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CONTROL OF FLYWHEEL ENERGY STORAGE SYSTEMS IN ELECTRICAL VEHICLE CHARGING STATIONS

BY
BO SUN

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AALBORG UNIVERSITY
DENMARK

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Bo Sun

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Dissertation submitted

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Assistant PhD supervisors:	Associate Prof. Juan C. Vasquiz, Aalborg University
	Associate Prof. Tomislav Dragicevic, Aalborg University
PhD committee:	Associate Professor Dezso Sera (chairman) Aalborg University
	Lecturer Antonio Griffo The University of Sheffield
	Associate Professor Sergio Busquets-Monge Technical University of Catalonia
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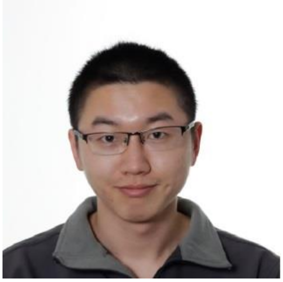

CV

Bo Sun received the B.S. and M.S. degrees in electrical engineering from Harbin Institute of Technology, Harbin, China, in 2011 and 2013, respectively. From 2016.4 to 10, he was a visiting scholar at center for power electronics system (CPES) in Virginia Tech. He is currently working toward the Ph.D. degree in the Department of Energy Technology, Aalborg University, Aalborg, Denmark.

His research interests include power electronics modeling, control, and energy management of distributed power systems based on renewable energy sources and energy storage technologies

ABSTRACT

Growing environmental awareness and strong political impetus have resulted in plug-in electric vehicles (PEV) becoming ever more attractive means of transportation. They are expected to have a significant impact to the overall loading of future distribution networks. Thus, current distribution grids need to be updated in order to accommodate PEV fleets, which are recognized in smart grid (SG) objective. The prevailing concern in that sense is the combined impact of a large number of randomly connected PEVs in the distribution network. On the other hand, continually growing PEVs are likely to impose more specific and acute challenges in short term, it is also expected to expect that grid operators will impose strict demand-response requirements for the operation of charging stations (CS)s.

Accordingly, this PhD project proposed a fast charging station structure which is combined with flywheel energy storage system (FESS). The proposed PhD project supports a corresponding smart control strategy that could be termed “charging station to grid (CS2G)”. It explores the possibility of using a dedicated energy storage system (FESS) within the charging station to alleviate grid and market conditions but not compromise the PEV’s battery charging algorithms or place the daily routine of the PEV owners in jeopardy. The overall control of FCS is divided into two layers organized into a hierarchical structure with the layer being the closest to the physical equipment termed as primary layer and the one on top of it as secondary layer. Control design is hence carried out by following the common principle for management of both large interconnected and small distributed generation (DG) systems.

For the purpose of control optimization and parameter tuning of the primary layer, detailed modeling of grid ac/dc and FESS converters is built and analyzed. |Based on modeling analysis, centralized and distributed control methods are both explored to realize the coordination control of each components in the system. Specially, this project proposes a “dc voltage vs speed” droop strategy for FESS control based on distributed bus signaling (DBS) concept. Then the concept is extended to apply for control of multi-parallel FESS structure. Additionally, an adaptive dc bus voltage control for grid converter is proposed to enhance the system stability and efficiency.

Aiming at alleviating the unexpected conditions in grid-side and providing ancillary services to distributed network, multi-functional controller in secondary control layer which enables four-quadrate operation ability is proposed to cope with different scenarios, such as PEV sudden connection and disconnection, active power compensation (load shifting), reactive power compensation, loss of grid power. Moreover, Centralized and distributed secondary control methods are explored and compared; especially a dynamic consensus control concept is applied into the system for coordinating paralleled grid interfaces and FESS.

Furthermore, stability issues are discussed and analyzed based on proposed control algorithm feature. First, small-signaling model of each component are built to study the dynamic stability of system operating at different stages in details. Due to the switching modes existing in the system, stability of switching system is studied based on common Lyapunov function method when the system switches its operation behavior between two modes.

Finally, a downscaled FCS prototype with FESS is built in the intelligent MG lab, and experiments and hardware-in-loop simulation results are conducted to verify the effectiveness and feasibility with the proposed FCS concept, control schemes, modeling and stability analysis.

DANSK RESUME

Voksende miljøbevidsthed og stærke politiske impulser har resulteret i plug-in elbiler (PEV) bliver stadig mere attraktive transportmidler. De forventes at have en betydelig indvirkning på den samlede belastning af fremtidige distributionsnet. Således skal opdateres for at imødekomme PEV flåder, der er anerkendt i smart grid (SG) målsætning nuværende distributionsnet. Den fremherskende bekymring i den forstand er den kombinerede effekt af et stort antal tilfældigt forbundne PEVs i distributionsnettet. På den anden side, til stadighed voksende PEVs sandsynligvis indføre mere specifikke og akutte udfordringer på kort sigt, er det også forventes at forvente, at netoperatørerne vil pålægge strenge efterspørgsel-respons krav til driften af ladestationer (CS)s.

