論文 / 著書情報
Article / Book Information

題目(和文)	大規模太陽光発電システム応用のためのモジュラー・マルチレベル・カスケード変換器の研究
Title(English)	Study of Modular Multilevel Cascaded Inverters for Utility-Scale Photovoltaic Systems
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出典(和文)	学位:博士(工学), 学位授与機関:東京工業大学, 報告番号:甲第10475号, 授与年月日:2017年3月26日, 学位の種別:課程博士, 審査員:赤木 泰文,安岡 康一,七原 俊也,千葉 明,藤田 英明,川上 紀子
Citation(English)	Degree:Doctor (Engineering), Conferring organization: Tokyo Institute of Technology, Report number:甲第10475号, Conferred date:2017/3/26, Degree Type:Course doctor, Examiner:,,,,,
学位種別(和文)	博士論文
Category(English)	Doctoral Thesis
種別(和文)	要約
Type(English)	Outline

Thesis Outline

Study of Modular Multilevel Cascaded Inverters for Utility-Scale Photovoltaic Systems
(大規模太陽光発電システム応用のためのモジュラー・マルチレベル・カスケード変換器の研究)
by Paul-Lukas Sochor (Supervisor: Prof. Hirofumi Akagi)

Abstract

This dissertation discusses the application of modular multilevel cascade inverters (MMCIs) in SSBC and SDBC configurations to utility-scale grid-tied photovoltaic (PV) systems. Compared to conventional PV inverters in utility-scale PV systems, MMCIs feature a modular and scalable structure that can generate three-phase medium voltage multilevel voltage waveforms and produce multi-MW output powers while requiring neither harmonic filters nor step-up transformers.

It is investigated and shown that the MMCI can optimally harvest electric power from a large number of individually interfaced and distributed PV solar arrays, even when the power generation among the PV solar arrays is imbalanced.

Two three-phase downscaled MMCI in SSBC and SDBC configuration rated at 10-kW with 18 individual power sources that emulate PV solar arrays are designed and experimentally verified under various operational conditions.

Introduction

Although energy generated from photovoltaics (PV) still represents only a small fraction of the overall global power generation, worldwide PV installations and power generation by solar PV have seen a remarkable growth in recent years. By the end of 2015, a total of 229 GW in PV system capacity had been installed worldwide, an increase of 50.6 GW (27%) compared to the end of 2014 [1].

This momentous development has been driven on one side by a steep and continuous decline in prices for PV modules and other system components such as PV inverters as a result of technological advances and economies of scale in manufacturing.

While the costs for PV modules in a PV installation still make up for the largest proportion of PV system prices, their share within the overall costs is continuously decreasing. This means that the portion of costs for other system components such as the inverters, cabling, grid connection etc. is becoming higher. Despite the significant price drop seen in recent years, it is expected that system prices will continue to decline in the coming years.

The decreasing cost proportion for PV modules in a solar PV installation implies an increased focus on reduction of costs for balance of system (BoS) components. These are among others, costs for the PV inverter, the racking and mounting system, ac and dc cables, combiner boxes, monitoring and control and all components related to grid connection, such as MV transformers, MV cables, MV switchgear, substations etc. The cost reduction potential for the next 10 years for BoS hardware components is expected at about 39% compared to 2015 [2]. The driver for this estimation are anticipated technological advances and new innovative systems designs. For example, these can be PV inverters featuring innovative power conversion topologies or an increase in voltage on both dc and ac side that allows reduced costs for inverters, cabling, combiner boxes and transformers.

Contemporary Utility-Scale Photovoltaics

The term *utility-scale photovoltaics* is commonly used in the PV industry and refers to large-scale photovoltaic systems (often also called as solar farms) that are ground-mounted (as opposed to roof-top systems), grid-tied and that sell the generated electricity directly to utilities or other buyers rather than consuming it on-site, such as with commercial systems on rooftops of factories or warehouses.

Utility-scale solar is currently the largest segment among PV installations worldwide and one of the main drivers of global growth of renewable energy. Utility-scale PV systems are among the cheapest to install on a price-per-Watt basis.

Fig.1 depicts a typical system design of a utility-scale PV power plant. Contemporary utility-scale PV systems typically employ so-called central PV inverters [3]. These are low-voltage, high-power inverters with nameplate ratings in the range of typically 1 MW at 400 V per unit. Each PV inverter is interfaced by thousands of PV modules which are connected in 200 or more parallel PV module strings. On the ac-side, the central PV inverter is connected to a LV/MV-step-up transformer that feeds a MV-collector (6.6 kV or higher) within the facility. Large systems are typically interfaced through a MV/HV transformer with a transmission substation that connects to a HV transmission line.

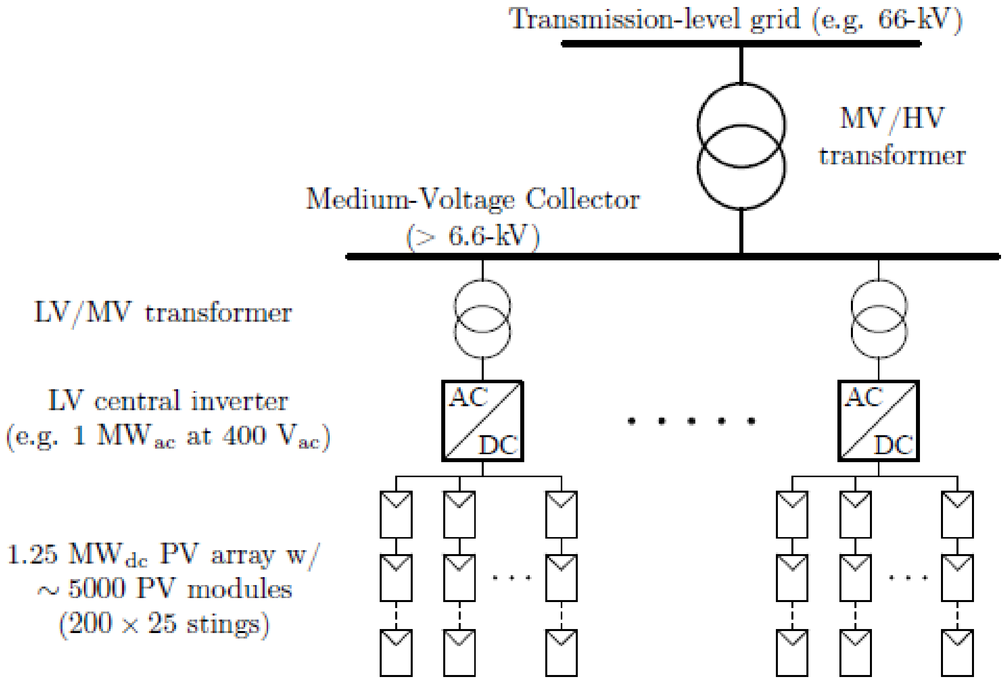

Figure 1 Single-wire diagram of contemporary utility-scale PV system.

