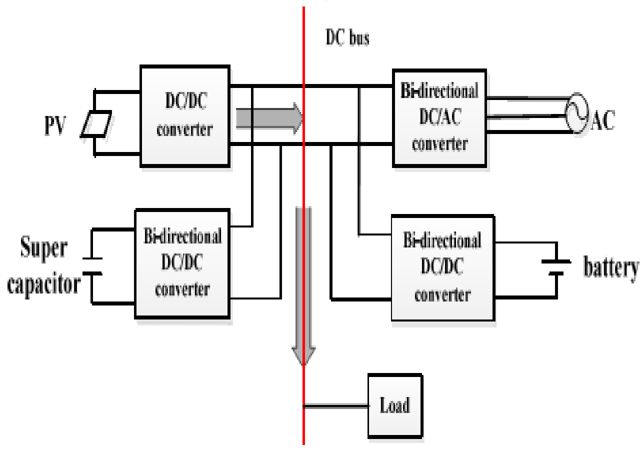

Fig.7. Power flow of mode I.

IV. INTRODUCTION TO FUZZY LOGIC CONTROLLER

L. A. Zadeh presented the first paper on fuzzy set theory in 1965. Since then, a new language was developed to describe the fuzzy properties of reality, which are very difficult and sometime even impossible to be described using conventional methods. Fuzzy set theory has been widely used in the control area with some application to dc-to-dc converter system. A simple fuzzy logic control is built up by a group of rules based on the human knowledge of system behavior. Matlab/Simulink simulation model is built to study the dynamic behavior of dc-to-dc converter and performance of proposed controllers. Furthermore, design of fuzzy logic controller can provide desirable both small signal and large signal dynamic performance at same time, which is not possible with linear control technique. Thus, fuzzy logic controller has been potential ability to improve the robustness of dc-to-dc converters. The basic scheme of a fuzzy logic controller is shown in Fig 8 and consists of four principal components such as: a fuzzification interface, which converts input data into suitable linguistic values; a knowledge base, which consists of a data base with the necessary linguistic definitions and the control rule set; a decision-making logic which, simulating a human decision process, infer the fuzzy control action from the knowledge of the control rules and linguistic variable definitions; a de-fuzzification interface which yields non fuzzy control action from an inferred fuzzy control action [10].

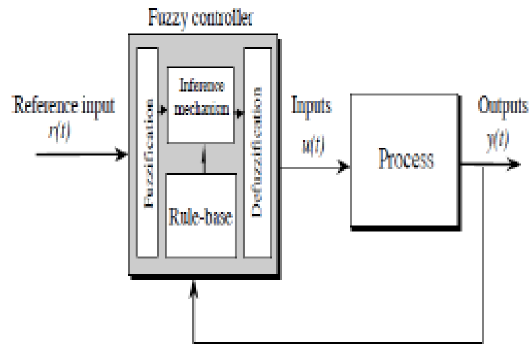

Fig.8. General Structure of the fuzzy logic controller on closed-loop system.

The fuzzy control systems are based on expert knowledge that converts the human linguistic concepts into an automatic control strategy without any complicated mathematical model [10] as shown in Fig.9. Simulation is performed in buck converter to verify the proposed fuzzy logic controllers.

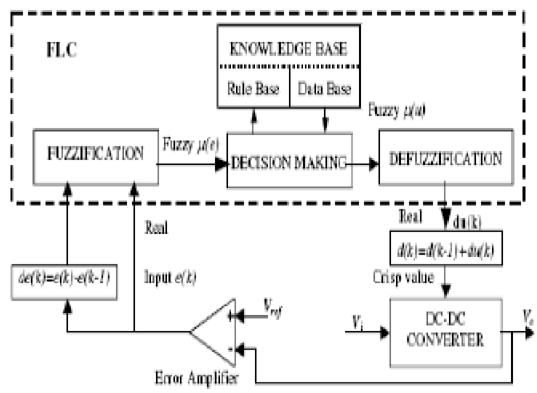

Fig.9. Block diagram of the Fuzzy Logic Controller (FLC) for dc-dc converters.

Fuzzy Logic Membership Functions: The dc-dc converter is a nonlinear function of the duty cycle because of the small signal model and its control method was applied to the control of boost converters. Fuzzy controllers do not require an exact mathematical model. Instead, they are designed based on general knowledge of the plant. Fuzzy controllers are designed to adapt to varying operating points. Fuzzy Logic Controller is designed to control the output of boost dc-dc converter using Mamdani style fuzzy inference system. Two input variables, error (e) and change of error (de) are used in this fuzzy logic system. The single output variable (u) is duty cycle of PWM output as shown in Figs.10 to 12.

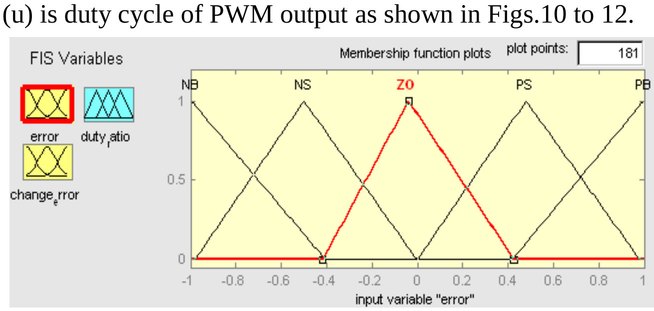

Fig.10.The Membership Function plots of error.