Derfor foreslog dette ph.d.-projekt en hurtig ladestation struktur, som er kombineret med svinghjul energilagring systemet (FESS). Det foreslåede ph.d.-projektet understøtter en tilsvarende Smart kontrolstrategi, der kunne kaldes "ladestation til gitter (CS2G)". Den undersøger muligheden for at anvende et dedikeret energilagringssystem (FESS) inden ladestationen for at lindre net- og markedsforhold, men ikke kompromittere PEV batteri opladning algoritmer eller placere den daglige rutine af Pev ejere i fare. Den overordnede kontrol med FCS er opdelt i to lag organiseret i en hierarkisk struktur med lag er tættest på det fysiske udstyr betegnes som primære lag og den ene oven på den som sekundær lag. Kontrol design er derfor udføres ved at følge den fælles princip for styring af både store sammenkoblet og små decentral produktion (DG) systemer.

Med henblik på kontrol optimering og parameter tuning af det primære lag, er detaljeret modellering af gitter AC/DC og FESS konvertere bygget og analyseret. Baseret på modellering analyse, er centraliserede og distribuerede bekæmpelsesmetoder både udforskes for at realisere koordineringen kontrol af hver komponent i systemet. Specielt, foreslår dette projekt en "jævnspænding vs hastighed" hænge strategi for FESS kontrol baseret på distribuerede bus signalering (DBS) koncept. Så konceptet er udvidet til at ansøge om kontrol af multi-parallel FESS struktur. Derudover foreslås en adaptiv dc bus spænding kontrol for gitter konverter til at forbedre systemets stabilitet og effektivitet.

Sigter mod at afbøde uventede forhold i grid-side og levere hjælpefunktioner til distribueret netværk, er multi-funktionelle controller i sekundær kontrol lag, som gør det muligt for fire-kvadratiske operation evne foreslået at håndtere forskellige scenarier, såsom PEV pludselig til- og frakobling, aktiv effekt kompensation (load shifting), reaktive effekt kompensation, tab af strømproduktionen. Desuden er centraliserede og distribuerede sekundære kontrolmetoder udforsket og sammenlignet, især en dynamisk konsensus kontrol begreb anvendes i systemet for koordinering af parallel gitter grænseflader og FESS.

Desuden er stabilitetsproblemer diskuteres og analyseres baseret på foreslået kontrol algoritme funktion. Først små-signalering model af hver komponent bygget til at studere dynamiske stabilitet, der opererer på forskellige stadier i detaljer. På grund af de skifte modes eksisterende i systemet, er stabilitet skifte system, undersøgte baseret på fælles Lyapunov-funktion metode, når systemet skifter driften adfærd mellem to tilstande.

Endelig er en nedskaleret FCS prototype med FESS indbygget i den intelligente MG lab, og udføres eksperimenter og hardware-in-loop simulering resultater for at kontrollere effektiviteten og gennemførlighed med den foreslåede FCS konceptet, kontrolordninger, modellering og stabilitet analyse.

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Bo Sun
Oct. 2016

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CHAPTER 1. INTRODUCTION

This chapter demonstrates the background, motivation and scope of the PhD project. It introduces the background and advancement of the electric vehicles (EV) along with the brief description of charging station (CS) industrial standards. Then the integration of the emerging large-scale electric vehicles in the grid utility is discussed and the relevant features and requirements of future smart grid are described, which employs the EVCS to support grid. To provide this support, the energy storage system (ESS) is applied in the CS and corresponding ESS technologies are introduced and compared. Then the contributions of the thesis are presented, followed by the thesis outline and publication list.

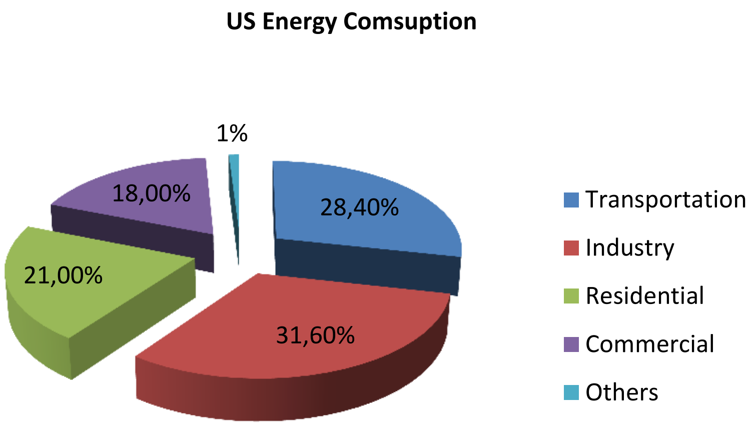
1.1. BACKGROUND

1.1.1. TRANSPORTATION ELECTRIFICATION

Transportation has developed significantly and brought enormous improvement to society and human being's life in last decades, while it also caused growing energy and pollution issues. According to the recent report regarding global energy consumption [1-10], as is shown in Fig.1-1, in the US, transportation sector consumed around 28.4% of total energy, while in the Europe, the transportation sector accounted for 33% of total consumption. Transportation also occupies 25% of total emissions. The depletion of fossil sources and environmental awareness has aroused global attention and motivated the development of the clean energy technology. Transportation electrification is regarded as a promising trend as it is more environmental friendly and efficiency. In vehicles industry, compared with conventional internal combined engine (ICE), electric driven engine is able to increase efficiency 30-40% [2-5].

Now EV can be classified into two main categories, plug-in hybrid EV (PHEV) and plug-in EV (PEV) [4]. The first type uses electric engine in cooperation with ICE, which has advantage of long-time and distance running, while the PEV is driven by purely battery hence there are no polluted gas emissions [4]. Currently, due to the limited number of CS and the relative high price of battery, PHEV is more welcomed by market. However, with the further penetration of EVCS and development of battery technology, PEV has much potential to be dominant in future from viewpoints of environment and efficiency [4].