Opportunities for Modular Multilevel Cascaded Inverters in Utility-Scale PV Systems

Modular multilevel cascaded inverters (MMCI) have attracted considerable attention in recent years for various high power medium-voltage applications [4-6]. MMCIs are a family of inverter circuits that share a set of common characteristics, which are modularity, cascadability and scalability. MMCIs employ circuit topologies with a large number of equally-constructed power cells that are cascaded to obtain output voltage with relatively high amplitudes while ensuring both a low harmonic content and low switching frequencies per cell. These characteristics make MMCIs particularly attractive to high-power applications, such as MV motor drives and utility-applications that require medium voltage and high output power levels.

Fig.2 shows a generalized structure of a utility-scale PV system that comprises MMCI-based PV inverters. Unlike central PV inverters in contemporary utility-scale PV systems, an MMCI-based PV inverter can produce a three-phase MV multilevel output waveform that requires neither additional output filters nor additional step-up transformers when interfacing a medium-voltage collector bus. This characteristic also allows circuit designs with much higher output power in excess of 20 MW compared to conventional central PV inverters. The highly modular and distributed structure of MMCIs that comprise many smaller dc-dc converters and bridge cells offers potential for easy scalability to different plant designs, higher plant availability due to a high level of redundancy and easy maintenance, since faulty cells can be bypassed and replaced. Moreover, the distributed maximum power point tracking (MPPT) capability can improve the overall system yield of a PV plant. MMCI-based PV inverters may allow significant cost-advantages for very large PV systems compared to conventional low voltage based PV inverter systems.

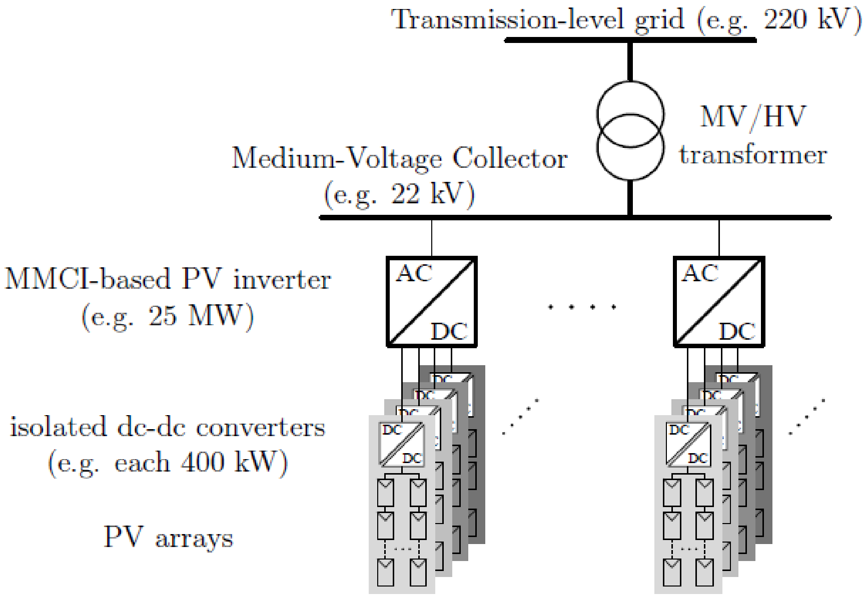

Figure 2 Structure of a photovoltaics power plant design employing MMCI-based medium voltage PV inverters.

Focus of Research and Structure of Dissertation

This dissertation discusses the application of modular multilevel cascaded inverters (MMCI) to future utility-scale PV power plants. It is investigated and shown how both circuits can optimally harvest electric power from a large number of individually interfaced and distributed PV solar arrays, even when the power generation among the PV solar arrays is imbalanced. The main objective of this research is the investigation of the operational behavior, when the power generation among distributed PV arrays connected to the MMCI inverter are severely imbalanced. This work focuses particularly on star-connected (SSBC) and delta-connected (SDBC) MMCI-circuit topologies. One major focus of this dissertation is, therefore, on identifying and highlighting the benefits of the SDBC inverter over the SSBC inverter in utility-scale PV applications. The approach sought in this dissertation is analytic, numerical and experimental.

The following items are the key research elements of this thesis:

Theoretical analysis and comparison of intercluster power balancing methods for SSBC and SDBC inverter. Both SSBC and SDBC inverter consist of three clusters that may experience unequal power generation of different degrees during any time of operation. For the SSBC inverter, different methods based on harmonic zero-sequence voltage injection are analyzed and compared on a quantitative basis with respect to power-balancing capability. The SDBC inverter relies on a different but analogous control method, the zero-sequence current injection. A quantitative comparison with the SSBC inverter shows that the SDBC inverter offers superior operating characteristics allowing it to operate under a much wider range of power-distribution imbalances.

Proposal and analysis of level-shifted permuted-carrier pulsewidth modulation (LSPC-PWM) for enhanced power balancing capability among bridge cells in an SDBC inverter.
Conventional phase-shifted pulsewidth modulation (PS-PWM) is limited in power-balancing capability and introduces harmonic distortions in output voltages and output currents when is applied to an SDBC inverter operating under power-distribution imbalances. A newly introduced LSPC-PWM modulation strategy applied to an SDBC inverter allows both an extended power-balancing capability and a high harmonic performance that is unaffected by power-distribution imbalances. Moreover, it is shown and supported by theoretical analysis how the power-balancing capability of the SDBC inverter can be enhanced even further by utilizing harmonic zero-sequence currents injected into each cluster.

