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DISTRIBUTED CONTROL STRATEGIES APPLIED TO PARALLEL-CONNECTED THREE-PHASE MODULAR UPS INVERTERS

BY
BAOZE WEI

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by

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AALBORG UNIVERSITY
DENMARK

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o   Baoze Wei, Albert Marzàbal, Santi Trujillo, José Pérez, Ruben Ruiz, Josep M. Guerrero, Juan C. Vásquez, "Distributed Secondary Control Strategy for Modular UPS System," *Power Electronics, IEEE Transactions on*, 2017, (submitted).
o   Baoze Wei, Albert Marzàbal, Santi Trujillo, José Pérez, Ruben Ruiz, Josep M. Guerrero, Juan C. Vásquez, "Adaptive virtual impedance control for voltage source inverter based modular UPS system," *Power Electronics, IEEE Transactions on*, 2017, (submitted).
o   Baoze Wei, Josep M. Guerrero, Juan C. Vásquez, Xiaoqiang Guo, "A Circulating Current Suppression Method for Parallel Connected Voltage Source Inverters (VSI) with Common DC and AC Buses," *Industry Applications, IEEE Transactions on*, vol. 53, no. 4, pp: 3758 - 3769, July/August 2017.

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- o Baoze Wei, Josep M. Guerrero, Xiaoqiang Guo, "Cross-circulating current suppression method for parallel three-phase two-level inverters", *International Conference on Consumer Electronics - Berlin (ICCE-Berlin)*, pp: 423 – 427, 6-9 Sept. 2015, Berlin, Germany.
- o Baoze Wei, Josep M. Guerrero, Juan C. Vásquez, Xiaoqiang Guo, "A circulating current suppression method for parallel connected voltage-source-inverters (VSI) with common DC and AC buses," *Energy Conversion Congress and Exposition (ECCE), 2016 IEEE,* pp: 1 - 6, 18-22 Sept. 2016, Milwaukee, WI, USA.
- o Baoze Wei, Xiaoqiang Guo, Josep M. Guerrero. Mehdi Savaghebi, "Leakage current suppression with a novel six-switch photovoltaic grid-connected inverter", *International Symposium on Diagnostics for Electrical Machines, Power Electronics and Drives (SDEMPED)*, pp: 22 - 26, 1-4 Sept. 2015, Guarda, Portugal.
- o Baoze Wei, Josep M. Guerrero, Juan C. Vásquez, Xiaoqiang Guo, "A modified droop control method for parallel-connected current source inverters", *Annual Conference of the IEEE Industrial Electronics Society (IECON)*, pp: 5195 - 5200, 23-26 Oct. 2016, Florence, Italy.
- o Baoze Wei, Josep M. Guerrero, Juan C. Vásquez, "A Power Sharing Method Based on Modified Droop Control for Modular UPS", *Annual Conference of the IEEE Industrial Electronics Society (IECON)*, pp: 1 - 6, 29 Oct. - 1 Nov. 2017, Beijing, China, (accepted).

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- o Xiaoqiang Guo, Baoze Wei, Tieying Zhu, Zhigang Lu, Longcheng Tan, Xiaofeng Sun, Chunjiang Zhang, "Leakage Current Suppression of Three Phase Flying Capacitor PV Inverter with New Carrier Modulation and Logic Function," *Power Electronics, IEEE Transactions on*, 2017, DOI: 10.1109/TPEL.2017.2692753.
- o Wen Wang, L. Yan, X. Zeng, Xin Zhao, Baoze Wei and Josep M. Guerrero, "Control Method of Single-phase Inverter Based Grounding System in Distribution Networks," *2016 IEEE Energy Conversion Congress and Exposition (ECCE)*, Milwaukee, WI, 2016, pp. 1-5.
- o Wenzhao Liu, Xiaoqiang Guo, Giorgio Sulligoi, Yajuan Guan, Zhao, Xin Zhao, Wei, Baoze Wei, Mehdi Savaghebi, Josep M. Guerrero, "Enhanced power quality and minimized peak current control in an inverter based microgrid under unbalanced grid faults," *2016 IEEE Energy Conversion Congress and Exposition (ECCE)*, Milwaukee, WI, 2016, pp. 1-6.
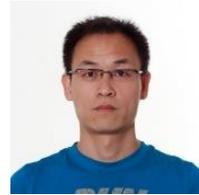
CV

Baoze Wei(S'15) received the B.S. degree in electrical engineering, and the M.S. degree in power electronics and power drives from the Yanshan University, Qinhuangdao, China, in 2010 and 2014, respectively. He is currently working toward the Ph.D. degree in power electronic systems, from the Department of Energy Technology, Aalborg University, Aalborg, Denmark.

His research interests include microgrid, modular power inverters for uninterruptible power system (UPS), photovoltaic generation system, paralleling power converter for renewable generation systems, power quality, as well as the applications of distributed control.

ENGLISH SUMMARY

Uninterruptible Power Supply (UPS) systems are widely applied in many industrial applications, especially for the critical loads that need a power supply of higher reliability and availability, such as distributed generation (DG) systems, high power electric drives, high speed elevators, and data base center that cannot afford power loss.

The modular design concept of UPS appeared at later 1990s. The basic idea is that in a modular UPS, it contains several converter modules working in parallel to feed power to the loads. The modular concept has some advantages, such as increasing the power capacity regardless the rating limited of switching devices, increasing the flexibility, reliability and maintainability of power supply systems to meet the requirements of customers. And some redundant power modules can be put in a modular UPS to ensure high availability: When one power module fails, another one can take over to continue supplying power to loads.

My PhD project is mainly associated with a modular UPS project which is cooperated with a UPS design and research company named Salicru in Barcelona, Spain. This project is named TROY. The aim of this project is to design a drawer type modular UPS using Neutral Point Clamped (NPC) three-phase three-level voltage source frequency converter. Control strategies based on distributed control concept are developed in the thesis for the modular UPS.

Some key issues related with control are considered in the project. First contribution of the thesis to the project is the current limit control under over load or short circuit condition in order to protect the hardware and the safety of human being. If the protection algorithm is under well operation, the other tests can be performed safely.

In a modular UPS, the converter modules work in parallel with each other, one of the other important topics that should be looked at is the average power sharing. Worse power sharing performance will lead to serious circulating current problem and cause different current stress on the switching devices. And in some worse cases, if the circulating current is large enough, it will lead to negative current to threaten the safety of DC link and significantly diminish the lifetime of higher power output modules. So the second contribution of the thesis is to provide two different control methods to enhance average power sharing performance. One is founded on the adaptive virtual impedance; another is based on a modified droop control. And what's more, another circulating current suppression method is also given which is likewise suitable for modular UPS and verified by three-phase two-level inverters in the microgrid laboratory in Aalborg University.

Since in the control diagram, the droop control method is adopted with virtual impedance, the secondary control is implemented for the voltage and frequency recovery. Accordingly, the third contribution of the thesis is to develop an improved distributed secondary control to guarantee a good dynamic performance.

In the thesis, a whole control diagram of a modular UPS (inverter side) will be discussed. The developed control method for current limit, distributed secondary control, average power sharing under different condition are given. And the proposed methods are verified both with simulation and test on a modular UPS platform in Salicru.

Beside the UPS project, a simplified control diagram is presented for the parallel operation of the grid connected current source inverters (CSIs).

Keywords: Uninterruptible power supply, modular, parallel connected, droop control, distributed control, virtual impedance, voltage source inverter; current source inverter, average power sharing.

DANSK RESUME

For at give en mere pålidelig og højere kvalitet til kritiske belastninger spiller uafbrydelige strømforsyninger (UPS'er) en vigtig rolle i mange industrielle og kommercielle applikationer, som f.eks. Distribuerede generationssystemer (DG-systemer), højeffektdrevne drev, højhastighedsløftere og data Base center, der ikke har råd til strøm tab.

Det modulære design koncept for UPS dukkede op senere i 1990'erne. Den grundlæggende idé er, at den i en modulær UPS indeholder flere konverteringsmoduler, der arbejder parallelt for at tilføre strøm til belastningerne. Modulkonceptet har nogle fordele, som for eksempel at øge strømkapaciteten, uanset hvilken begrænsning der er begrænset af omskiftere, hvilket øger fleksibiliteten, pålideligheden og vedligeholdelsen af strømforsyningssystemerne for at imødekomme kundernes krav. Og nogle overflødige strømmoduler kan placeres i en modulopbygget UPS for at sikre høj tilgængelighed: Når et strømmodul fejler, kan en anden overtage for at fortsætte med at forsyne strøm til belastninger.

Mit PhD-projekt er hovedsageligt forbundet med et modulært UPS-projekt, der samarbejdes med et UPS-design- og forskningsfirma ved navn Salicru i Barcelona, Spanien. Dette projekt hedder TROY. Formålet med dette projekt er at designe en UPS-type af skuffetype ved brug af Neutral Point Clamped (NPC) trefaset tre-niveau spændingskilde frekvensomformer. Kontrolstrategier baseret på distribueret styringskoncept udvikles i afhandlingen for den modulære UPS.

Nogle vigtige spørgsmål relateret til kontrol overvejes i projektet. Projektets første bidrag til projektet er den nuværende grænsekontrol under overbelastning eller kortslutningstilstand for at beskytte hardware og sikkerhed for mennesket. Hvis beskyttelsesalgoritmen er under drift, kan de andre test udføres sikkert.