It is estimated that there will be millions EV on roads in the US by 2020, and Europe EV market is also going to have an explosion in next decade, 5 times more EV are expected to be put into market. Therefore a large amount of EVCS system is in urgent need for adaption to the penetration of fast growing EV fleets [1-5].



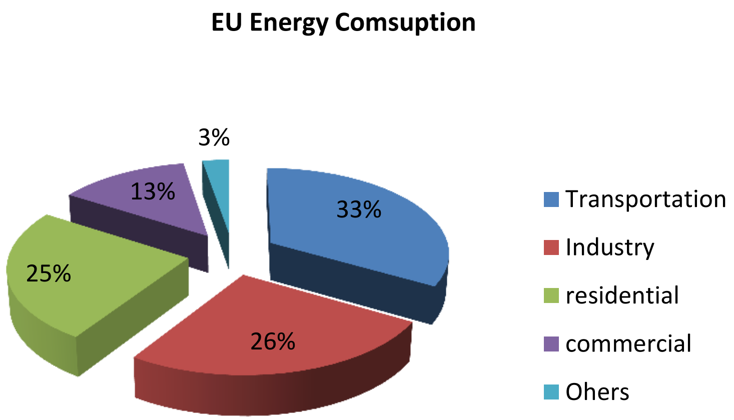


Figure 1-1 Energy Consumption Sector

1.1.2. EVCS SYSTEM

1.1.2.1 EVCS industrial classification

In currently EV industry, the EVCS systems are classified into 3 categories according to the power level, as is shown in Table 1-1. The level I utilizes an on-board charger with maximum power is around 1.9kW, which usually take places at personal home or work place, the charging time of level I is always over 4 hours which is not suitable for long-distance running. Level I charger system is usually combined into vehicles and cost $500–$880 in some reports [11]-[35]; no additional hardware cost is needed but the charging time is also the longest.

Level II is suitable for both private and public cites, with power from 4 to 20 kW and takes around 1-6 hours. At present, Level II is regarded as the main method for EV application due to its voltage level can be easily obtained in most home garages. It is reported that the price for installation of Level II charger is around 3000 $ with a home unit costing 2150$ [4].

Level III charging is the fastest method which takes only less than 1 hour. Similar to the gas station today, it is suitable for commercial CS application located in the highway and city recharging cites. An off-board charger is usually required in the system for ac-dc conversion, and the EV can be directly connected to dc bus. Currently the price for a commercial Level III dc CS is about 30000$. With the increasing number of EV and decreasing cost, Level III CS has potential to be widely installed as part of smart grid interface in future [4].

EVCS Levels	Charger Position	Charging location	Charging Power	Charging Time
I	On board 120-V ac in US 240-V ac in EU	Private house	1.4-1.9kW (10-20A)	4-36 hours
II	On board 240-V ac in US 400-V ac in EU	Public cites	4-20kW (17-80A)	1-6 hours
III	Off board 208 to 600-V ac or dc	Commercial station	Up to 100kW	0.2-1 hours

Table 1-1EVCS classification[4]

1.1.2.2 CS grid interface converter

In the typical CS system as is shown in Fig 1-2, an ac/dc converter is required as grid interface for ac/dc conversion, and then PEV battery is connected to the dc bus by a dc/dc converter [35-50].

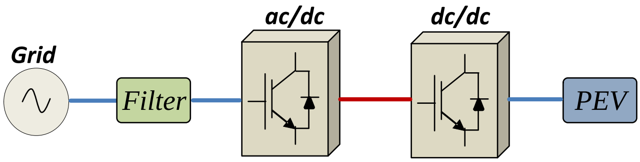


Figure 1-2 A typical CS system

The grid interface converter should be efficient and reliable, the utility current should be ensured with low harmonic distortion. A large number of topologies are applied into the CS application, including single phase and three phase topologies with unidirectional and bidirectional power flow, several examples are shown in Fig 1-3 to 1-6.

Among all the topologies, single phase topologies are usually suitable for Level I and II applications and three phase topologies are typically applied in Level III dc CS applications. Multi-level topologies can achieve a reduction on size and lower stress on devices and are suitable for Level III applications [35]-[50].