Experimental implementation and performance verification of SSBC and SDBC inverters under very high power imbalance ratios. A 10-kW, six-cascade downscaled experimental setup with 18 isolated dc power sources is prepared for experimental verification of the operational performance and power-balancing capability of both SSBC and SDBC inverters. The high amount of individually controllable dc power sources enables investigation of the various different power-imbalance situations among both clusters and bridge cells. The high cascade number further allows experimental investigation of secondary effects that emerge with higher cascade numbers such as harmonic degradation of current and voltage waveforms.

The dissertation is structured as follows:

•**Chapter 1** gives an introduction into the development of photovoltaics over the past years and motivates the research topic.

•**Chapter 2** gives an in-depth introduction of the structure and functioning of contemporary utility-scale photovoltaic systems including contemporary PV inverter topologies. It explains important technical aspects that are fundamental to the understanding of the concept of applying modular multilevel cascaded inverters to photovoltaic systems.

•**Chapter 3** provides a literature review on modular multilevel cascaded inverters, major circuit configurations and their main applications. The second part is dedicated to discussing modular modular multilevel cascaded inverters for PV applications that are discussed in technical literature.

• **Chapter 4** provides a theoretical discussion and comparison in intercluster balancing between SSBC and SDBC inverter. Both qualitative and quantitative evaluation metrics are introduced to assess the power-balancing capability of both circuits.

• **Chapter 5** discusses the 10-kW, six-cascade downscaled experimental system with 18 individually controllable dc power sources that is used for experiments of both SSBC and SDBC inverters. Experimental waveforms are presented that show good agreement with the results from the theoretical investigation of chapter 4.

- **Chapter 6** discusses and compares the conventional method intracluster balancing method based on PS-PWM and a proposed method that is based on LS-PWM. It is shown that the new method offers several benefits in an SDBC inverter, such as a largely improved power-balancing capability and an insusceptibility towards harmonic distortion at the ac side during power imbalances. The contents of this chapter are not covered by this thesis outline.

- **Chapter 7** summarizes the findings obtained in this research.

Modular Multilevel Cascaded Inverters for Utility-Scale PV Systems

PV has traditionally been a natural candidate for applications of cascaded inverters, because one of the major drawbacks of that topology, which is the requirement of isolated dc sources, is automatically cleared [7]. PV applications further benefit from the highly modular and distributed structure of MMCIs that allow PV system designs based on the attractive distributed-centralized system architecture. The advantages associated with this topology are distributed MPPT, high system efficiency, easy scalability, high plant availability and enhanced monitoring and diagnostics capability. MMCI-based PV inverters are especially suitable to high-power medium-voltage utility-scale PV systems that can have system capacity ratings in excess of 100 MW. However, low-voltage PV has been and continuous to be a highly popular application in technical literature.

Utility-scale PV requires, due to the high power rating of solar farms, interconnection to higher voltage levels. Modular multilevel cascaded inverters are particularly attractive for this application, since they allow power outputs in excess of 10-MW, a power region unfeasible with low voltage inverters. Due to their multilevel medium-voltage ac output, MMCI-based utility-scale PV inverters require little or no filtering and allow direct connection to a medium-voltage collector of a large solar farm that eliminates the requirement for LV/MV step-up transformers. Their modular, scalable and distributed structure allows simple scaling, fault tolerant operation and distributed MPPT for improved energy harvesting yields.

Fig.3 shows the circuit configuration of the SSBC inverter suitable for utility-scale PV systems that includes isolated dc-dc converters. Each bridge cell is interfaced by one or more PV subconverters, which consist each of a PV array and an isolated dc-dc converter. An utility-scale PV system employing SSBC-based inverters fits into the distributed centralized plant concept and combines advantages from both centralized and distributed plant concepts.

SSBC-based inverters for utility-scale PV systems are suitable for large PV power plants in excess of 20 MW that are connected to the high voltage grid. SSBC-based PV inverters require neither harmonic filters nor LV-to-MV step-up transformers, while the low switching frequency per bridge-cell enables a high conversion efficiency. Despite allowing a very high output power, the highly modular structure of this inverter topology that comprises multiple identical units, allows an easily-scalable and redundant fault-tolerant system design. The maximum power point tracking is performed for each PV array individually, effectively improving the energy yield and efficiency of the whole PV system.

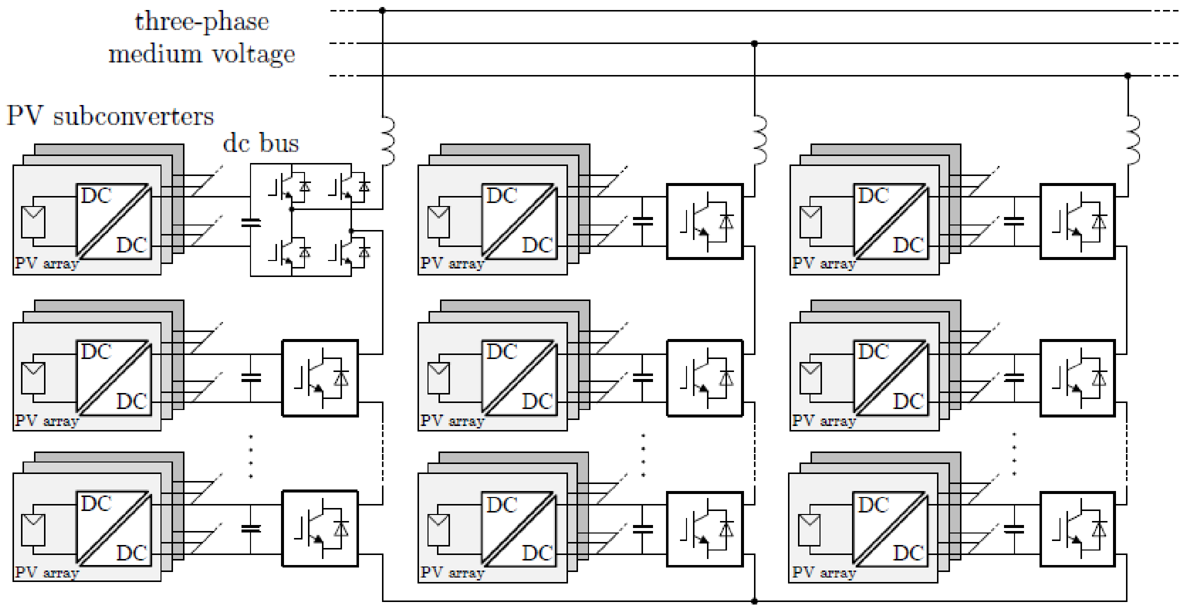

Figure 3 An SSBC-based (star-connected) medium-voltage PV inverter for utility-scale PV systems [7].