I en modulær UPS arbejder konvertermodulerne parallelt med hinanden. Et af de andre vigtige emner, der bør ses, er den gennemsnitlige strømdeling. Sværere strømfordelingspræstationer vil medføre alvorlige kredsløbsproblemer og forårsage forskellig strømspænding på omskifterenhederne. Og i nogle værre tilfælde, hvis cirkulationsstrømmen er stor nok, vil det føre til, at negativ strøm truer sikkerheden ved DC-forbindelsen og reducerer levetiden for de højere effektudgangsmoduler betydeligt. Så det andet bidrag fra afhandlingen er at give to forskellige kontrolmetoder til forbedring af den gennemsnitlige effektdelingsydelse. Den ene er baseret på den adaptive virtuelle impedans; En anden er baseret på en modificeret droop kontrol. Og derudover gives der også en anden strømningsundertrykkelsesmetode, som også er velegnet til modulopbygget UPS og verificeret af trefaset to-niveau-omformere i mikrogridlaboratoriet på Aalborg Universitet.

Da i den virtuelle impedans er anvendt i kontrol diagrammet, er der brug for en sekundær styring for at genoprette spændingen og frekvensen. Tesens tredje bidrag er at udvikle en forbedret distribueret sekundær kontrol for at sikre en god dynamisk ydeevne.

I afhandlingen vil der blive diskuteret et hel kontroldiagram over en modulær UPS (inverter side). Den udviklede kontrolmetode for nuværende grænse, distribueret sekundær kontrol, gennemsnitlig strømdeling under forskellige betingelser gives. Og de foreslåede metoder er verificeret både med simulering og test på en modulær UPS platform i Salicru.

Ved siden af UPS-projektet præsenteres en kontrolmetode for netforbundet strømkildeomformer for at forenkle kontroldiagrammet for den parallelle arbejdstilstand.

Nøgleord: Uafbrydelig strømforsyning, modulær, parallelt tilsluttet, droop control, distribueret kontrol, virtuel impedans, spændingskilde inverter; Nuværende kilde inverter, gennemsnitlig strømdeling.

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CHAPTER 1. INTRODUCTION

1.1. UNINTERRUPTIBLE POWER SUPPLY

The power quality and reliability is a major concern for an electric power system. Especially the critical loads, such as telecommunication systems, network servers, database system, and medical equipment, require a power supply of higher reliability and capability. Unexpected failures of the power supply system will lead to serious accidents, not only to the equipment but also to the human beings, like the patients in the hospital [1-5].

In order to provide clean and reliable power to these kind of critical loads, an Uninterruptible Power Supply (UPS) system is often equipped. A UPS is an electrical power device that can feed power to the loads under emergency, such as the failure of the input power source [1]. Based on standard IEC62040-3 of International Electrotechnical Commission, there are mainly three kinds of UPS systems, online UPS, line interactive UPS and off line UPS [3-4]. Compared with the other two kinds of UPS, the online UPS has a major characteristic of isolation from grid to the load [2], [4]. The capability of providing more conditioned power makes it more and more popular in the industrial applications [1], [2-6].

1.1.1. THREE TYPES OF UPS TECHNOLOGY

1.1.1.1 Online UPS System

A typical structure of an online UPS is shown in Fig.1. It mainly consists an AC/DC rectifier, a DC/AC inverter and a backup power supply system, normally a battery pack is equipped as the energy storage system. It is also known as the online double conversion UPS [6].

Typically, it has three different working states: online double conversion state, back up state and bypass state. Normally, it will work in online double conversion state unless serious problems happen to the grid or the UPS itself.

Under online double conversion state, the power fed to the load will always pass through the double converters. Because the total regeneration of the AC power, the output voltage and frequency can be controlled precisely to provide stable output power. So the influence of the grid voltage fluctuation or the harmonics in it will be suppressed by the control of the double converters. The decoupling capability of the grid and load makes it work with wider range of input voltage than the other two kinds of UPS [6].

When serious problem happens to the grid or the AC/DC converter fails to get power from the grid, the UPS will switch to the back up state. At this moment, the AC/DC converter will be shut down, the DC/AC converter will be supplied by the energy storage system. The UPS will continue feed power to the load until the battery bank is out of power.

If malfunction occurs in the UPS, the UPS should be bypassed by the static bypass switch. The load will be supplied by the grid until the problem is resolved [6].
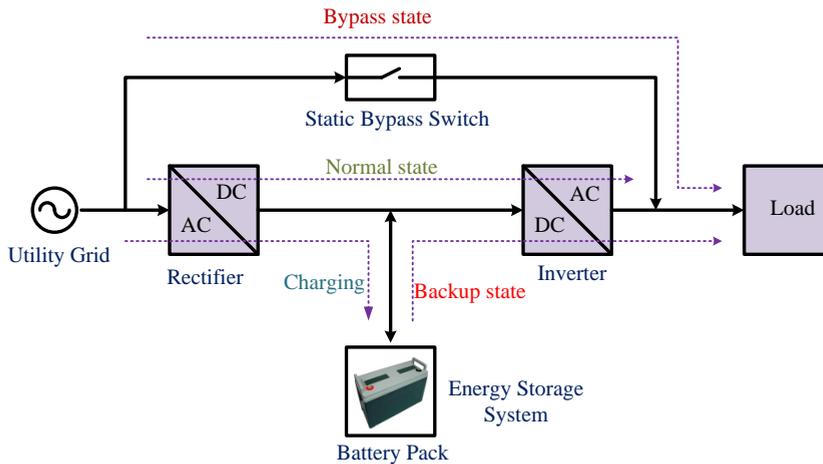
Figure 1- 1 Structure of the online double conversion UPS.

1.1.1.2 Line-interactive UPS System

Figure 1-2 depicts a typical structure of the line-interactive UPS system, it operates in a similar way as an offline standby UPS, the difference is that the converter has two working modes: AC/DC rectifier to charge the battery, DC/AC inverter to feed power to the load. There is usually a power interface between the grid and the load, which is used to filter the ac power and suppress the spikes in the voltage, and to provide a sufficient quality of power for well operation. It is often built with a passive filter and a tap-changing transformer [7].

The utility grid will charge the battery through the rectifier mode to keep the battery fully charged while the grid power is provided. An advance feature is that normally the rated power of the charging mode is 10% or less of the UPS power rating, which can keep the converter running in a cool condition. It is positive to prolong the lifetime of the UPS system. Once a problem happens to the grid, the transfer switch will open to cutoff the grid to the load, and the inverter will be turned on at the same time. The UPS will be bypassed once the grid power is recovered.

Although there are some good features of the line-interactive UPS. But it has a limited ability to keep a stable output power supply with a grid voltage of large swing. Then the UPS will switch to battery mode frequently to provide a sufficient power quality, which will influence the lifetime of the battery [7].
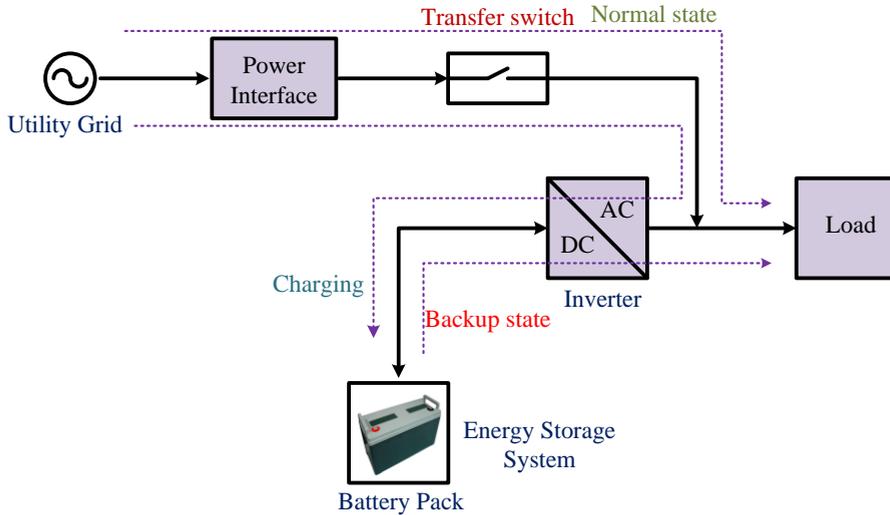
Figure 1- 2 Structure of a line-interactive UPS system.

1.1.1.3 Offline UPS System
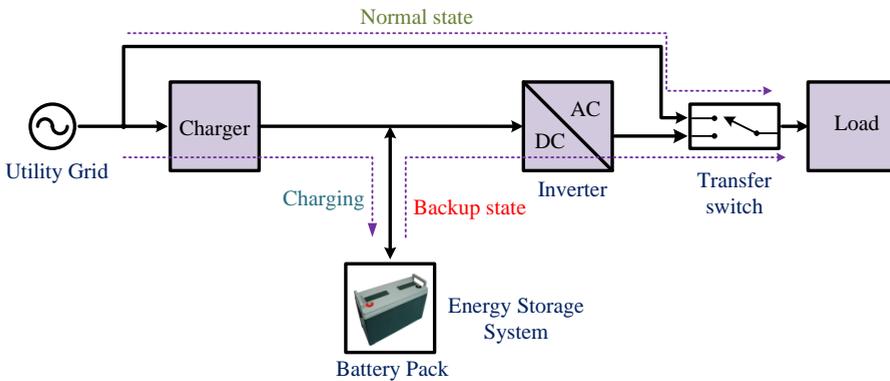
Figure 1- 3 Structure of an offline UPS system.

Like the line-interactive UPS, with an offline UPS, the loads are supplied by the utility grid under normal working condition. There is a standalone charger to keep the battery fully charged. The power supply will switch from the grid to the battery through the inverter if the grid fails to provide a power of sufficient quality. Once the grid power

is available, it will transfer back to the grid. It normally takes 4-10ms for the transfer between normal and backup states. Among the three different types of UPS systems, the structure of the offline UPS is the most simple but with the lowest cost of fabrication [7], [8].