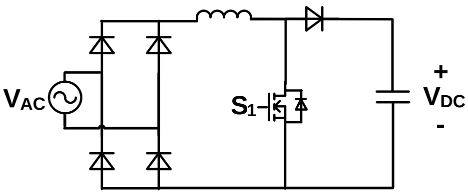


Figure 1-3 Single phase unidirectional ac/dc converter

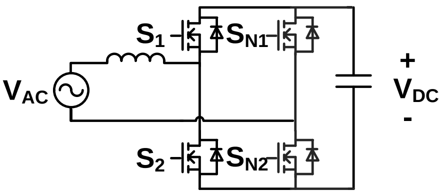


Figure 1-4 Single phase bidirectional bridgeless boost converter

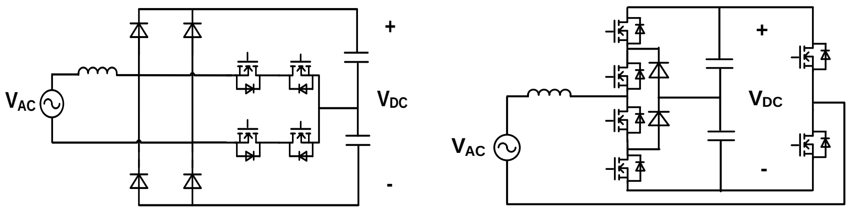


Figure 1-5 Multi-level topology

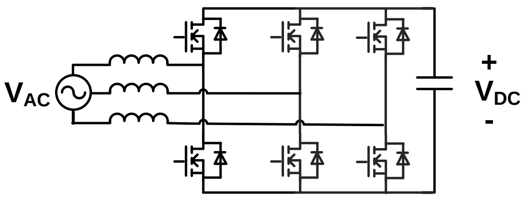


Figure 1-6 Three phase bidirectional boost converter

1.2. INTERGRETION OF EV IN SMART GRID AND MOTIVATION

A large number of EV fleets are anticipated to be connected to the power grid in future, which brings both possibilities and challenges to the future smart grid operator. On one hand, the penetration of EV fleets will cause great burden to the grid, the sudden connection or disconnection of large number of EV may lead to instability of grid network. On the other hand, flexible electricity consumption is recognized as a key prerequisite for achieving the ambitious goal that renewable energy sources (RES) covers much more portion of traditional annual electricity consumption. A variety of methods related with how this flexibility can be achieved is currently under consideration. Among possible ways, EV CS integrations are already recognized as one of the most promising appliances in that sense.

1.2.1. FLEXIBLE SMART GRID AND LOAD CONTROL

In future smart grid, a large number of RES will account for much more proportion of total electricity generation. Due to the instability and variety of renewable energy such as solar and wind, it can be forecasted that more unexpected power unbalance would be introduced to grid utility, especially in some weak or micro grid area mainly powered by RES. Therefore, corresponding ancillary services are required to balance the supply and load. The ancillary services usually includes: peaking shifting, frequency restoration, regulation and load following, energy imbalance

[35]-[42]. Traditionally, such ancillary services are provided from supply-side generator (synchronous machine) by transmitting certain active or reactive power.

However, in recent smart grid concept, it is proposed that such services can be also provided by controlling a large number of local flexible loads, which is called “Load control”. And it is reported that load control have several advantages:

- Fault tolerance. The failure of one supply-side generator has critical influence on the service provision, while a large number of local loads can be controlled more flexible in a distributed manner [39].
- Fast response. Loads can act at once according to the demand from distributed grid operator while supply needs more time to respond [39].
- Loads are located throughout the network, they are able to provide services more precisely [39]
- Flexible load control can well compensate the imbalance caused by intermittence of RES [39]
- Loads are already integrated in the network, and the communication infrastructure is available. The service can be provided once the relevant model and control methods are developed [39].

1.2.2. VEHICLE TO GRID

Among the flexible loads candidates, EVs are regarded as one promising load to provide such services. With the aim of achieving load control capability of EV, a concept termed vehicle to grid (V2G) has been proposed as part of a general smart grid strategy where the aim is to reduce peak loads in the energy system to curb price peaks and to alleviate unwanted states in the grid or in grid components [5-8],[32-37]. It refers to the task whereby the system operator is free to use the energy stored in batteries of all grid connected EV for maintaining the safe operation of the network. However, in its basic form, it implies disruption of prescribed battery charging patterns, hence causing their accelerated degradation. Furthermore, due to unpredictable nature of short-term load and renewable energy fluctuations for which V2G EVs should provide reserve, their recharging time could not be strictly defined which is unacceptable to most vehicle owners [5-8].

1.2.3. CS TO GRID

To overcome the drawback of V2G, the dedicated ESS is installed in the CS system to provide the ancillary services to grid, which can be termed as CS2G. The installation of the ESS can fast respond to alleviate the adverse impact caused by the connection and disconnection of EV, while provide the support to power grid operator. In this way, the EV can be charged safety and not interfered, while the grid can also obtain support and keep stable, the grid operator and EV drivers can both benefit from this concept.

1.3. ENERGY STORAGE SYSTEM

To fulfill the requirements of CS2G concept, the dedicated ESS technology should have the following features:

- The ESS should operate in high efficiency, and be able to afford a lot of frequent charge/discharge cycles before end-of-life, due to the frequent connection and disconnection of EV fleets.
- The ESS should have high power density and moderate energy density.
- The ESS can deliver a large amount of power quickly.

Several main ESS technologies are introduced and compared in the following chapter to obtain the suitable ESS.

1.3.1. BATTERY ENERGY STORAGE SYSTEM (BESS)

BESS is the most commonly used ESS technology, and it includes Lead acid, NiCd/NiMH, Li/ion and other types of batteries [63].

Lead acid has been applied for more than 100 years, which is a rather cheap ESS. However, it has low efficiency and power density, and the health of Lead acid BESS is significantly reduced due to its chemical materials when overcharged or discharged [63].

NiCd battery has been widely used in from 1970s to 1990s, the power density are much increased compared to Lead acid but its life cycles are short, and suffered obvious memory effect [57-63].

NiMH battery came into usage after NiCd between 1990s to 2000s, it improved a lot in the power and energy density, while its capacity is still reduced critically in overcharge conditions [59-63].

Li/ion battery has been commonly used nowadays in phone, computers and EV. The performances are gained dramatically in most aspects, and it can operate in higher current conditions. However the degradation issues still exists in the condition of deep charge and discharge in peak rate. Additionally, the price of the Li/ion battery is also high compared to others [63].