Imbalanced Power Distribution

Unlike other MMCI applications such as STATCOM, BESS or MV motor drives, MMCI-based PV inverters for utility-scale PV applications should provide the capability of stable and continuous operation even when the generated power at the PV arrays is imbalanced. This also applies to the SSBC inverter in Fig.3 that faces challenges during operation under imbalanced power generation from the PV arrays.

Power imbalances among the bridge cells occur as a result of the dependency on the PV array power output on local environmental conditions. The two main contributors in varying PV module output performance are the PV module and the incident radiance on each PV module within a PV array. An imbalanced power generation among the PV arrays may have different causes. These include, but are not limited to:

- shading and reflections due to near or far objects
- cloud movement
- soiling (e.g. snow and dirt)
- uneven ground level or PV module mounting direction
- manufacturing tolerances and inhomogeneous aging.

The difficulty to operate under imbalanced power generation is known in technical literature and currently one of the main challenges of applying the SSBC topology to PV applications. The dc-dc converters allow a controlled reduction of extracted power from individual PV arrays as a last resort to enforce stable operation of the SSBC inverter. However, this active curtailment of individual cells reduces the amount of harvested energy and lowers the overall system efficiency. Generally, it is feasible to extract the maximum available power from the PV generator.

Power imbalances can occur either among bridge cells, among the three clusters or among both bridge cells and clusters. One of the most commonly referred methods for handling power imbalances among three clusters is based on injecting a sinusoidal zero-sequence voltage to shift excess power from one cluster to the others. This method was already developed early and applied to applications other than PV, albeit at relatively low power imbalances. The disadvantage of this method is that the degree in power imbalance, which can be compensated, is limited by the total available dc capacitor voltage within each cluster.

A higher compensation capability requires significant inverter overrating by connecting more bride cells per cluster. Some authors have shown that adding harmonic components to the sinusoidal zero-sequence voltage allows extended operation under imbalanced power generation. Unfortunately, little quantitative evaluation has been presented regarding the effectiveness or limitations of the proposed methods.

Intercluster Power Balancing Control of SSBC and SDBC Inverter

One aim of this study is to analyze and discuss the power balancing capability of both SSBC and SDBC inverters for power imbalances among the three clusters (intercluster). Imbalanced active-power generation among both bridge cells and clusters causes the dc-capacitor voltage of each bridge cell to diverge if the outflow of energy is not regulated to be equal to its inflow. This ultimately leads to stability issues and makes the three-phase grid currents imbalanced and distorted. Various methods based on injecting zero-sequence voltages and currents are introduced and investigated.

For the SSBC inverter, non-sinusoidal zero-sequence voltage waveforms are analyzed and compared from a viewpoint of their power-balancing limitations. This dissertation proposes a third-harmonic square-wave injection characterized by easy implementation and enhanced power-balancing capability. In addition, power-balancing and limitations for the SDBC inverter are investigated in-depth.

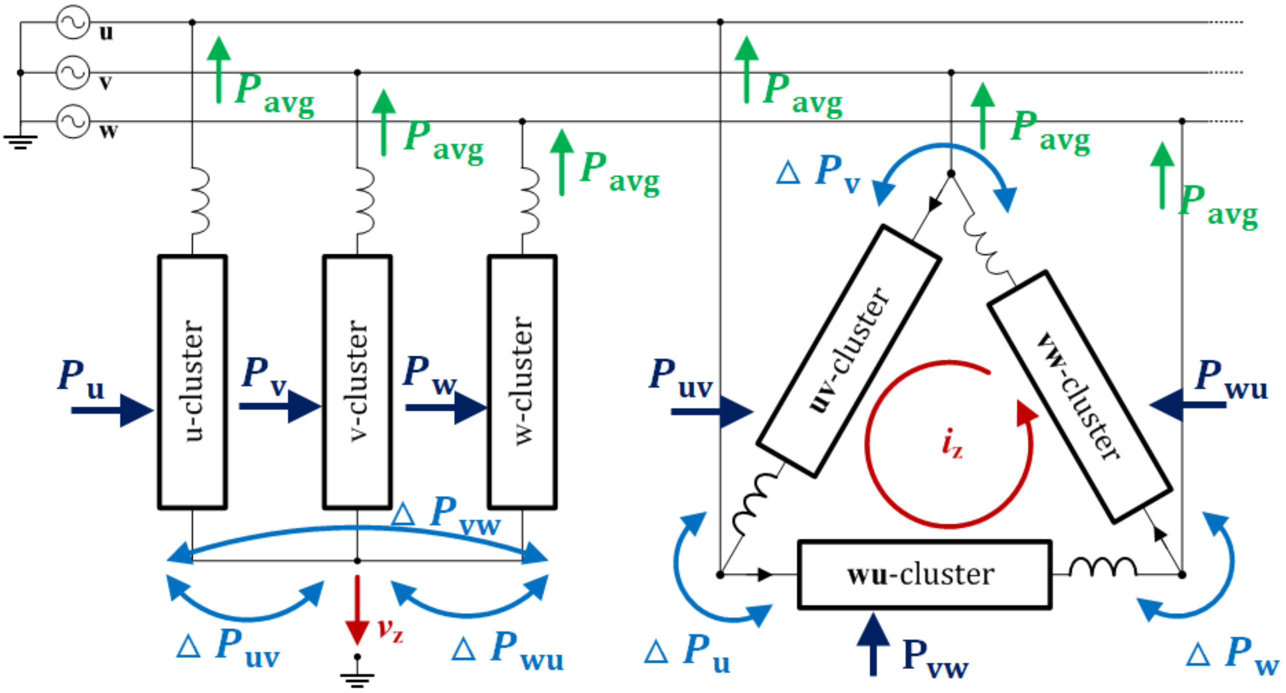

Figure 4 Principle of intercluster power balancing in SSBC and SDBC inverters.