1.1.2. MODULAR UPS CONCEPT

The modular design concept of UPS appeared at later 1990s [2]. Now the modular UPS products can be found in many companies, like ABB, Delta, AEG power solutions, STATRON, etc.

The conventional centralized UPS system is mounted in a large cabinet, which is very complicated for installation and maintenance service. Concerning the power reliability of suppling critical loads, there is usually one more of this large UPS cabinet for backup system. The system can be switched to the backup UPS when the primary one fails to provide power. Thus, it is difficult to realize capacity expansion for a centralized UPS system. A time-consuming and expensive process that in most cases requires the scheduling of downtime [7], [8].

The modular UPS becomes popular for the ability of avoiding interruption of operation during maintenance work or replacement. With distributed control architecture, it conquers the drawback of single point of failure of the centralized control and with less time-consuming for maintenance and installation. Each module in the system contains all the components that required for full operation including the AC/DC and DC/AC converters, control board, display for monitoring and control, static bypass switch and battery back mode transfer switch [7], [8].

Normally, at least one extra power module will be mounted in a modular UPS for redundancy beyond the power needed of the critical loads. When any single module fails to feed power or otherwise needs maintenance, it can be removed from the system while the system continue operations with full double conversion mode without interruptions and no needs to transfer to bypass mode [7], [8].

What is more, as the growth of the power needed for a critical load, more power modules can be simply housed in the cabinet to reach the rated power easily, with no need to change the entire system as the conventional centralized system [7], [8].

As a conclusion about the features and advantages of a modular UPS, easier installation, maximizing flexibility and reliability while reducing the cost of ownership, more availability during maintenance or replacement of broken modules; it makes easier to configure the architecture of the system. Compared with the conventional centralized UPS, the modular UPS has some advantages, such as increasing the power capacity regardless the rating limited of switching devices, increasing the flexibility, reliability and maintainability of power supply systems to

meet the requirements of customers. And some redundant power modules can be put in a modular UPS to ensure high availability which is called N+X configuration. When one power module fails, a standby module can take over the work to continue supply power to load. And the modular concept makes it possible of fast design and manufacture of UPS with specified rated power [2], [3], [7], [8]. Figure 1-4 shows a modular UPS product from ABB.

Figure 1- 4 A modular UPS product of ABB.

1.1.3. THE CHALLENGES FOR THE CONTROL OF A MODULAR UPS

As for now, modularity is rapidly becoming the standard for UPS. Advanced control strategies are needed to ensure the availability and reliability of the modular UPS. Some of the technical challenges for the control are listed below.

- Over load and short circuit protection.
  For the requirement of higher reliability and availability, control strategies must consider the over load and short circuit condition to ensure the safety of the load and the UPS itself.
- Voltage and frequency recovery.
  The deviation of voltage and frequency sometimes happens when the load is changing or because of the characteristic of the control itself, like the droop and virtual impedance control. So the voltage and frequency recovery is an important issue to be considered in the control strategy.

- Average power sharing among the parallel modules.
  The maintenance and service are the essential cases for a product. Compared with the conventional UPS, the modular UPS is more efficient and convenient to repair or replace the broken modules. But for a simplified repairs and maintenance, extending the life time of a product is important. For a modular UPS, in order to balance the life time of different modules, the performance of average power sharing among them should be obtained with the control strategy.

- DC link protection. There is a DC link between the AC/DC converter and the DC/AC converter. For a unidirectional UPS, the DC link cannot absorb power from the DC/AC converter. So the negative active power flowing form the ac side to the DC link through the inverter is totally forbidden. A stable DC link voltage is needed for the well operation of the UPS system. The safety of the DC link should be considered. The fault from the inverter side may cause negative active power flowing from the ac side to the DC link, which will lead to a voltage boost of the DC link. However, with a reliable average active power sharing control along with a backup overvoltage protection logic, it can be sure there is no current flowing from one module to another, the safety can be guaranteed.

1.2. THE DISTRIBUTED CONTROL THEORY

It is necessary to briefly introduce the control strategies that commonly used for the power systems during the past decades, they are mainly classified into centralized control, decentralized control, master slave and distributed control strategies [9], [10].

The centralized control strategy was often adopted for the control of a system in large scale from 1950s, which can be implemented to the control of a distributed generation (DG) system [9], [10]. All the data that needed in the control loops of a centralized control scheme will be sent to the central control unit, the control logic or command is implemented in the central controller and distributed to the subsystems through the communication link [9]. The single point of failure is the main drawback of this kind of control algorithm, and it needs a high bandwidth transmission line to deal with a large amount of data [8]-[10]

Different from the centralized control, there is no need of transfer data to a central controller in the decentralized control algorithm by just using local information for the controllers [9], [10]. But without any data sharing among the DGs or the power modules in a modular UPS, the reliability could not be guaranteed [10]. The feature of wireless makes droop popular for the decentralized control. And the droop is more convenient to realize modular design of a UPS system or the decentralized control of DGs in a microgrid. However, it suffers from the disadvantages of slow dynamic response and lower stability for abandoning of data sharing [9], [10].

The master slave control algorithm is also popular for the control of parallel-connected converters, which is known as quasi-decentralized control. For a power system using the master slave control, one of the converter operates as the master to generate current references for the slave converters. The reliability cannot be guaranteed since the failure of the master converter will influence the performance of the entire system [10].

In order to conquer the drawbacks of the existing control strategies discussed previously, but combine the advantages, the distributed control theory is proposed and treated as a tradeoff among the decentralized and the centralized control [8]-[10], which is attracted more and more study for the control of large-scale power systems, such as the microgrids, windfarms, and so on [11]-[17]. Compared with the decentralized control, it can improve the reliability by data exchanging among the DGs or converters in the control. Nevertheless, unlike the centralized control, a lower-bandwidth communication link is required for a distributed control strategy [9], [10].

For the modular UPS studied in this thesis, it contains several converter modules in one cabinet. It can be seen as a microgrid with multi DGs inside. All of the control strategies mentioned above can be applied to a modular UPS. However, the disadvantages of the centralized control and the master-slave control make it no meaningful of building a modular UPS. It will lose the significance of "modular". And for the decentralized control, the reliability and performance cannot be guaranteed since there is no information exchange among the modules. The most suitable control strategy for a modular UPS is the distributed control. On one hand, it conquers the disadvantage of single point failure of centralized control; on another hand, it improves the reliability of the system based on local communication.

So in this thesis, the developed control strategies for the modular UPS are using the theory of distributed control. Such as the improved distributed secondary control and the adaptive virtual impedance control methods are based on the data sharing through a CAN bus communication link. For a UPS system, the structures of the centralized and distributed control are shown in Figure 1-5. The design of the modular UPS studied in this thesis is based on the distributed control structure.

For such a system, proper control methods should be developed; the hierarchical control strategy attracted more attention in the past few years for the control of DGs in a microgrid (MG) or the parallel operation of converters in an industrial application. In the hierarchical control, it mainly contains three levels, which are named primary, secondary, and the tertiary control levels [18-21]. The primary control level is adopted to maintain the stability of the voltage and frequency in a system. The droop algorithm [22-26] is widely adopted for the primary level. It normally consists of the droop control loop and the fundamental current and voltage control loops [19]. When the voltage or frequency of the UPS or an MG system cannot be regulated to the nominal value under the control of the primary level, the deviations will be eliminated through

a secondary control level [19], [21], [27], [28]. And for some instance, the secondary control is very important for voltage balance and average power sharing performance [26], [29]. Finally, the tertiary control is responsible for power management concerning the economic optimization of a system [19], [21].

In this thesis, the developed distributed control theory based strategies are mainly implemented in the primary and the secondary control level.

(a)

(b)
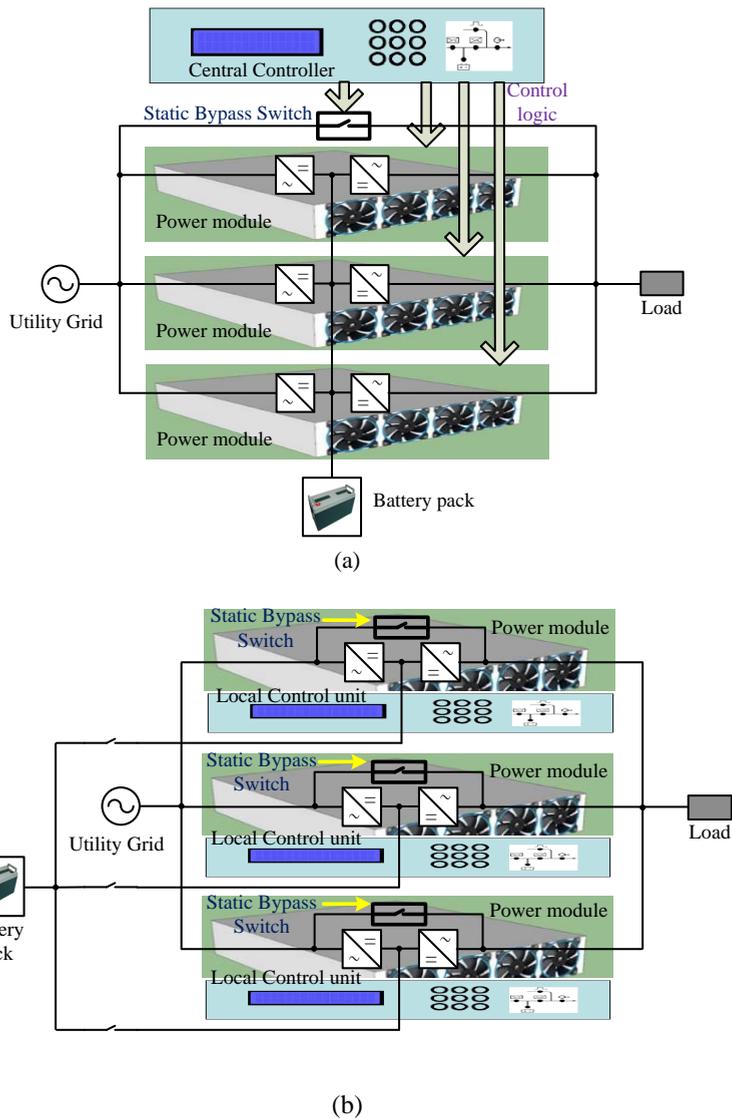
Figure 1- 5 Structure of the centralized control and distributed control.