Type	Efficiency (%)	Energy Density (Wh/kg)	Power Density (W/kg)	Cycle life (cycles)
Lead acid	70-80	20-35	25	200-2000
Ni-cd	60-90	40-60	140-180	500-2000
Ni-MH	50-80	60-80	220	<3000
Li-ion	70-85	<50	360	500-2000
EDLC	95	<50	4000	>50000
FLYWHEEL	95	>50	1000-5000	>20000

Table 1-2 ESS[63]

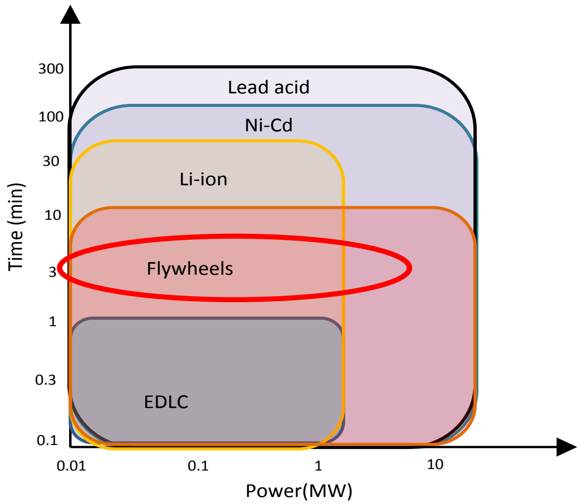


Figure 1-7 ESS Comparison [63]

1.3.2. ELECTROCHEMICAL DOUBLE-LAYER CAPACITORS (EDLCS)

EDLC works in the similar way to traditional capacitor; hence there are no chemical reactions. It has much higher efficiency, power density and energy density. As the energy is stored physically not chemically, it supports deep charge and discharge. However the price of EDLC is relatively higher.

1.3.3. FLYWHEEL ENERGY STORAGE SYSTEM (FESS)

FESS employs a rotating steel or composite mass to achieve energy store. The development of motor drive, power converters and new material advancements have improve the performance of FESS critically [63-78].

FESS is driven by an electric machine, including induction machine, permanent magnetic machine and brushless dc machine. The performance of the machine and bearing also determines the efficiency of the system. According to the rotation speed of the machine, FESS can be typed into low speed and high speed FESS. The higher the speed, the more power density can be achieved [63-78].

One feature of FESS is to provide high power in short time, and it supports a large number of charging/discharging cycles. Compared with BESS, the energy is stored as kinetic energy, so FESS has a longer lifetime and no issues of degradation. Another advantage of FESS is the state of charge (SoC) is directly and only related with speed and inertia, so it can be easily calculated by measuring the speed of motor, while the estimation of BESS SoC is still an unsolved issue in industry. The price of FESS is lower compared with EDLC [63-78].

Taking into account the consideration above, FESS is the most suitable technology for the CS2G applications [63].

1.4. DISTRIBUTED CONTROL

As is shown in Fig. 1-8, the CS2G system concept is presented with installation of FESS. In the local CS, the grid interface converter generates the dc bus and the EV and FESS are connected to the dc bus through power converters. It needs to be mentioned that more FESS can be installed in the system in parallel connection. The CS can also communicate with system level controller to respond to the ancillary services commands from grid operator.

1.4.1. HIERARCHICAL CONTROL STRATEGY

According to the structure of the system, the overall control of CS can be divided into two layers organized into a hierarchical structure with the layer being the closest to the physical equipment termed as primary layer and the one on top of it as secondary layer. Control design is hence carried out by following the common principle for management of both large interconnected and small distributed generation (DG) systems .

The primary level in hierarchical control structure is targeting the control of each power electronics converter in the system, which enables the converter respond to the system dynamics and follows the reference, therefore the bandwidth of this level is required to be fast. In microgrid applications, converters are connected in parallel in ac or dc bus, and the primary level is using droop method to regulate voltage and frequency in ac grid or dc voltage in dc grid. Therefore the power can be shared between paralleled converters. For the purpose of analyzing the system dynamic and parameter tuning, detailed small-signal models of converter are usually needed.

Secondary level control is usually targeting at provide power support in response to the variety in the network, such as unbalance or voltage drop of the bus, the bandwidth of this level is commonly slower than the primary level. Additionally, droop control in primary level usually causes a difference between voltage and frequency and their reference, secondary control is also able to alleviate the poor effect caused by primary control. Secondary control can be implemented in a centralize controller, however the distributed secondary controller are drawing more attraction due to its capability of avoiding single point communication failure.

