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## Review of multilevel converters for application in solid state transformers

**Abstract.** This paper presents an overview of AC-DC, DC-AC and DC-DC power converter topologies used in the context of the application of solid state transformers. It describes the features of individual solutions, with an emphasis on multi-level topologies connected to the medium voltage AC grid, what allows to apply commonly available and relatively inexpensive low-voltage semiconductor switches. Such systems maintain high efficiency as well as high switching frequency, resulting in reduction of converter passive elements volume and weight as well as overall price.

**Streszczenie.** Niniejszy artykuł przedstawia przegląd topologii przekształtników energoelektronicznych AC-DC oraz DC-DC, pod kątem zastosowania w energoelektronicznych transformatorach inteligentnych. Opisano w nim cechy poszczególnych rozwiązań, ze szczególnym naciskiem na przekształtniki wielopoziomowe, które pracując wraz z siecią elektroenergetyczną średniego napięcia (SN), umożliwiają zastosowanie standardowych i stosunkowo tanich niskonapięciowych łączników półprzewodnikowych, a także zmniejszenie rozmiarów, wagi i ceny transformatora. (Przegląd topologii przekształtników wielopoziomowych pod kątem zastosowania w inteligentnym transformatorze).

**Keywords:** power electronics, smart transformer, multi-level converters, SST.

**Słowa kluczowe:** energoelektronika, inteligentny transformator, przekształtniki wielopoziomowe.

### Introduction

Development of Smart Grid (SG) calls for flexible solutions to control power flow at a distribution level. Recently a group of devices called Custom Power Systems have emerged. By definition these are power electronic converters applied to distributions systems that are designed to control power flow and power quality.

To improve SG functionality, there is a desire to implement power conversion and power control functionality in one device. Future trend is to replace conventional distribution transformers with “smart” solutions, based on power electronic converters. Therefore application of power electronic converters as a distribution transformer have become a wide area of interest.

Increasing availability of medium voltage IGBT's is making applications of power electronic converters directly with Medium Voltage (MV) grid technically and economically feasible. However, current state-of art semiconductor devices are still not ready to operate with MV directly. Common voltage classes of semiconductors are: 600V, 1200V, 1700V, 3.3kV and 6,5kV. Applicable solutions include: connection of a converter via LV/MV transformer, series connection of semiconductor devices or multilevel converter topologies.

Although multilevel converters have been described in literature since 1980's [1], they have gained wide interest in industry just lately. The falling price of standard semiconductor devices, the availability of advanced DSP and FPGA control platforms and the trend of reducing the overall dimensions of devices and passive components, as well as increasing the switching frequency and maintaining high performance are only some of a number of factors influencing the high interest in multi-level power electronic converter systems.

### Solid State Transformer concept

SST is designed to replace conventional distribution transformer that is to convert MV AC to LV AC at power levels ranging from few hundred kVA up to few MVA. Typical arrangement of SST is presented in Fig. 1 SST performs multistage power conversion:

- Medium Voltage AC-DC Converter (MVC) converts MV AC to MV DC,
- DC-DC converter reduces DC voltage level from MV to LV. This converter incorporates medium frequency transformer (MFT), that provides galvanic isolation between circuits,
- Low Voltage DC-AC converter (LVC) converts LV DC to LV AC.

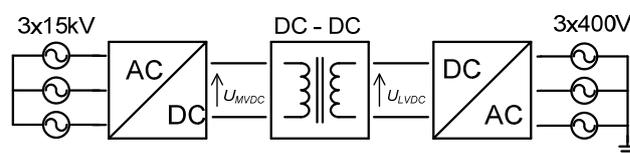


Fig. 1. Block scheme of SST with medium frequency intermediate transformer

Presented structure is only one of possible solutions, however, this structure is the most advantageous [2]. Although SST structure is much more complex compared to conventional transformer it may eliminate some of the disadvantages and add a completely new functionality that was not yet available, such as:

- The presence of DC-link allows to direct connection of DC grid as well as additional energy storage components, eliminating the need for application of additional power converters,

- Proper operation with voltage unbalance, voltage dips and other voltage disturbances that will not be transferred from one side of the transformer to the other,
- SST is able to fully control the amount and direction of the power flow and can compensate reactive power independently on both sides,
- SST can dynamically control voltage at LV side and compensate for disturbances caused by disturbing non-linear loads,
- SST can communicate each other and with other elements of the power grid, forming so called Smart Grid (SG). SSTs exchanging data each other, may also control the flow of energy and its parameters to reconfigure the power grid in case of failure and adapt it to work in new conditions, limiting the negative effects for end users.