1.3. THE MODULAR UPS STUDIED IN SALICRU S/A

The UPS project is cooperated with UPS design and manufacture company named Salicru in Barcelona, Spain. The name of the project is given as TROY. A prototype of the modular UPS is shown in Figure 1-6. It is a drawer type modular UPS. Each module is flexible, normally, it will work with three phases, but it also allows single phase or two phases working mode based on the demand of the consumer. Each modules contains their own AC/DC and DC/AC converter, a DSP control board, bypass switch and a CAN bus for data sharing. Obviously, one can notice that, with the modular design concept, it is more flexible for UPS building and maintenance work.

The DC/AC converter used for the UPS is the Neutral Point Clamped (NPC) three-level three-phase topology shown in Figure 1-7. Compared with the two-level converter of the same rated power, it has some advantages such as lower voltage stress on the power switch, smaller THD in the output voltage. Therefore, the NPC topology is more suitable for a higher power industrial application. The rated power of a single module is 40kVA; the target of the project is to have up to 5 modules in one cabinet along with one standby module.

A software called Odyssey Explorer is developed as a control interface running on the computer. Through the control interface, one can control the power modules running in open loop or close loop from single phase to there-phase, and the operation of the relays. It is very convenient to do the test of verifying the effectiveness of the proposed control.

As discussed in the previous section, the droop control is often adopted for the primary control for the features of expandability and modularity [30]-[32]. In order to have a similar performance with the centralized control, but conquer the drawbacks of it, the distributed control concept relies on a low bandwidth communication link is adopted in the thesis. The distributed concept is mainly applied in the secondary control level for the voltage and frequency sharing [33]-[42].

The distributed control concept helps to improve the reliability but with less communication network, so the control diagram proposed in the thesis for the modular UPS is based on the distributed control theory. A CAN bus is used for data exchange among the parallel modules. It is a low bandwidth communication link. The data exchange in the control of the modular UPS is updated every 20ms, a fundamental cycle. The configuration of the CAN bus is shown in Table I.

Figure 1-8 shows a simplified control diagram. In the control diagram, it mainly contains the primary droop control, the distributed secondary control, the PLL, and the voltage and current control loops. Along with basic control scheme, some other control methods are added to obtain a higher reliability and performance, like the

improved distributed secondary control, the current limit strategy for over load and short circuit protection, and the adaptive virtual impedance control. In the following sections, the proposed or improved control strategies for the modular UPS will be presented in detail.
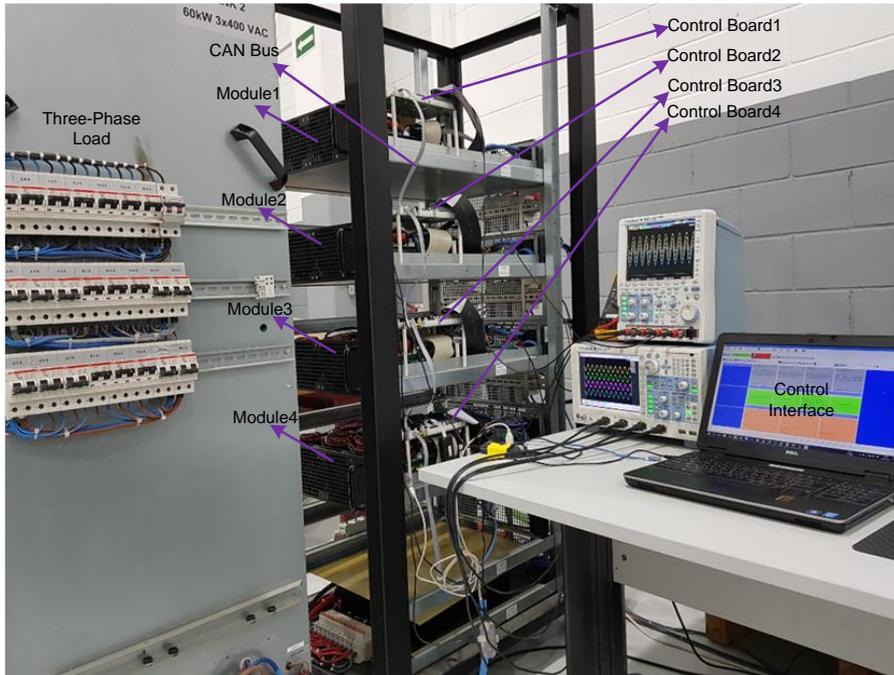
Figure 1- 6 Modular UPS platform in Salicru.
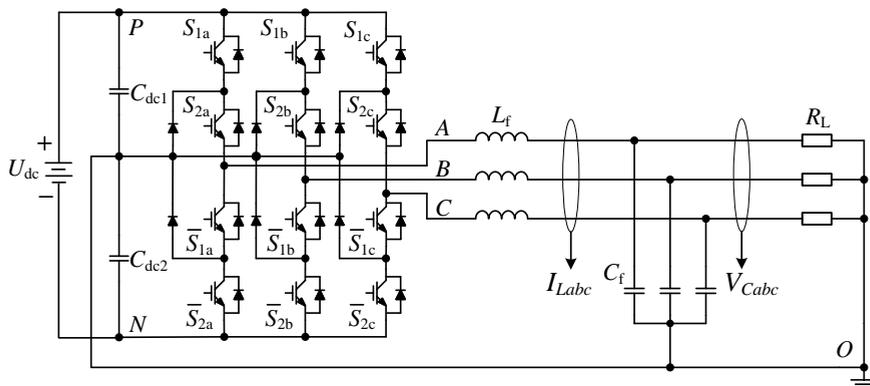
Figure 1- 7 Topology of the NPC inverter.
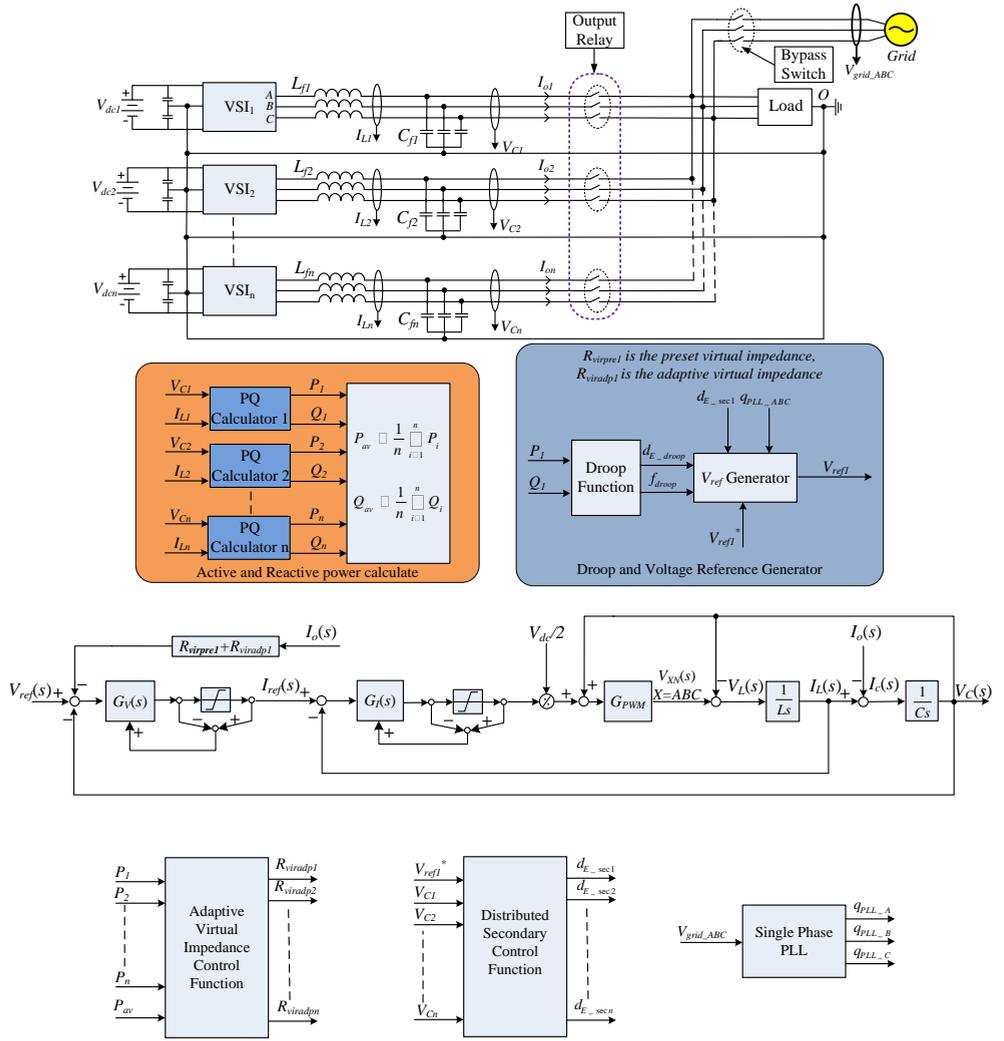
Figure 1- 6 A simplified control diagram of the modular UPS.