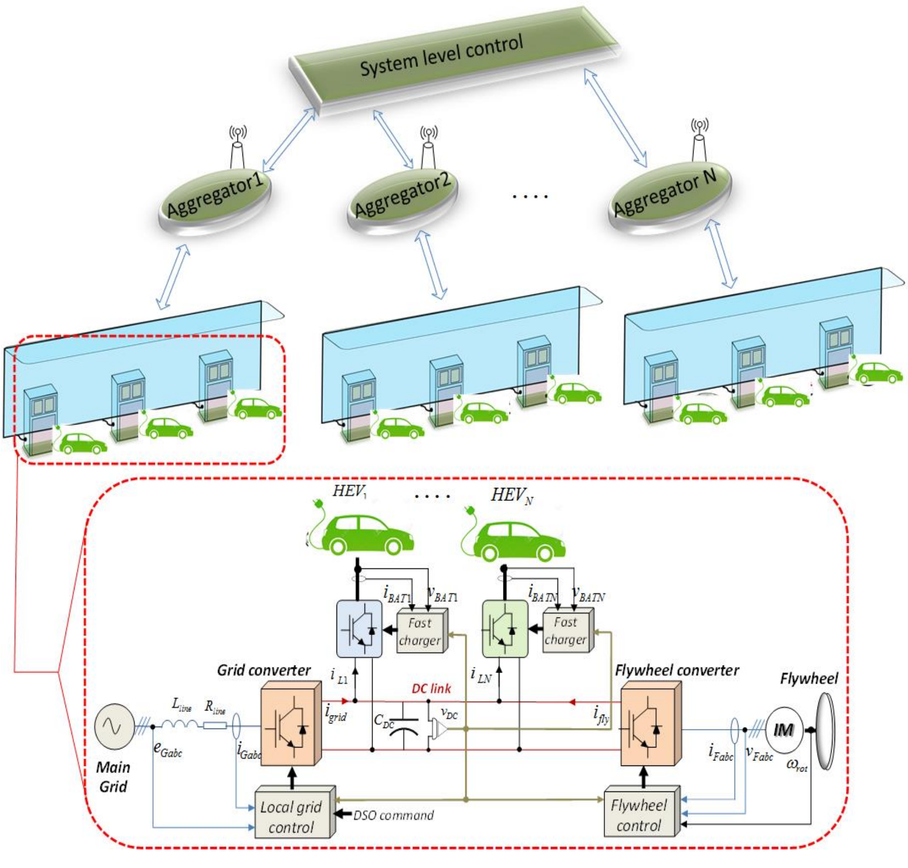


Figure 1-8 CS2G system structure

1.4.2. DISTRIBUTED BUS SIGNALING (DBS)

DBS is a means of controlling a hybrid system in a distributed fashion by employing the dc bus as the communication line [43]. DBS is a low-cost strategy that is implemented among the controllers that are located throughout the system without the dependence on an external communication link [43]. DBS method is commonly applied in ac and dc microgrids which contain several RES and ESS [40]. RES and ESS controllers adapt their status in response to dc or ac bus variety in order to reach power balancing between each component.

1.5. SYSTEM STABILITY

1.5.1. SWITCHED SYSTEM STABILITY

Small signaling model is commonly used to study the dynamic and stability of the system by observing the root locus. In some systems, due to the control strategy employed the system would operate and switch between different conditions. Even though the system is stable in each independent condition by root locus, the switching behavior may still lead to the instability of the system, as is shown in Fig.1-9.

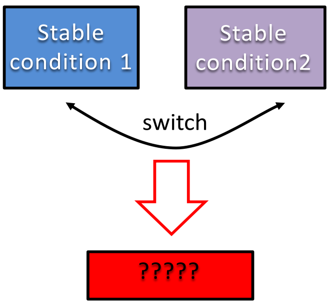


Figure 1-9 Switched System

The common Lyapunov function can be used in the switched system to define the system stability. If there exists a common Lyapunov function which is shared by all the subsystem in a switched system, the switched system is stable [86].

1.5.2. IMPEDANCE STABILITY

In a cascaded converter system, shown in Fig 1-10, the stability of system is not only determined by the good tuning of each single converter, but also influenced by the impedance interaction between them. Middlebrook Criterion can be used to justify the stability of the system, if the output impedance Zo of the source is significantly less than input impedance Zin of the load, the system is stable [88]. In last decades, more critical criterions have been studied and proposed [89]. If the converter can operate in bidirectional power flow, such as FESS in charging and discharging conditions, the impedance interaction will vary according to different power flow direction.

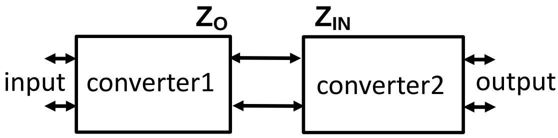


Figure 1-10 Bidirectional Converter System

1.6. CONTRIBUTION OF THE PHD PROJECT

To address the issue discussed above, a CS2G based EVCS structure is proposed by equipping FESS and a hierarchical control strategy is proposed for the purpose of providing the comfortable environment for EV and provision of ancillary services to grid can also be achieved.

To investigate the grid interface converter, a SPWM scheme for a single phase seven-level converter is proposed for simply implementation in DSP and a zero-crossing disturbance elimination method is presented with the Spectrum analysis. A flexible five-level online variable topology-type converter is also proposed for dc bus voltage variable applications, the topology can operate in two-level and multi-level mode according to the dc bus voltage variety to realize the improvement of efficiency. Regarding three phase boost converter control, a dc adaptive controller is proposed to improve the converter efficiency and reliability, and the strategy is finally implemented with SVPWM and DPWM in consideration of the effect of the minimum pulse width.

Regarding the coordinate control of total EV CS system, a DBS based strategy is proposed to realize the power balancing between grid and FESS interface, especially an speed vs dc bus voltage droop method is proposed to control FESS to avoid the digital communication with grid converter and realize the automatically charging and discharging. To provide the grid ancillary services, several scenarios are taken into account, such as EV sudden connection and disconnection, active and reactive support, hysteresis-style load following, loss of grid connection. Targeting each scenario, corresponding control strategy is designed to fulfill the requirement of grid and EV user. Additionally, a consensus algorithm based distributed secondary controller are employed to strengthen the dc bus regulation precisely.