Fig. 4 shows the principle of power balancing in both SSBC and SDBC inverter. The SSBC inverter utilizes a zero-sequence voltage to transfer power among the three clusters. The SDBC inverter on the other hand utilizes a zero-sequence current for the power transfer. The limitation for both circuit topologies derives from the maximum permissible cell or cluster voltage for the SSBC inverter and the maximum permissible cell or cluster current for the SDBC inverter.

Intercluster Power Balancing Limitation and Enhancements of SSBC Inverter

The standard method found in literature for power balancing in the SSBC inverter for various applications requires injection of a sinusoidal zero-sequence voltage with respect to the starpoint of the inverter [8-10]. The increased voltage requirement under intercluster power imbalances puts a constrain on the operating range of the SSBC inverter.

Because only the fundamental frequency component of the zero-sequence voltage contributes to an exchange of power among the three clusters, addition of any arbitrary harmonic content to the zero-sequence voltage does not affect the transfer of power. However, harmonic voltage components may be used to reduce the peak cluster voltage reference. This effectively allows a higher fundamental voltage component, hence enabling an extension to the power-balancing range without increasing the available dc-link cluster voltage through either higher cell count or higher voltage rating.

Fig. 5 shows power-balancing diagrams for both standard and advanced zero-sequence voltage injection method. It can be seen that the advanced method features the better capacitor voltage utilization as it covers a larger area of imbalance at any given cluster dc-link voltage (e.g. 140% of grid-peak voltage).

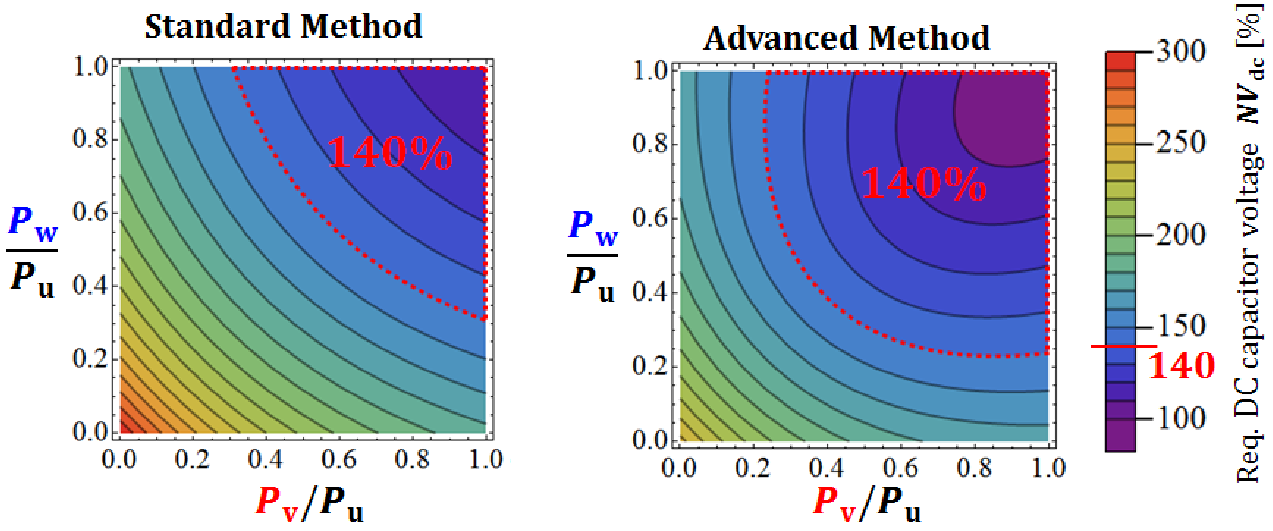

Figure 5 Power balancing Diagram for standard and advanced zero-sequence voltage injection method.

Operational Behavior of SSBC Inverter During Intercluster Imbalances

In the course of this dissertation a 10-kW, six-cascade downscaled MMCI-based PV inverter with 18 individually controllable dc power sources was designed and build. The experimental setup was designed and constructed with the aim of experimentally verifying control and behavior of SSBC inverter and SDBC inverter during different situations of imbalanced power generation.

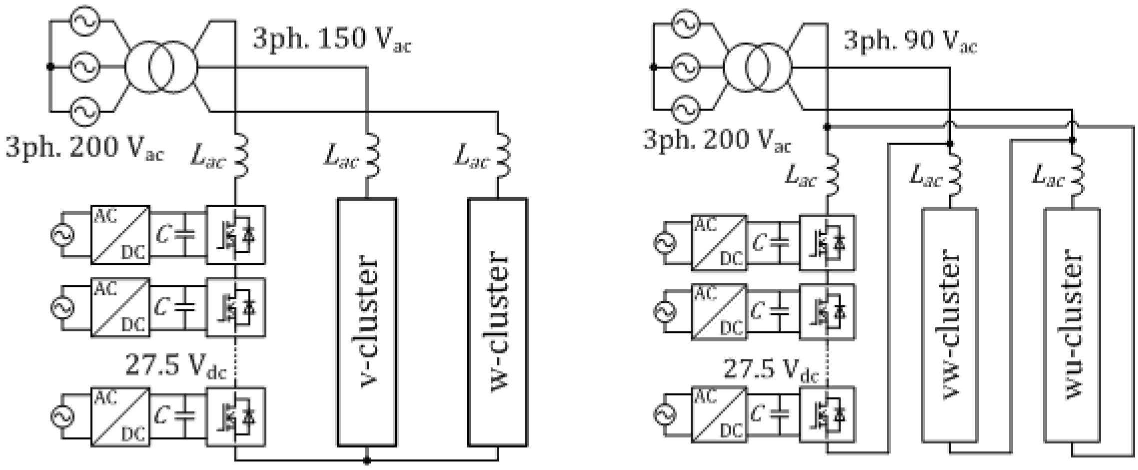

Figure 6 Circuit configuration of the downscaled experimental SSBC and SDBC inverters.