Table I Parameters of CAN bus

BitRate	Frame length	Frame Rate	Frame time	1 data sending time
500kbps	44 (bits control) + 64 (bit data) = 108 bits	500kbps / 108bits = 4629,629	1 / 4629.629 = 216us	216us

1.4. CURRENT LIMIT CONTROL UNDER OVER LOAD AND SHORT CIRCUIT CONDITION

One converter module in a modular UPS consists several semiconductor switches, such as IGBTs. Based on the research, about 38% of the failure of the converters in a power system is because of the fault of the power switches [43]. So the power converter based industrial applications, especially for the high power system, high reliability is one of the most important issue that should be considered [43].

Therefore, the fault detection and protection system occupies an important position in the UPS. Switching devices can be broken under over current condition [44]. And the typical reason of the destruction of the power switches is the overheat of the chip. This kind of failure will happen if the inverter is working under over load condition or a short circuit fault. For the requirement of high reliability of a power system, the short circuit is one of the most critical situation to be considered [45-47]. This thesis will focus on the over load and short circuit protection of the UPS.

A traditional solution for over current solution is to shut down the converter or cutoff the transmission line as soon as possible, like the primary hardware protection and the driver circuit based hardware protection.

For the primary hardware protection, overcurrent fuses [47], relays [48-52], or breakers perform one of the most commonly-used in power systems and are used as backup protection to isolate the inverter from the transmission lines [53-57]. However, the breaker cannot provide a fast response for the primary protection in many cases [58]. Using the relays will lead to the chattering of contacts at high currents. Lower time delay fuses are non-resettable which means the converter requires a manual replacement each time the fuse is blown. But the auto-resettable fuses have a longer time delay before activation [59].

Another kind of hardware protection strategy is based on the characteristic of the switching devices under different working mode [60-68]. Typically, there will be a detection and protection logic circuit integrated into the driver circuit to turn-off the switching devices under fault condition.

But for a UPS system, normally it is used to supply the critical loads, which require higher reliability and availability. Sometimes the UPS should remain connected even under overload or short circuit condition, so a control strategy is required to limit the output current to a preset constant value [69-73]. With an effective over current control method, the system can return to normal operation as soon as the fault is cleared [57], [74], [75].

There are mainly two kinds of solutions for the overcurrent protection: hardware based and software based [72]. There are mainly two kinds of faults will cause over

current: fault-under-load (FUL) (at output phases) or hard switching fault (HSF) which will cause high collector currents [44], [69]. Normally, if HSF exists, the short circuit already happens at the load side before turning on the power switches. Once running the converter under such an HSF, the load current will increase the same rate as a normal switch-on operation. However, the FUL short circuit happens when the converter is already running. So typically, a larger current spike will exist in the FUL than the HSF [69], [76], [77].

The HSF happens mainly because of the failure of the dead time, the problem of the PWM modulation or the problem of the driver circuit. This thesis will focus on the protection under the condition of the FUL.

For a fast protection of the switching devices by avoiding overheat, a quick detection of overcurrent and short circuit scheme is necessary [69]. Different kinds of schemes of IGBT protection under short circuit condition were proposed [43], [44]. Since when short circuit happens, normally the switching devices are damaged in a very shot time by overheating, it is difficult to provide a fast protection through the control. So hardware based method for overcurrent detection and protection are commonly developed [44].

In this thesis, an algorism based over current protection method for power inverters is proposed which is suitable for both over load and short circuit conditions at output phases. Compared with the abovementioned protection method, it doesn't need auxiliary circuit or changing of control logic. Therefore, it is suitable for high power application design to decrease the cost and increase the reliability as well. The effectiveness and reliability are verified by both simulation and experiments on a UPS platform.

The proposed control diagram is shown in Figure1-9. In the proposed control scheme, in order to have a fast and accurate current limit under overload or short circuit conditions, if the output current is bigger than the limited value, the integral part output of the PR controller in current control loop will be reset to zero. With the coordination of the capacitor voltage feedforward and the quick reset operation of the integral part of the current controller, the output current will be limited to the preset constant value immediately, which will help keeping the UPS operating in the safe condition. Once the fault is cleared, the UPS can return to the normal working condition quickly without powering off the entire system within a preset time window if over current happens, which will improve the availability and reliability when suppling a critical load. By the feedforward of the capacitor voltage, over current happens, especially under short circuit condition, one can suppress the influence of the capacitor voltage to the output current. And the reset of the resonate part of the current controller can reduce the modulation waveform quickly to the limited value to avoid the inverter going into uncontrollable condition or the overshoot of the current.
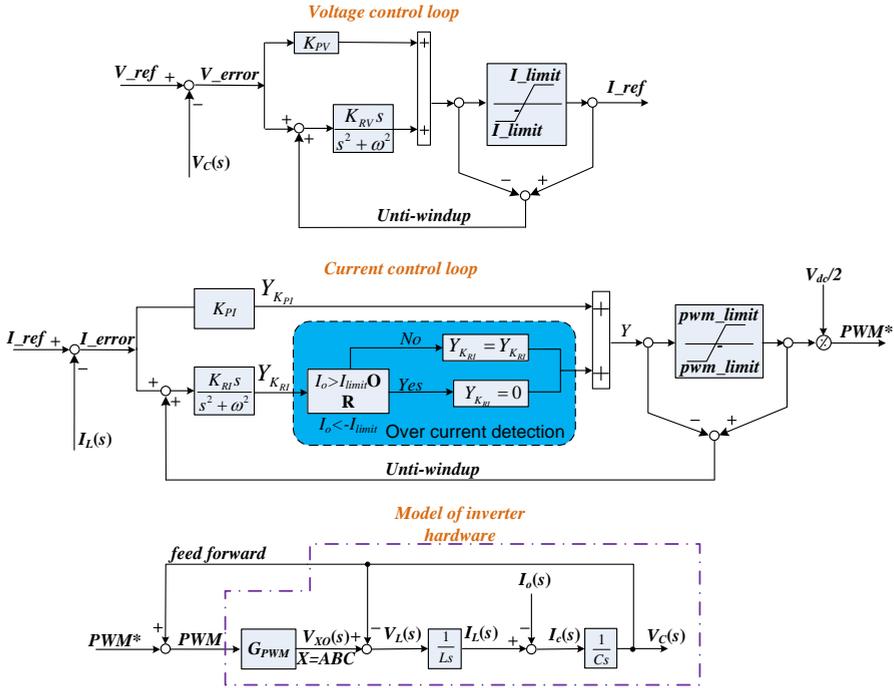
Figure 1- 7 Control diagram of over load and short circuit protection.

1.5. THE IMPROVED DISTRIBUTED SECONDARY CONTROL

In the general distributed secondary control, the voltage and frequency are the most common information that needed to be shared among the parallel DGs or converters, each controller will collect and get the average value of voltage and frequency for the secondary control loop. A general approach is proposed in [42].

However, during the dynamic test of distributed secondary control method in [42], a problem occurs. In the dynamic test, at first, all the modules are connected to the load to feed power, at a time, one of the modules is disconnected, at this instant, the power still can be average shared among the other modules, then after a moment, reconnect the disconnected module to the system again, then a problem appears, the power cannot be average shared again, the output power of the reconnected module is a lot more downcast than the others.

In order to resolve the problem of the distributed secondary control in [42], an improved distributed secondary control based on low bandwidth CAN communication is proposed in this paper. Compared with [42], the difference is that, in the proposed secondary control, it is not to get the average value of the sampled voltages and frequencies, instead, the secondary control is finished locally, than the output value

of the integral part of the secondary control will be sent to the CAN bus, once all the modules receive these information, an average value of integral controller will be used to replace the local integral output value. In the thesis, this method is named as the improved distributed secondary control II since it is ameliorated from the proposed improved distributed secondary control I. With the improved distributed secondary control II, at any time one can guarantee that each module can recover the voltage and frequency immediately during the dynamic test.
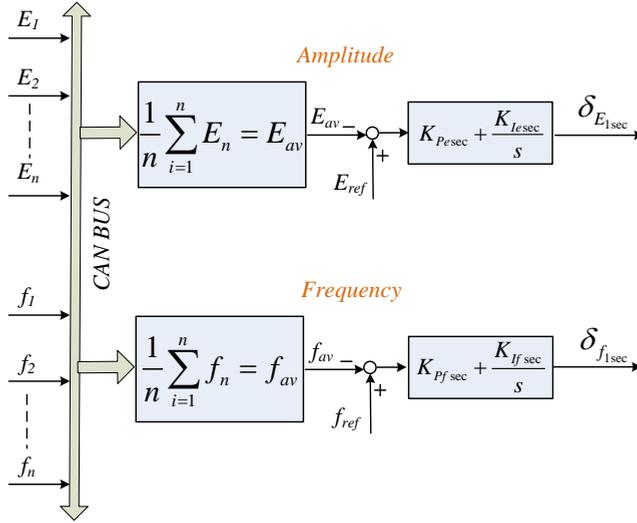
Figure 1- 8 The conventional distributed secondary control scheme.