Regarding the system dynamics investigation, a small signal modeling of grid and FESS interface converter are built respectively to analyze the operation in each individual condition. Furthermore, a common Lyapunov function method is studied to analyze the stability of the switched system produced by the relevant control strategy. Moreover, an impedance model of the FESS system is built to study the feature of impedance interaction between grid and FESS converter in charging and discharging condition.

In order to validate feasibility of the proposed control strategy, a lab-scale experimental setup is built in Microgrid Lab. DSPACE is employed to implement primary controller, and an LabVIEW is used to develop an management system to observe the status of CS system and send power support commands. Finally, relevant experiments are carried out to present the validity of the system.

1.7. OBJECTIVE OF THE PHD PROJECT

- Review the current development of EV industry and technology on EV integration in smart grid.
- Investigate the grid interface converter, including single phase, three phase and multilevel topologies.
- Develop averaged and detailed switching simulation models of EV CS, dynamic and degradation models for FESS technology, and deploy the primary control layer.
- Develop secondary control layer that incorporates necessary functionalities to make full use of primary lever equipment and control design.
- Develop overall control strategy to fulfill ancillary services requirements of grid operator
- Develop detailed small signal model and impedance model of system to investigate the stability
- Assemble reduced scale experimental test bench and verify the simultaneous operation of primary and secondary layer control

1.8. THESIS OUTLINE

The rest of the thesis is organized as follows:

The Chapter 2 is the investigation of grid interface converter. Paper 2 and 3 are presented regarding a single phase 7 level converter, modulation, zero-crossing distortion elimination and spectrum analysis. Then paper 4 and 5 are presented regarding a 5-level flexible converter, the operation principle, modulation, loss and THD calculation are demonstrated. Paper 6 presents an adaptive dc voltage controller for three phase boost converter, the effect of minimum pulse width and different modulation are taken into account.

The Chapter 3 introduces the coordinated control for CS system with FESS. Paper 7 demonstrates the EV connection in the CS with paralleled connection, Paper 8 shows the active and reactive power compensation, and a four-quadrant operation of CS is demonstrated. Paper 9 presented a distributed secondary control strategy to increase the precision of the dc voltage regulation.

Chapter 4 analyzes the stability issues, the small signal modeling are presented in paper 1 and paper 7. In paper 10, the stability of the switched system is studied, and in paper 11, the impedance model of FESS is investigated, the impedance interaction shows different performance in charging and discharging power flow.

Chapter 5 gives the conclusion and summaries the conclusion and future work.

CHAPTER 2. GRID INTERFACE CONVERTER INVESTIGATION

2.1. SINGLE PHASE 7-LEVEL CONVERTER STUDY

Paper 2:

A Single Phase Seven-level Grid-connected inverter Based on Three Reference SPWM Strategy

Sun, Bo; Wu, Fengjiang; Dragicevic, Tomislav; Guerrero, Josep M.; Vasquez, Juan

Proceedings of the 2014 IEEE International Energy Conference (ENERGYCON) IEEE Press, 2014. p. 222-227

Paper 3:

Zero-Crossing Disturbance Elimination and Spectrum Analysis of Single-Carrier Seven-Level SPWM

Wu, Fengjiang; Feng, Fan; Duan, Jiandong; Sun, Bo

In: IEEE Transactions on Industrial Electronics, Vol. 62, No. 2, 02.2015, p. 982 - 990.

2.2. ONLINE VARIABLE TOPOLOGY TYPE CONVERTER

Paper 4:

Online Variable Topology-Type Photovoltaic Grid-Connected Inverter

Wu, Fengjiang; Sun, Bo; Duan, Jiandong; Zhao, Ke.

In: IEEE Transactions on Industrial Electronics, Vol. 62, No. 8, 08.2015, p. 4814

Paper 5:

A flexible five-level cascaded H-bridge inverter for photovoltaic gird-connected systems

Sun, Bo; Wu, Fengjiang; Savaghebi, Mehdi; Guerrero, Josep M.

Proceedings of 9th International Conference on Power Electronics and ECCE Asia

2.3. DC VOLTAGE ADAPTIVE OF THREE PHASE BOOST CONVERTER

Paper 6:

Effects and Analysis of Minimum Pulse Width Limitation on Adaptive DC Voltage Control of Grid Converters

Sun, Bo; Trintis, Ionut; Munk-Nielsen, Stig; Guerrero, Josep M.

Submitted to IEEE Transactions on industrial application.
Partly published in Proceedings of the 31st Annual IEEE Applied Power Electronics Conference and Exposition (APEC). IEEE Press, 2016. p. 1376 - 1380.

CHAPTER 3. COORDINATED CONTROL FOR ELECTRIC VEHICLES CHARGING STATION WITH FLYWHEEL ENERGY STORAGE SYSTEM

3.1. CS2G ANCILLARY SERVICE

Paper 1

A Control Algorithm for Electric Vehicle Fast Charging Stations Equipped with Flywheel Energy Storage System

Bo Sun, Tomislav Dragiˇcevi ́c, Francisco D. Freijedo, Juan C. Vasquez, Josep M. Guerrero

In: IEEE Transactions on Power Electronics, Vol. 31, No. 9, 09.2016, p. 6674 - 6685.

Paper 7:

System Distributed Bus Signaling Control for a DC Charging Station with Multi Paralleled Flywheel Energy Storage

Sun, Bo; Dragicevic, Tomislav; Vasquez, Juan Carlos; Guerrero, Josep M.; Savaghebi, Mehdi.