Fig.6 depicts the electric circuit diagrams of the downscaled modular multilevel cascaded inverter in SSBC and SDBC configuration, respectively. The experimental system is made of three clusters that are configured in either star or delta configuration. Each cluster consists of six bridge cells and is equipped with a floating dc capacitor to which each one isolated ac-to-dc power converter is connected.

Figs.7 and 8 show experimental waveforms that demonstrate the capability of the SSBC inverter to operate under imbalanced power generation among its three clusters. For the SSBC inverter, two types of zero-sequence voltage waveforms were implemented for a direct comparison; the standard sinusoidal zero-sequence voltage and the advanced third-harmonic square wave zero-sequence voltage.

In the beginning, all bridge cells are operating at the rated power causing no power imbalance among the three clusters. Once the generated active power in bridge cells of clusters v and w starts decreasing, a zero-sequence voltage is gradually injected to balance the power flow among the three phases.

Figs.7 and 8 also show the three cluster reference voltages as well as the available average cluster dc-link voltage v_C order to ensure a stable inverter operation, power balancing always needs to be satisfied. It can be seen that with increasing power imbalance the cluster reference voltages approach the available cluster dc-link voltage v_C. The increase in power imbalance stops shortly before reaching the overmodulation boundary. In case of using sinusoidal zero-sequence voltage injection, this limitation is reached earlier than for the case of third-harmonic square-wave zero-sequence voltage injection (Fig.8), which can tolerate higher power-imbalance ratios at the same v_C. In both cases all 18 floating capacitor voltages v_{ij}. are kept balanced and close to their set value.

It could be shown that the SSBC inverter can stably extend its operating range during imbalanced active power generation, when an advanced zero-sequence voltage waveform is injected into each cluster.

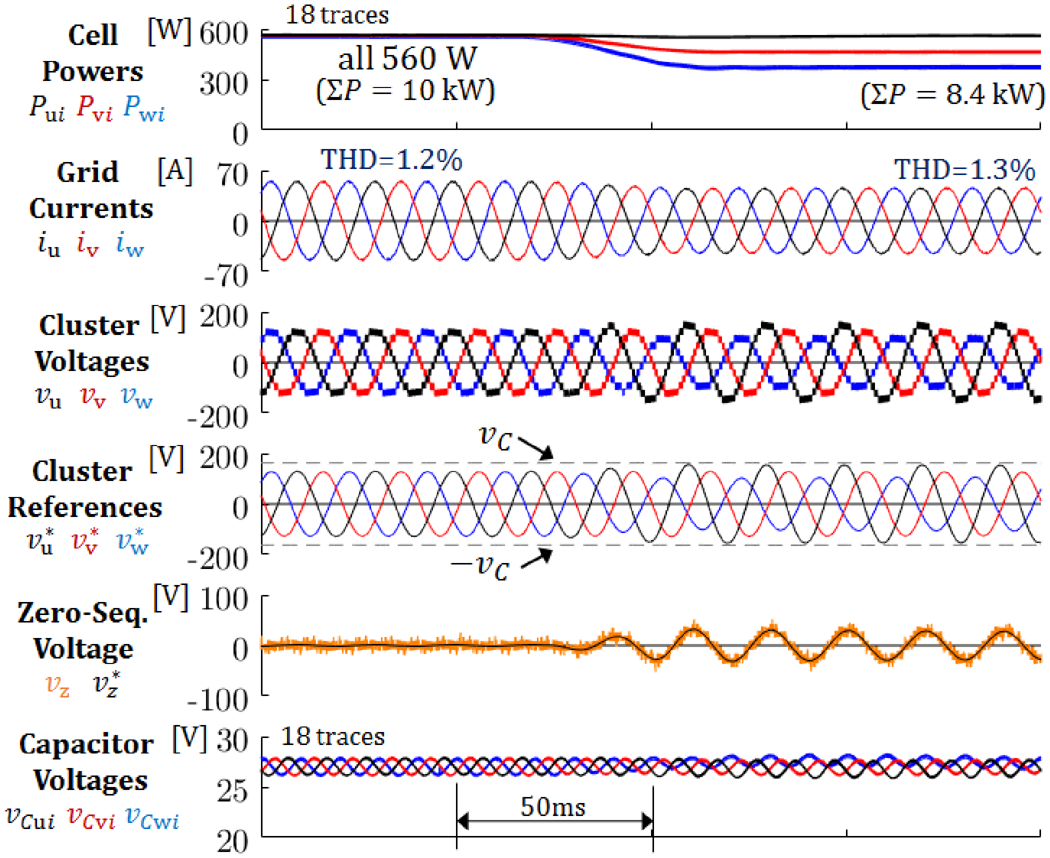

Figure 7 Experimental waveforms of SSBC inverter using standard sin zero-sequence voltage injection.