Figure 1-11 presents the control scheme of the improved distributed secondary control I, the output voltages of the units are not sent to the CAN bus. In every unit, the secondary control is done locally, then the output of secondary control $\delta_{Ei\,sec}$ are sent to the CAN bus, then in each module, it will calculate the average compensation value $\delta_{E\,sec}$. The same principle is used to obtain the frequency compensation value $\delta_{f\,sec}$.

However, a problem was also founded in the improved distributed secondary control I during the test in the simulations. The windup happens in the output of the local secondary control, even the average value of the secondary control is stable. This problem can be solved by adding the anti-windup control loop in the secondary controller.

It should be noticed that the improved distributed secondary control II is finally implemented in the modular UPS project since it has a better performance and can guarantee a higher reliability of operation.
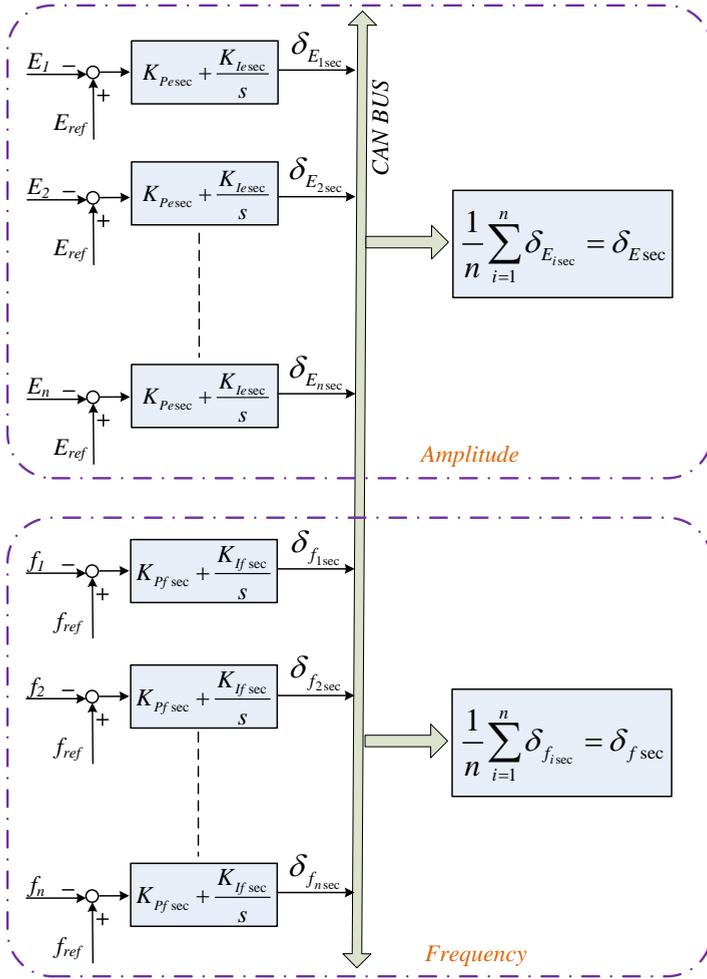
Figure 1- 9 The diagram of improved distributed secondary control I.

Figure 1-12 depicts the control scheme of the improved distributed secondary control II. Compared with the improved distributed secondary control I, only the integral part of the local secondary control will be sent to the CAN bus to obtain an average value of the integral part. Then it will be added to the proportional part of local secondary control to get the final voltage and frequency compensation value. By this kind of improvement, once the local integral part of secondary control is sent to the CAN bus, it will always be equal to the average integral value, the windup will never happen.

More details about the proposed distributed secondary control method can be found in Paper 2 in CHAPTER 3.
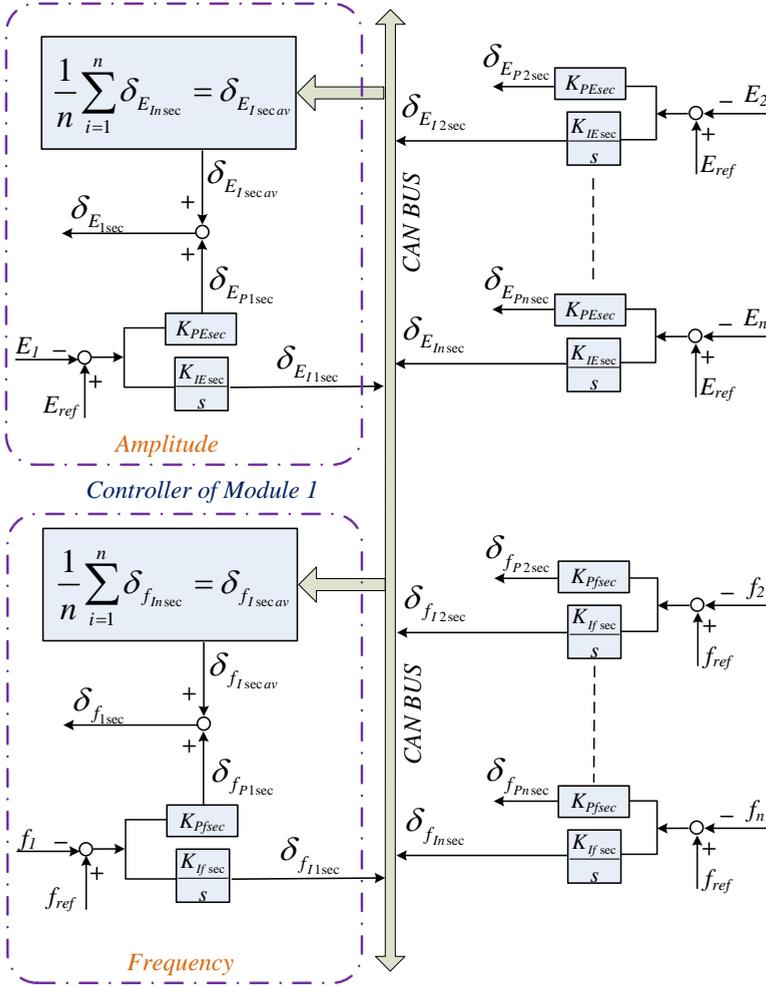
Figure 1- 10 The control diagram of the improved distributed secondary control II.

1.6. AVERAGE POWER SHARING CONTROL

1.6.1. ADAPTIVE VIRTUAL IMPEDANCE CONTROL

The output impedance of the parallel converters plays an important role to influence the performance of parallel operation since the droop control is sensitive to it [78], [79]. The output impedance can be regulated by using the virtual impedance [79]-[83], which has been verified with a result of better power sharing performance. But it is hard to design an accurate virtual impedance in the real applications since the working environment of the power system, the stray parameters of the converters and the line impedance will influence the output impedance, so one can just give it a preset

constant value, the performance cannot be guaranteed [79], [84]. If the virtual impedance is not well performed, it may cause distortions in the current or voltage, decease the power quality and influence the stability of the system. And under the worst condition, the current can flow from one module to another, this will threaten the safety of the DC link of the module who is absorbing power from the others. For the purpose of improving the performance of parallel operation, the adaptive virtual impedance control is proposed in several literatures [84-88].

In the real applications, like the modular UPS, even it is the same model, the output impedances of the converter modules cannot be exactly the same. Now almost all the UPS are controlled by digital signal processers (DSP), since the control boards are independent among the parallel units, maybe there is offset between the settings or control parameters in the control boards.

In the thesis, three main cases are considered to simulate the real UPS hardware in the simulation before implementing on the modular UPS platform since all of them will influence the parallel operation performance.

   1) The unmatched set of virtual impedance to simulate the different output impedance of different modules.

   2) A worse calibration of voltage sample circuits.

   3) The unmatched set of voltage reference to imitate the inner offset of the digital controller (DSP).

Considering the above mentioned three cases, an adaptive virtual impedance control method is presented in the thesis for the modular UPS. The value of the adaptive virtual impedance will be regulated by the difference between the local output active power and the average active power of the parallel modules, this value is then added to the preset virtual impedance. When the adaptive virtual impedance control is implemented, the total value of the virtual impedance is not a constant value; it will be regulated by the difference of local active power and average active power of all the modules. It can be sure, at any time, the total power can be average shared among the parallel converters, so there will be no current flowing from one module to another to keep the safety of the DC link. The adaptive virtual impedance is calculated by the difference of the active power among the power modules. Suppose that there are a number of n converter modules in a modular UPS, for the ith module, the adaptive virtual impedance is calculated as shown in Figure 1-13.

R_{vir_pre} is the preset virtual impedance, R_{vir_adp} is the adaptive virtual impedance. The final virtual impedance will be $R_{vir\_pre} + R_{vir\_adp}$. First, the local active power P_i will be compared with the average active power of the paralleled modules in the UPS. Then through the PI controller, the adaptive virtual impedance R_{vir_adpi} is obtained. The reason of P_i in the position of minuend is that, suppose that P_i is higher than the average active power of the parallel-connected modules, it means the virtual

impedance of the ith module should increase to decrease the output power of P_i. In Figure 1-13, R_{vir_adpi} will be positive through the calculation, so the final total virtual impedance of ith module will increase which is the correct compensation direction. More details about the proposed adaptive virtual impedance control, and the simulation and experimental results can be found in Paper 3 in CHAPTER 4. It is interesting to find that the adaptive virtual impedance control is valid for the above mentioned three cases.
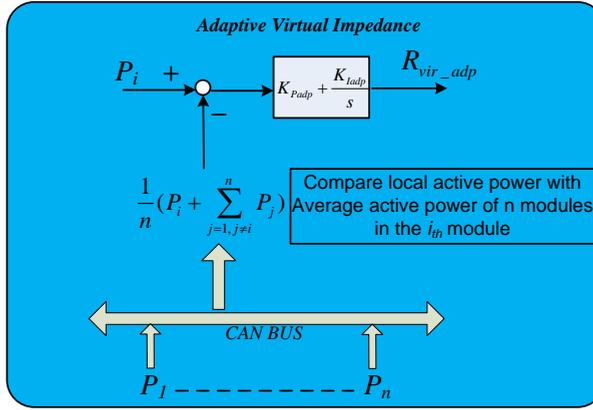
Figure 1- 11 Control scheme of the adaptive virtual impedance for the number i^{th} module in a modular UPS.