Proceedings of the 2015 6th IEEE Power Electronics, Drives Systems & Technologies Conference (PEDSTC) IEEE Press, 2015. p. 65 - 70.

Paper 8:

Four-Quadrant Bidirectional Operation of Charging Station Upgraded with Flywheel Energy Storage System

Sun, Bo; Dragicevic, Tomislav; Lexuan, Meng; Vasquez, Juan Carlos; Guerrero, Josep M.

Proceedings of 42nd Annual Conference of the IEEE Industrial Electronics Society (IECON’16). IEEE Press, 2016. p. 1-5.

3.2. DISTRIBUTED SECONDARY CONTROL

Paper 9:

Distributed Cooperative Control of Multi Flywheel Energy Storage System for Electrical Vehicle Fast Charging Stations

Sun, Bo; Dragicevic, Tomislav; Vasquez, Juan Carlos; Guerrero, Josep M.

Proceedings of the 2015 17th European Conference on Power Electronics and Applications (EPE'15 ECCE-Europe). IEEE Press, 2015. p. 1-8.

CHAPTER 4. STABILITY ISSUE OF SYSTEM

4.1. SWITCHED SYSTEM STABILITY

Paper 10:

Provision of Flexible Load Control by Multi-Flywheel-Energy-Storage System in Electrical Vehicle Charging Stations

Sun, Bo; Dragicevic, Tomislav; Andrade, Fabio ; Vasquez, Juan Carlos; Guerrero, Josep M.

Proceedings of the 2015 IEEE Power & Energy Society General Meeting. IEEE Press, 2015. p. 1-5.

CHAPTER 5. CONCLUSION REMARKS

5.1. SUMMARY

This thesis focuses on the control and relevant technology of FESS in EV CS application. The thesis begins with review of the development of EV CS system and proposes a CS structure equipped with FESS. This thesis has studied the grid interface converter and makes the improvements on single phase and three phase topology respectively. Then for the purpose of fulfill the requirements of both grid and EV sides, the coordinated control strategies are investigated to adapt different grid scenarios and guarantee the common EV battery charging. Besides, in order to cope with the stability issues, the detailed small signal model are built for better understanding the system dynamics at each operation stage, and the stability of switched system and impedance interaction in bidirectional power flow are also demonstrated. The detailed conclusions are shown in the following aspects.

Grid interface converter study

Single phase seven level converter: the proposed simplified SPWM modulation scheme can be implemented on one DSP chips without FPGA, and relevant improvement on zero-crossing distortion elimination has been shown effectively without compromising the voltage quality through spectrum analysis.

Single phase online variable topology type converter: the proposed topology has been demonstrated that it is suitable for dc bus variable applications. The efficiency is improved by changing the operation modes with the dc bus voltage variety. The experimental results show identical with the loss calculation and THD analysis.

Three phase converter: A dc bus voltage adaptive controller is proposed for three phase boost rectifier, the experimental results considering the minimum pulse width analysis and different PWM gives instruction on the tuning and parameter selection of proposed controller. The approach can benefit to increase the system reliability and efficiency.

Coordinated control for EV CS

A DBS based algorithm is applied in the control and the power balance is achieved, a speed vs droop method is employed for FESS control and overall supervisory control is designed to provide ancillary services to power grid.

Furthermore, a distributed secondary control can further enhance the performance for parallel FESS operation. With the proposed control strategies, the CS can operate in the scenarios including:

- EV connection and disconnection
- Active and reactive power support
- hysteresis-type load following
- Loss of grid connection
- EV connection and disconnection

In all the scenarios, FESS can adjust its operation to provide the support to grid, at the same time, the common charging process of EV is not compromised.

Stability issue

At first detail small signal model is built and the dynamic behavior of the model shows highly identity with the simulation and experimental results at each operation stage; due to the control features, the system would switch to operate between several conditions, common Lyapunov function method is used to illustrate the stability of the switched system.

All the proposed control algorithm and modeling methods have been validated in Matlab/Simulink, DSP+FPGA based controller or dSPACE 1006 based environments.

5.2. FUTURE WORK

Three phase multi-level grid interface

For the type III CS, three phase converter are most suitable due to high power and voltage, several three phase multi-level converter can be explored as grid interface. It could be expected that the power quality, filter size and losses will be improved. Also the multilevel grid interface may also bring the new CS structure with two split dc bus in the system. However, corresponding challenges such as capacitance balancing and cost will also be taken into consideration.

Optimization for parallel FESS control

The control for FESS especially in parallel connection has potential to be optimized, considering the different operation status of FESS. Existed control method such as fuzzy, predictive control and other optimization method can be applied into the paralleled FESS application. A higher efficiency and state of charge balancing are expected as the objectives.

System level control for CS cluster

An energy management system for supervising and control a number of CSs is a necessary in next steps. Relatively, the system level control for balancing the utilizing distributed CS cluster is potential topic. Centralized and distributed control strategy can be investigated for comparison to obtain a reasonable solution.

Hybrid ESS

Considering the cost and some long-term ancillary services, a combination of BESS and FESS sounds attractive and reasonable. FESS can take charge of fast services while BESS can provide long-term services. The challenges are also brought such as how to balance the different ESS technology and maximize the hybrid ESS efficiency.

CHAPTER 6. LITERATURE LIST

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