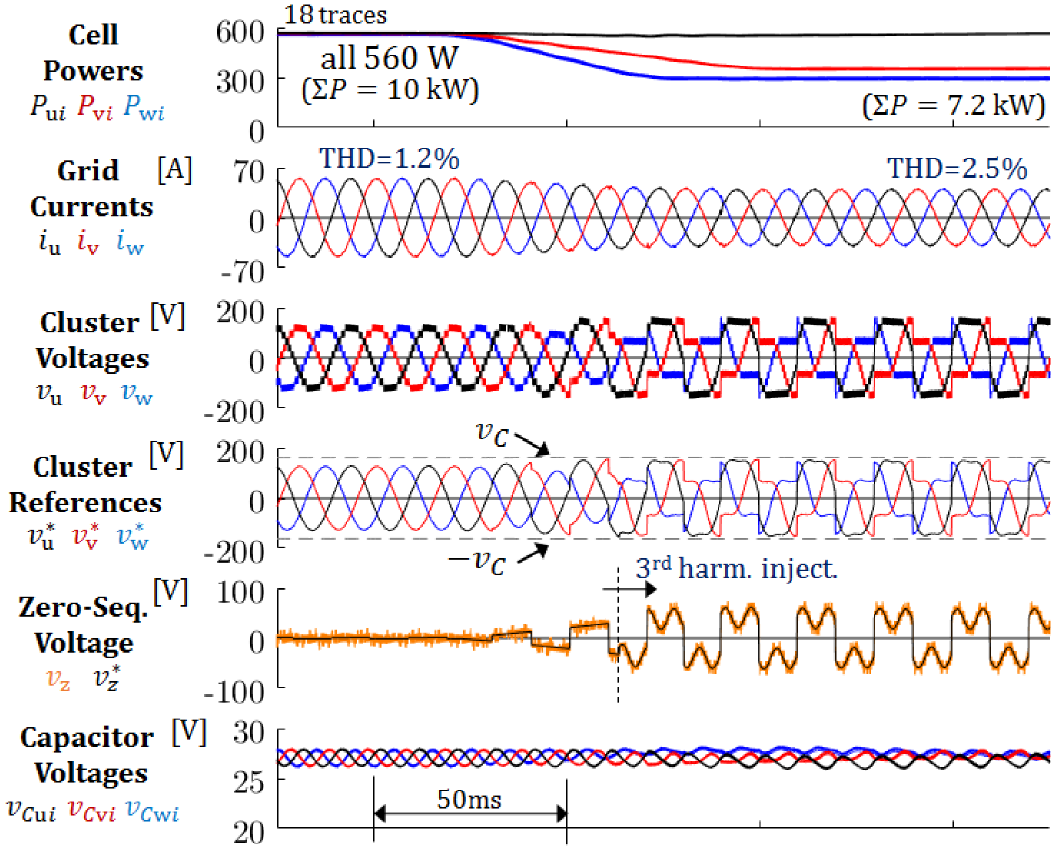

Figure 8 Experimental waveforms of SSBC inverter using advanced zero-sequence voltage injection.

Intercluster Power Balancing Limitation of SDBC Inverter

The SDBC inverter constitutes the dual circuit topology of the SSBC inverter. In analogy to the zero-sequence voltage for the SSBC inverter, a zero-sequence current flows through each cluster that is used to compensate for power generation imbalances among the three clusters. Since the cluster voltage is tied to the grid line-to-line-voltage, the zero-sequence current is the only means to control the transfer of power among the three clusters.

Contrary to the SSBC inverter, in which the intercluster power balancing capability is limited by the available cluster dc-link voltage, the SDBC imposes the limitation on the maximum cluster current that is allowed to flow during operation. The rms current in each cluster shall not exceed the design current, that is typically set as the current I_{rated} at the rated power condition.

The hypothetical worst-case scenario occurs, when cluster uv and another cluster (e.g. cluster vw) generate rated power while one cluster (e.g. cluster wu) generates no power. In this case the relative increase in cluster current for clusters uv and vw accounts to only 15% higher than the rated cluster, when no power imbalances exist. The reason for the relatively small increase in cluster current for the SDBC inverter is the decreasing three-phase grid current at higher imbalances. This is contrary to the SSBC inverter, where a decrease in inverter output power has only a very small impact on the amount of required cluster dc-link voltage.

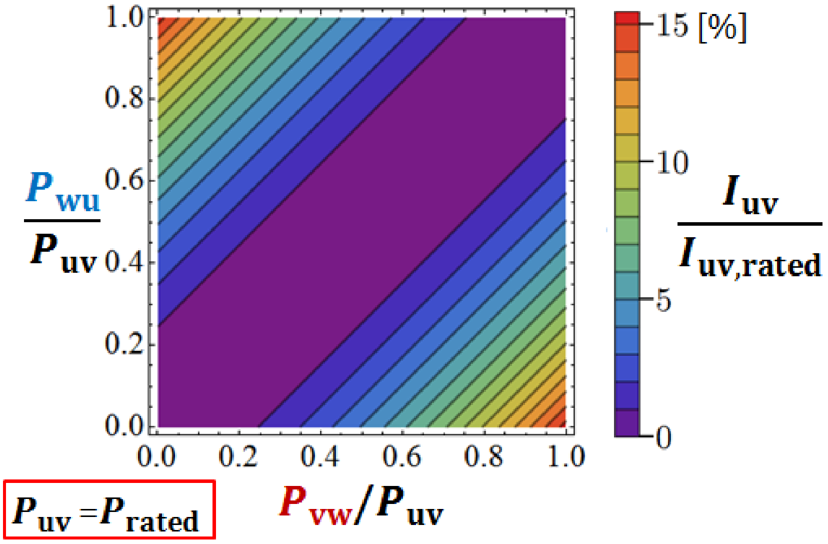

Figure 9 Power-balancing diagram for the SDBC inverter.

Fig.9 shows the energy-balancing diagram of the SDBC inverter. The diagram depicts the normalized current of cluster uv during arbitrary imbalanced operation. It can be seen that in the worst case, when one cluster generates zero active power, while the remaining two clusters operate at the rated power, the maximum increase in cluster rms current yields only about 15%. It can further be observed that over a wide range of power imbalance, the relative increase in cluster current is only marginal. A sufficient margin on the current rating theoretically allows the SDBC inverter to operate under any imbalance condition.