1.6.2. MODIFIED DROOP CONTROL

As mentioned before, the output impedance of the converter will influence the droop performance, the reason is that different droop function should be selected for different kinds of output impedance [80]. With the traditional droop, the frequency is related with the active power P while the voltage amplitude is regulated by the reactive power Q. The droop function is known as [80]:

$$w = w^* - m_p P \tag{1}$$

$$E = E^* - m_q Q \tag{2}$$

in which, w^* is the frequency reference, and E^* is the voltage amplitude reference while m_p and m_q are the droop coefficients for the active power and reactive power, respectively [24], [80], [89], [90]. Moreover, to guarantee a better performance of the conventional droop control, the close loop output impedance of the system near fundamental frequency should be highly inductive, the purpose is to decouple the influence of active power to the voltage amplitude and the reactive power to the frequency [80], [90].

However, based on the filter topology used in this UPS project and chosen of the control parameters and the virtual resistance, the output impedance is more resistive. The droop function will be modified as:

$$w = w^* + m_q Q \tag{3}$$

$$E = E^* - m_p P \tag{4}.$$

It is the contrary side of traditional droop method, the reactive power will be adjusted by the frequency while the active power is regulated by the voltage amplitude. More details about the chosen of droop function and the analysis of output impedance can be found in [24], [80], [89], [90].

Like the three cases discussed in section 1.6.1, another control method was presented in this thesis, which can obtain the same control target as the presented adaptive virtual impedance control for the modular UPS project. The proposed control strategy is modified from the conventional droop function. Compared with the conventional droop, the average power among the parallel modules has been used to modify the droop function, by this modification, the droop control can adjust the voltage quickly according to the difference among the output power of local module and the average power of the parallel modules. And simulation has been done considering the three cases mentioned in 1.6.1. Compared with the conventional droop, a better average power sharing performance is obtained using the modified droop control.

The modified droop functions are shown in (5) and (6), in which P_{av} and Q_{av} are the average value of the active and reactive power of the parallel modules, respectively; P and Q are the local value of active and reactive power. With the modification, the difference among the local value and the average value of both active and reactive power of all converter modules are considered in the control, so a faster regulation of voltage and frequency and a better power sharing performance can be obtained among the paralle modules.

The functions are simple, but there is still something to be noticed. As we know, one of the reason of unbalaced active power sharing is the unbalaced output voltage, higher voltage lead to higher output current. Through the function (5), one can notice that, if the active power P of the local module is lower than the average active power, with the additional part of the modified the droop function, the droop function will be added a positive value to increase the output voltage which lead to a higher ouput current. So with proper control parameters, a better active power sharing performance can be obatined. And with funciton (6), the frequency (angel) of the output voltage can be ajusted by the average and local reactive power, which can gurantee a better reactive power sharing and at the same time a better sychnization performance is obtained. More details and simulation results can be found in Paper 4 in CHAPTER 5.

$$E = E^* - m_p P + m_p'(P_{av} - P) \tag{5}$$

$$w = w^* + m_q Q + m_q'(Q_{av} - Q) \tag{6}$$

1.6.3. CIRCULATING CURRENT CONTROL LOOP

For the same purpose of average power sharing discussed in 1.6.1 and 1.6.2, before doing the modular UPS project, another method of suppress circulating current is presented in the thesis.
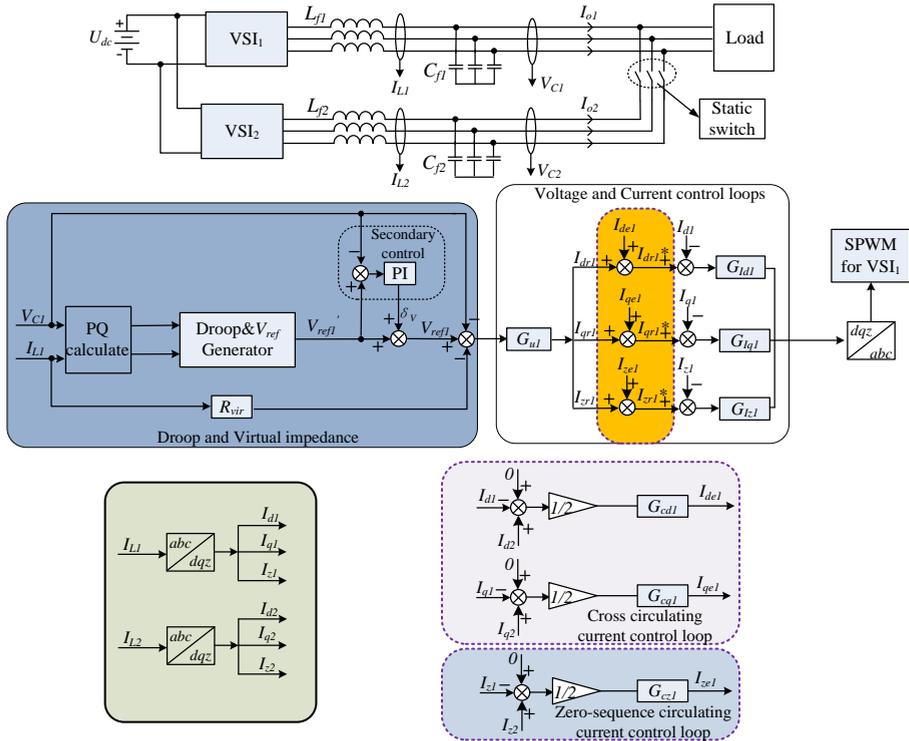
Figure 1- 12 The control scheme of circulating current suppression method.

Figure 1-14 describes the control diagram of the proposed circulating current suppression method. In the control scheme, both of the cross and zero-sequence circulating currents were considered. The concept of the presented control method is to regenerate the current references for both d-axis, q-axis and zero-axis. New current references were generated with the compensation of the error currents among the parallel inverters. Functions (7)~(10) explain the progress of generating new current reference for the d-axis of the inverters. More details about the presented method and the simulation along with experimental results can be found in Paper 5 in CHAPTER

6. This circulating current method was also verified with parallel current source inverters that presented in Paper 6 in CHAPTER 7.

$$[0 - (I_{d1} - I_{d2})] / 2 = I_{de1} \tag{7}$$

$$[0 - (I_{d2} - I_{d1})] / 2 = I_{de2} \tag{8}$$

$$I_{dr1} + I_{de1} = I_{dr1}^{*} \tag{9}$$

$$I_{dr2} + I_{de2} = I_{dr2}^{*} \tag{10}$$

1.7. SIMPLIFIED DROOP CONTROL FOR THE GRID-CONNECTED CURRENT SOURCE INVERTER

Beside developing control strategies for the volatge sourece inverter based modular UPS, a control method was carried out for the grid-connected current source inverter (CSI) The control method was modified from the conventional droop control, it is simplified because the voltage control loop is removed.
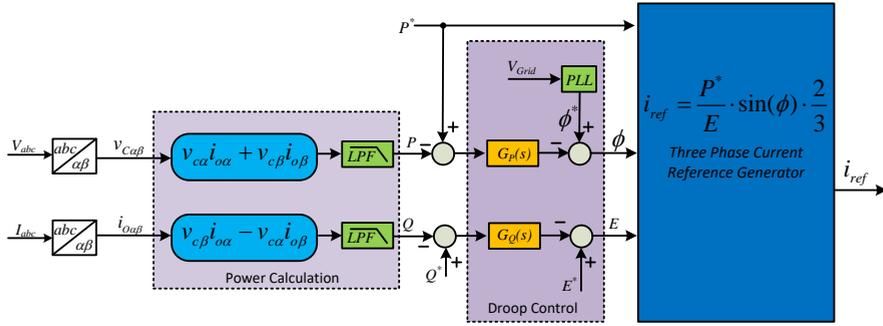
Figure 1- 13 The control diagram of the simplified droop for gird-connected current source inverter.

Figure 1-15 shows the diagram of the proposed simplified droop control. The basic idea of the control is to generate current references for the CSI instead of voltage references in the conventional droop. Once the output voltage V_{abc} and current I_{abc} of the inverter are obtained, the active power P and reactive power Q will be calculated and sent to the droop control, and then with (11), the current references will be generated. In (11), ϕ and E are from the conventional droop control loop, and E is the voltage amplitude, $P*$ represents the active power reference that will be fed from the CSI to the grid. In (11), "2/3" is used to obtain the amplitude of the current references, which is deduced from (12). More details about the presented control can be found in Paper 7 in CHAPTER 8.

$$i_{ref} = \frac{P^{*}}{E} \cdot \sin(\phi) \cdot \frac{2}{3} \tag{11}$$

$$i_{ref} = \frac{P^*}{E/\sqrt{2}} \cdot \frac{1}{3} \cdot \sqrt{2} \cdot \sin(\phi) \tag{12}$$

1.8. THESIS CONTRIBUTION

Considering the requirements of the TROY modular UPS project, control strategies have been proposed to address the aforementioned challenges. The whole control scheme is based on the distributed control concept. As a low bandwidth communication link, CAN bus is applied for data exchange to meet the demand of the control strategies.