Industrial implementation of SST requires use of standard components, as well as flexibility in design. Such objectives can be met with use of Power Electronic Building Blocks (PEBB) approach. For MV and HV applications a specific class of converters have been proposed – Modular Multilevel Converters (MMC) [3-6]. Siemens already offers a MMC system for STATCOM (SVC Plus) applications that operates at MV ranges [7]. However in previously proposed approaches only single-phase half-bridge or full-bridge converters are considered as modules.

In author's opinion recent development in power electronics, mainly introduction of multilevel IGBT modules indicate, that also multilevel topologies should be considered as PEBBs [8]. Therefore, in the next chapters a brief survey of possible topologies suitable to build modular SST is presented. If such blocks are properly chosen and their design is optimized, SSTs for various power and voltage levels can be easily constructed.

### Medium Voltage Converter

AC-DC converter operating at MV level is particularly suitable to be designed as a MMC. Block scheme of such solution is shown in Fig. 2. Each phase consists of  $n$  series-connected modules (cascaded topology). Each unit in cascade modulates the voltage, and the sum of AC voltages of all modules in one leg is the output voltage. At the same time DC voltage of each module is  $n$  times smaller compared to solution with single converter.

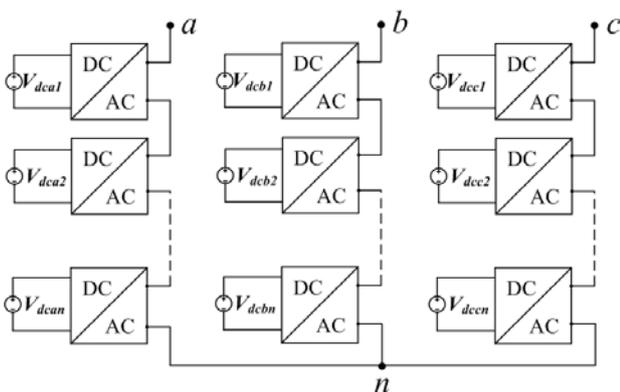


Fig. 2. Block scheme of three-phase Modular Multilevel Converter [9], [10]

Modularity of cascaded topology allows for easy expansion of converter unit for desired voltage level by increasing number of modules and therefore number of output voltage levels. Multilevel cascade converter designed with adequate voltage reserve, in case of damage of one of transistors in any module, should be able to work properly, but with less voltage levels. In such a situation the

damaged module exhibits a voltage equal to 0 V, the other modules must work with a higher output voltage. Summed increased voltage should be equal to the phase voltage before the failure.

The modules forming the highest voltage levels are loaded with less power than modules forming levels at zero pass of phase voltage. This results in unequal heating of the semiconductor switches and in the long term can lead to damage of semiconductor structure. Implementing the control method which will properly manage a switching of transistors, will not only eliminate the problem of uneven heating and uneven distribution of power, but also increase the power of the entire system.

Cascade topology achieves high switching frequency while maintaining a relatively low switching losses. Because most of the time transistors in module do not participate in voltage modulation, but are on or off, when does not occur switching losses on them.

In MMC topology modules may be composed from any  $j$ -level inverters. In general, the number of voltage levels in one phase for multilevel converters can be described by the equation [11]:

$$(1) \quad m = 1 + \sum_{j=1}^n (m_j - 1)$$

where:  $m$  – number of levels in leg,  $n$  – number of modules in leg,  $j$  – number of levels in  $n$ -level module.

A larger number of voltage levels, relative to the two-level topology, with the same values of filter elements, can achieve smaller voltage and current THD [12].

In recent solutions half-bridge and full bridge modules were proposed. Two-level half-bridge module, built with two transistors (Fig. 3a) can have two output voltage levels:  $+V_{dc}/2$  and  $-V_{dc}/2$ , while the full-bridge topology (Fig. 3b) built with transistors is a three-level system with the possible output voltages:  $+V_{dc}$ ,  $0$  and  $-V_{dc}$ .

In these modules transistor legs can be potentially replaced with three-level Neutral Point Clamped (NPC) or Flying Capacitor (FCC) topologies. These solutions provide similar functionality and complexity and both can be successfully applied for this application. In this paper NPC solution will be shown as an example.