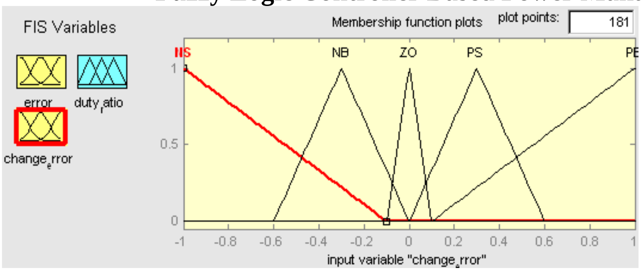

Fig.11. The Membership Function plots of change error.

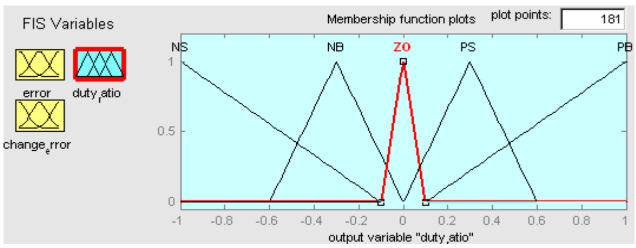

Fig.12.the Membership Function plots of duty ratio.

Fuzzy Logic Rules: The objective of this dissertation is to control the output voltage of the boost converter. The error and change of error of the output voltage will be the inputs of fuzzy logic controller. These 2 inputs are divided into five groups; NB: Negative Big, NS: Negative Small, ZO: Zero Area, PS: Positive small and PB: Positive Big and its parameter [10]. These fuzzy control rules for error and change of error can be referred in the table that is shown in Table II:

TABLE II: Table Rules for Error and Change Of Error

(de) \ (e)	NB	NS	ZO	PS	PB
NB	NB	NB	NB	NS	ZO
NS	NB	NB	NS	ZO	PS
ZO	NB	NS	ZO	PS	PB
PS	NS	ZO	PS	PB	PB
PB	ZO	PS	PB	PB	PB

V. SIMULATION RESULTS

Simulation results of this paper is as shown in bellow Figs.13 to 18.

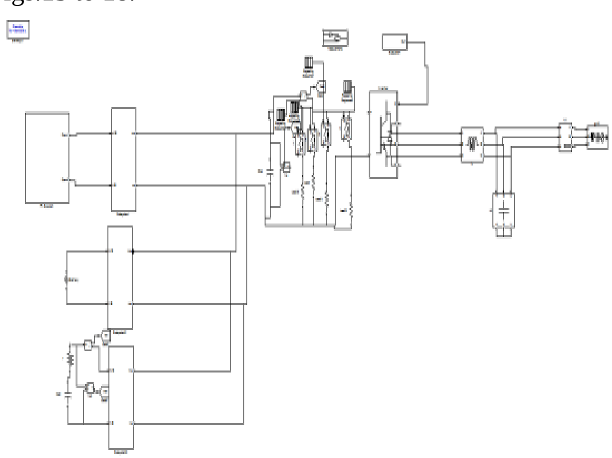

Fig.13.MATLAB/Simulink model of DC microgrid.

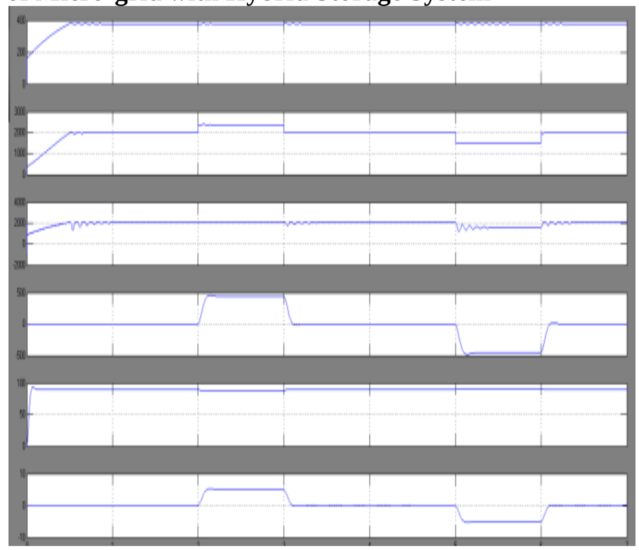

Fig.14. Transition process between Mode Ⅰ and Mode Ⅱ.