To protect the load and UPS itself, and obtain a higher reliability, a current limit control method was proposed for over load and short circuit protection, which stays in the priority position of the tasks of the project.

To address the weakness of the existing distributed secondary control, two kinds of improved distributed secondary control were developed. In addition, one of them additionally figured out the windup problem of the integral part of the PI controller, it is discussed in detail in the following chapter and finally implemented in the modular UPS product.

The adaptive virtual impedance control is presented to enhance the performance of conventional droop with virtual impedance control. To obtain the adaptive virtual impedance, the output active power of each module will be sent to the CAN bus, then the average value of active power will be calculated in each module and compared with their own output active power, the error will pass through PI controllers to get the adaptive virtual impedance. A better power sharing performance is obtained using the proposed control.

Along with the adaptive virtual impedance control, a modified droop control has been presented as a backup solution. The interesting thing is that a similar performance was obtained in the simulation. Compared with the conventional droop function, the average value of active and reactive power are inserted into the droop control function to compare with the local value of them. Then the output voltage of each module will be adjusted by the difference between their output power and the average power of all the modules. Thus a good power sharing performance is obtained.

All the presented control strategies for the modular UPS were implemented on the platform in Salicru. Availability and effectiveness of the control methods have been affirmed with both simulations and experimentations.

Except the contributions of developing control strategies for the modular UPS project, some other researches have been carried out before doing the project. A circulating current suppression method has been proposed, which is suitable for both voltage

source inverter and current source inverter under parallel operation. The key point of the proposed control is to use the difference of the output current among the parallel inverters to generate new current references. The effectiveness of the method was verified through experiments and simulation.

The last contribution is to propose a simplified control for the gird-connected current source inverter. Since for a grid connected converter, the objective is to inject a stable and grid voltage synchronized current into the grid, then the voltage control loop can be removed in the conventional droop to simplify the control scheme. Simulations have been implemented to verify the control.

1.9. THESIS OBJECTIVES

The objectives of the study are listed below.

- To review the technical papers related with the converter control under paralle operation, to find the challeges when the methods are applied into a real industrial application, like the modular UPS.

- To propose a control method to suppress the circulating current for voltage source inverters or current source inverters under parallel operation.

- To propose a simplified droop control method for the grid-connected current source inverter.

- To propose a current limit control method for over load and short circuit protection, and verfied on a modular UPS platform.

- To propse an adaptive virtual impedance control used for modular UPS to have a better power sharing performance.

- To propse a modifed droop function to be applied for modular UPS to conquer the weakness of the conventional droop control.

- To propsed an improved distributed secondary control to get a better performance of a modular UPS.

To verify the presented control strategies for the modular UPS, experiments has been done using a modular UPS prototype in the company Salicru S/A. The other control methods carried out in the study were implemented in simulations or doing experiments in the lab of microgrid group in Aalborg University.

1.10. THESIS OUTLINE

The thesis content is organized as follows.

Chaper 2 presents the paper 1, submited to IEEE Transactions on Power Electronics, which explains the current limit control under over load and short circuit condition applied to a UPS system.

Chapter 3 presents the paper 2, submited to IEEE Transactions on Power Electronics, which explains the improved distributed secondary control for a modular UPS system.

Chapter 4 presents the paper 3, submited to IEEE Transactions on Power Electronics, which explains the adaptive virtual impedance control for a modular UPS system.

Chapter 5 presents the paper 4, pulished in IECON 2017, which explains the modifed droop control for a modular UPS system.

Chapter 6 presents the paper 5, pulished in IEEE Transactions on Industrial Applications, which explains the circulating current supression strategy used for voltage source inverters under parallel operation.

Chapter 7 presents the paper 6, pulished in ECCE-Asia 2016, which explains the circulating current supression strategy used for current source inverters under parallel operation.

Chaper 8 presents the paper 7, pulished in IECON 2016, which explains the simplified droop control method for the grid-connected current source inverters.

CHAPTER 2. PAPER 1

Over Load and Short Circuit Protection Strategy for Voltage Source Inverter Based
UPS

Baoze Wei; Albert Marzàbal; Santi Trujillo; José Pérez; Ruben Ruiz; Josep M. Guerrero; Juan C.
Vásquez

CHAPTER 3. PAPER 2

Distributed Secondary Control Strategy for Modular UPS System

Baoze Wei; Albert Marzàbal; Santi Trujillo; José Pérez; Ruben Ruiz; Josep M. Guerrero; Juan C. Vásquez

CHAPTER 4. PAPER 3

Adaptive virtual impedance control for voltage source inverter based modular UPS system

Baoze Wei; Albert Marzàbal; Santi Trujillo; José Pérez; Ruben Ruiz; Josep M. Guerrero; Juan C. Vásquez

CHAPTER 5. PAPER 4

A Power Sharing Method Based on Modified Droop Control for Modular UPS

Baoze Wei, Josep M. Guerrero, Juan C. Vásquez

CHAPTER 6. PAPER 5

A Circulating-Current Suppression Method for Parallel-Connected Voltage-Source Inverters With Common DC and AC Buses

Baoze Wei; Josep M. Guerrero; Juan C. Vásquez; Xiaoqiang Guo

CHAPTER 7. PAPER 6

Control architecture for paralleled current-source-inverter (CSI) based
uninterruptible power systems (UPS)

Baoze Wei; Juan C. Vásquez; Josep M. Guerrero; Xiaoqiang Guo

The paper has been published in

8th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia), 22-26 May
2016, Pages: 151 - 156, Hefei, China.

CHAPTER 8. PAPER 7

A modified droop control method for parallel-connected current source inverters

Baoze Wei; Josep M. Guerrero; Juan C. Vásquez; Xiaoqiang Guo

CHAPTER 9. CONCLUDING REMARKS

9.1. SUMMARY

The thesis mainly focus on developing the control strategies applied to a modular UPS product. And the project is supported by a UPS research and manufature company named Salicru S/A in Barcelona, Spain.

In the modular UPS, each power module mainly contains a rectifier, an inverter, a control board, the static bypass switch, and a switching power supply for DC power requirments of the control board and the driver circuits. The rectifier is responsible for providing a stable DC bus voltage for the inverter. On the control board, it consists two Delfino digital signal processors (DSPs) TMS320F28377D from Texas Instruments (TI). One DSP is responsible for the control of the rectifier; another is responsible for the inverter. In each DSP, there are two standalone cores, each core is a full functional 32-bit floatting-point processor. The advance feature of the DSP is that it contains a co-processor with each core, it is called Programmable Control Law Accelerators (CLAs). The CLA is a 32-bit floatting-point math accelerator, which can operate in paralle with the main control unit.

The control strategies presented in this thesis are for the operation of the inverter. The targets include:

- Single inverter operation. Flexible running of the inverter, three phases, any two phases or single-phase operation. The advantage of the flexible running is not only for the consumer with different kinds of load but also for the test and maintenance work of the producer. To realize this target, control strategies under *abc* stationary coordinates were development.
- Multi-inverter parallel operation. Since it is a modular UPS, several power modules are working in parallel. Droop with virtual impedance control is adopted for cooperative control of the parallel inverters.
- Current limit under overload and short circuit condition. The protection is one of the important issues for a power system. A well operation scheme of protection not only can protect the UPS and the loads under fault condition, but also can return back to normal state quickly when fault is cleared. With the proposed current limit control method, the output current can be limited to a pre-set constant value to guarantee the safety of the hardware when overload or short circuit happens without need of shut down the whole system if the fault can be cleared within the time allowed.
- Voltage and frequency recovery. The voltage and frequency may deviation sometimes because of the control itself, like the droop and virtual impedance control that will cause voltage or frequency drop or fluctuation, or the reason

of load change. With the proposed distributed secondary control strategy, it can guarantee the stable of the output voltage and frequency, and it provides advantages over the existing secondary control, such as better dynamic performance and inherent integral anti-windup capability.

- Average power sharing among the modules. In order to have a similar lifetime of the power modules, and avoid negative power flowing from one module to another, average power sharing control is necessary. With the proposed control methods, a good power sharing performance is obtained. Different kind of conditions have been considered and verified in the simulation and experiments. Once there is no negative current, the DC link will stay safety, at least there is no threat from the inverter side.

Most of the presented control methods in this thesis are developed for the modular UPS product, verified by simulations on PLECS and experiments on a modular UPS platform in Salicru. Before doing experiments, each proposed control will be implemented in the simulation first, and in order to have a similar result with experiments, all the simulations are realized with C language for the control, and most of the hardware features are considered in the simulation, so that with an accurate simulation model, the same control parameters are adopted in the simulations and experiments, by doing this, it also makes it is easier to transfer the code into the DSP that can reduce the time-consuming of implementing experiments.

9.2. FUTURE WORKS

- Bypass test on the modular UPS platform
  Since bypass is an important mode for a UPS system, the smooth transfer from UPS to bypass state is an essential issue to be considered.

- Burning test on the modular UPS platform
  In order to test the reliability of the control strategies and the performance of a UPS system, the burning test should be established before going into production.

- Eco-mode test
  The working state of eco-mode is similar to the burning test, especially when there is no load connected, but for a fast response or turning back to normal working state, an eco-mode is necessary. The power loss of the system in eco-mode is much lower than burning test or normal working mode.

- Parallel operation of several modular UPS platforms
  For higher power demand, several modular UPS platforms can be connected in parallel to form a larger system. It is suitable for fast build and design. The cooperation of different platforms is the important case.

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