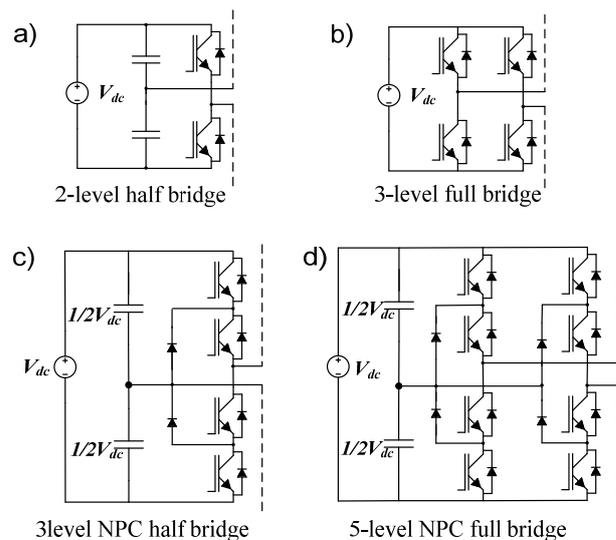


Fig. 3. Module topologies: a) half-bridge – 2-level, b) full-bridge – 3-level, c) NPC half-bridge – 3-level, d) NPC full bridge – 5-level

It is worth pointing out, that using generalized NPC and FCC topologies it is possible to build converter legs with  $2m+1$

output voltage levels and output voltage increased respectively. These converters could theoretically provide MV operation without connecting modules in series. However, with more, than 5 levels topologies as well as modulation and control issues become too complex to be applied practically. For this reason only three-level converters operating as modules are considered.

Half-bridge three-level NPC converter (Fig. 3c) maintaining the same DC-link voltage as 2-level half-bridge can be built with transistors having twice lower voltage class. It is able to generate three voltage levels:  $+V_{dc}/2$ ,  $0$  and  $-V_{dc}/2$ . By adding a second transistor leg to the three-level NPC half-bridge, there is obtained five-level full-bridge NPC (Fig. 3d), with of output voltage levels:  $+V_{dc}$ ,  $+1/2V_{dc}$ ,  $0$ ,  $1/2V_{dc}$  and  $-V_{dc}$ .

There is also possibility of using transistors of the same voltage class in all topologies. Then, the DC-link voltage in NPC topology would be twice higher than in topologies shown in Fig. 3a and 3b.

From the above it is clear that full-bridge inverter can provide twice the output voltage compared to half-bridge, irrespective of number of levels in converter leg. Obtaining the same AC voltage will require twice more half-bridges than full-bridges. The number of semiconductor devices will be equal in both cases, but half-bridges requires twice as much DC capacitors, as well as other auxiliary equipment such as measurement, control, chassis, connectors etc. This increases modularity, but significantly raises the cost of the system. This fact supports the use of full-bridge topology in intelligent transformer.

An example of waveform of the 15-level converter is shown in Fig. 4. It can be obtained by using [13]:

- 14 half-bridges,
- 7 full-bridges,
- 7 NPC half-bridges,
- 4 NPC full-bridges (can produce 17-levels).

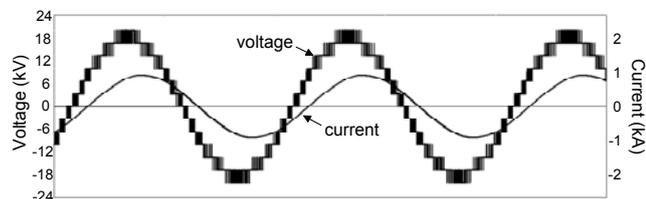


Fig. 4. Waveforms of cascaded 15-level converter

### DC-DC Converter

The task of the DC-DC converter module is to provide galvanic isolation between MVC and LVC and match DC voltage levels to the values required by respective modules [14]. Considering increasing amount of distributed generation units, DC-DC converter should be capable of bidirectional energy transfer, while maintaining as high efficiency as possible. Utilization of medium frequency transformer has a fundamental advantage of reduction in core size and thus reduction in overall system volume [2]. Increase frequency in transformer is essential, therefore use of lower voltage class transistors with smaller turn-on/turn-off times is recommended. Again, multilevel topologies are desired, as they enable increase in DC operating voltage, while using same semiconductor switches. Lower voltage class of semiconductors reduces switching losses, thus they can work with higher frequency, reducing volume and mass of transformer.

There are two groups of topologies that can fulfil these requirements, namely: Dual Active Bridge (DAB) and Series Resonant Converter (SRC). Both of these groups can be used in different configurations regarding number of phases

and voltage levels. The most promising topologies are described below.

DAB, presented in Fig. 5a contains of two full-bridges connected by medium frequency transformer. There are three modulation techniques possible for DAB [15]:

- Phase Shift (PS) modulation,
- Duty Cycle (DC) modulation,
- Phase Shift + Duty Cycle (PS+DC) modulation.

PS modulation is based on variable phase shift between primary voltage and secondary voltage of transformer. Phase shift should be in a range of  $\langle -90^\circ \text{ to } 90^\circ \rangle$ . Beyond this range transformer reactive current will rise, while amount of transferred energy will fall. In PS modulation switches can operate with Zero Voltage Switching (ZVS) or Zero Current Switching (ZCS), but only in certain phase shift ranges.