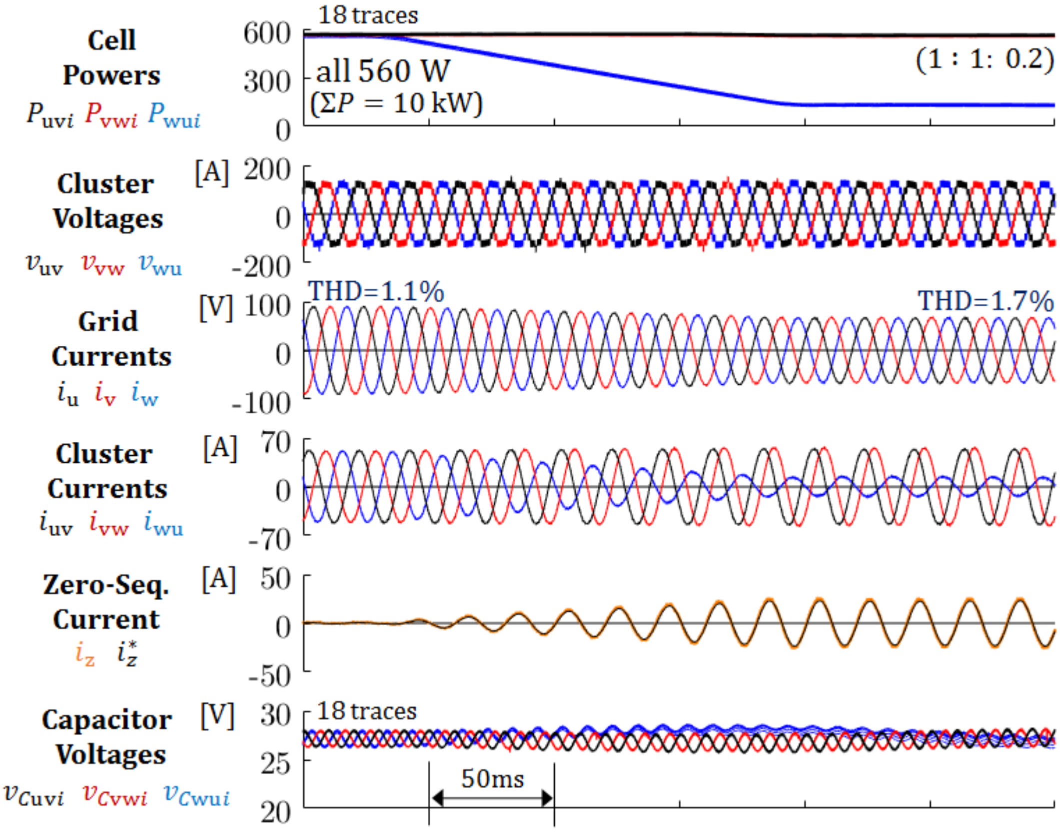

Figure 10 Experimental waveforms of SDBC inverter during single-cluster power drop.

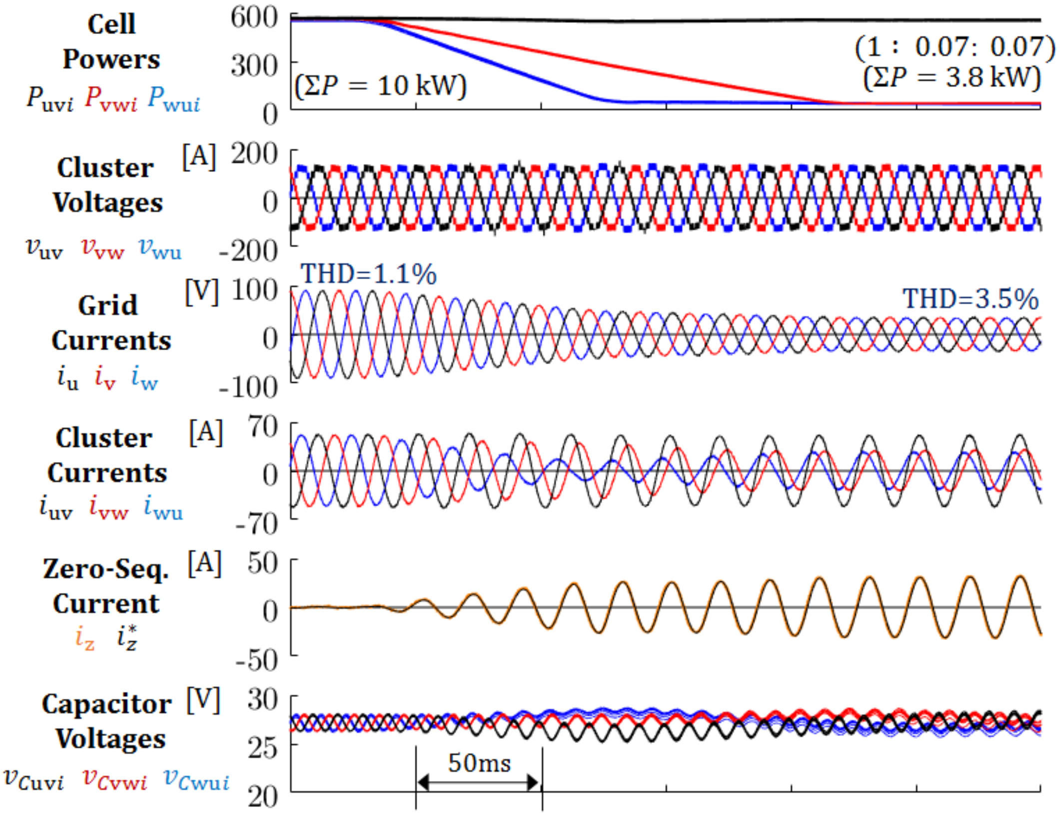

Figure 11 Experimental waveforms of SDBC inverter during two-cluster power drop.

Figs.10 and 11 show experimental waveforms demonstrating the capability of the SDBC inverter to operate even when the generated active power in each cluster becomes highly imbalanced. In Fig.10, the active power generation in cluster wu gradually decreases to 20% of its initial condition, while the active power generation in clusters uv and vw remains unchanged. A zero-sequence current is injected as a consequence of the imbalanced power generation. The voltage of the 18 floating capacitors v_{ij} is kept balanced close to the set value of 27.5~V for each capacitor.

In Fig.11 the active power generation in both clusters vw and wu reduces to 7% of its initial value, while the active power generation in cluster uv remains constant at rated value. Despite the very high imbalance ratio, the SDBC inverter can produce balanced grid currents and keep the 18 capacitor voltages balanced at their set value. The zero-sequence current i_z follows its reference i_z^* without showing any significant deviation.

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