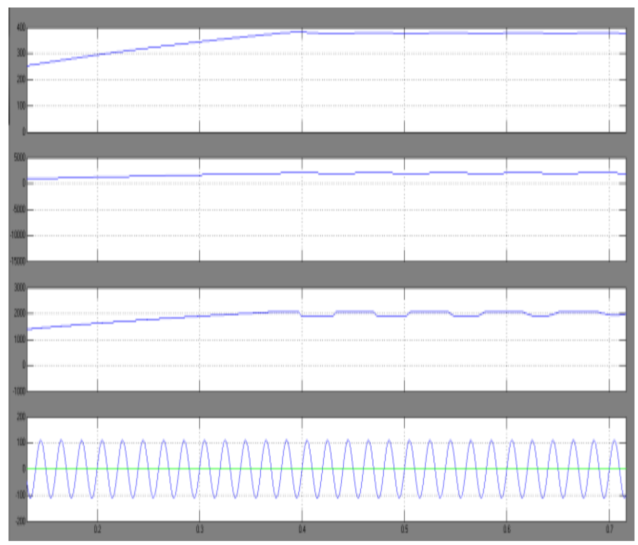

Fig.15.Transition process between Mode Ⅰ and Mode Ⅲ.

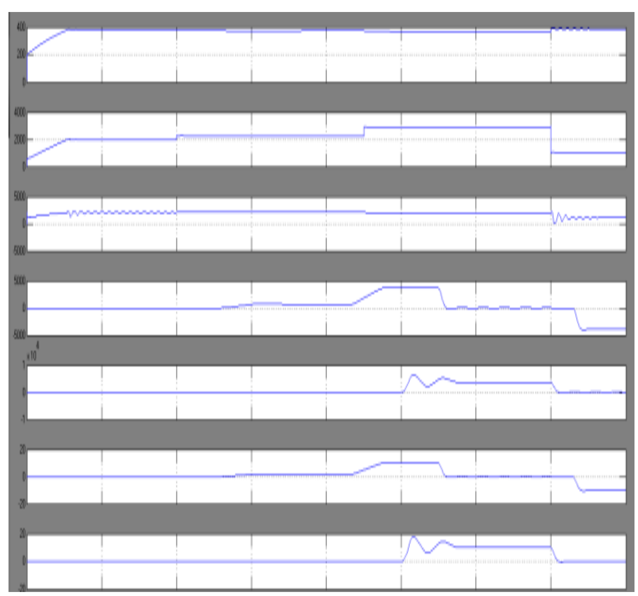

Fig.16.Transition process between Mode Ⅱ and Mode Ⅳ.

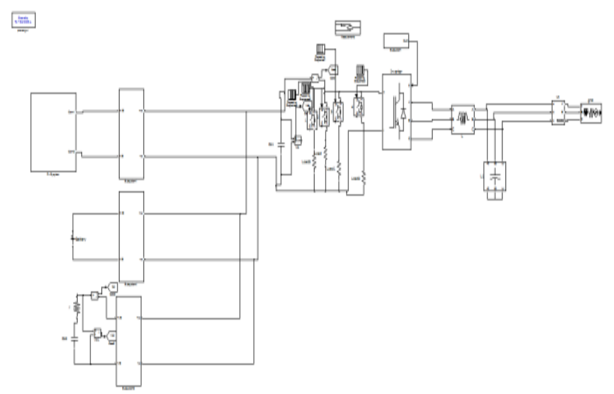

Fig.17. MATLAB/Simulink model of DC microgrid with fuzzy logic controller.

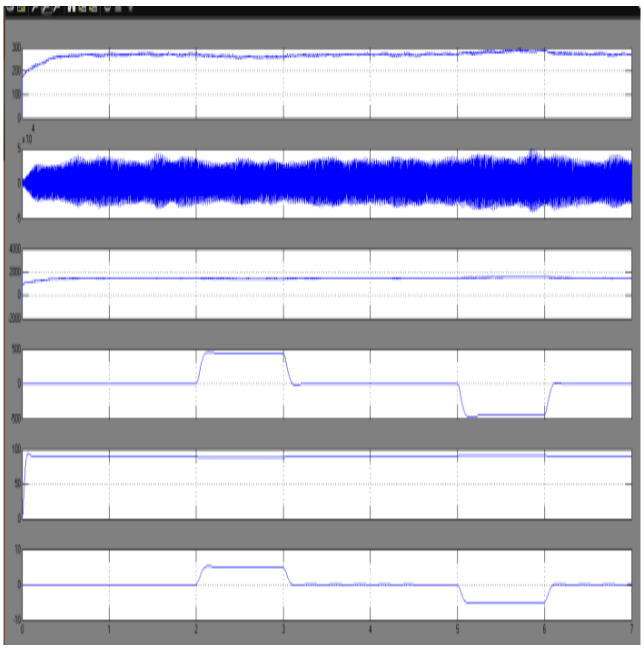

Fig.18. simulation wave form of DC microgrid DC voltage and current, power and source voltage and current with fuzzy logic controller.

VI. CONCLUSION

In the paper, a DC microgrid with hybrid storage system is investigated. A power management strategy for this DC microgrid is proposed, in which the bus voltage is employed as a carrier to represent different operation modes. The hybrid energy storage system in this microgrid that contains two complementary type storage elements---battery and super-capacitor, can enhance the reliability and flexibility of the system based on their special supply logical. Different from the previous studies, the ac grid has a new supply status in the system. The practical feasibility and the effectiveness of the proposed control strategies have been validated by fuzzy logic controller and simulation of MATLAB model.

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