DC and PS+DC modulation techniques enable further reduction in switching losses. To achieve this either zero voltage states need to be used. Therefore, a full-bridge can be substituted by NPC half-bridge, as shown in Fig. 5b.

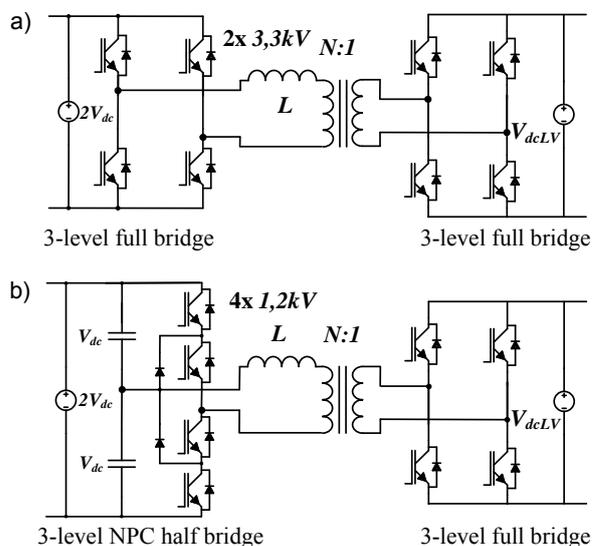


Fig. 5. Dual Active Bridge with multilevel converter on MV side

Both topologies shown in Fig. 5 can work with the same DC-link voltage, but there is significant difference between them. NPC half bridge (Fig. 5b) operating at the same voltage can be built with lower voltage class transistors, which enables increase in switching frequency. Moreover, half-bridge topology produces half the output voltage compared to full-bridge, so that transformer turn ratio can be reduced by a factor of two.

On the market there are many of semiconductor modules available, containing in one package all 4 IGBT switches and 2 diodes connected in NPC topology. High-density packing of switches minimize volume of converter, reduces parasitic inductances and capacitances further more reduces EMI.

Second promising topology - SRC is presented in Fig. 6. Capacitor  $C$  and transformer leakage inductance  $L$  are forming LC series resonant circuit. SRC operates with switching frequency near resonant frequency, therefore voltage and current of transformer are nearly sinusoidal [16]. This also reduces EMI.

Operation at resonant frequency results in ZCS, which is great advantage of this converter allowing it to operate at high frequency with low losses. In contrast to DAB, SRC presents no advantages of multilevel voltage operation – it would be necessary to switch transistors with non-zero current, which cancels out main advantage of this topology.

Increase of DC voltage would require either use of series-connected semiconductor devices. Also series resonant capacitor is high-voltage and high-current rated, thus it is relatively large and expensive. These drawbacks are significant in high power applications, therefore DAB topology is preferred.

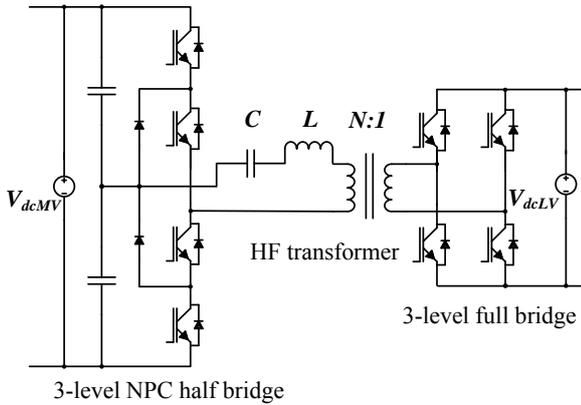


Fig. 6. Series resonant converter with multilevel module on MV side

Both DAB and SRC can be realized as a three-phase converters. DAB3 topology, presented in Fig. 7 consist of a two three-phase bridges connected with HF transformer [17-19].

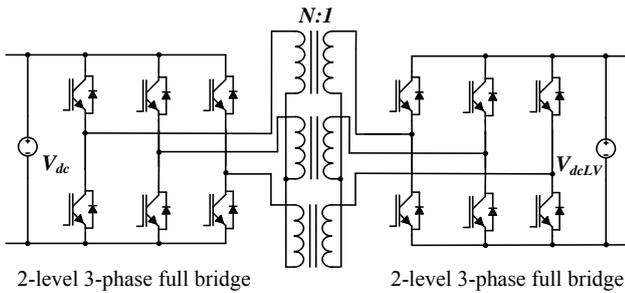


Fig. 7. Three-phase Dual Active Bridge

Presented circuit is able to connect a DC voltage source with different values through appropriate transformer ratio and the use of multilevel inverter on the side of medium voltage and a three-level full-bridge on low-voltage side. There is the ability to use simpler solution also on the medium voltage side, we can use 3 level full-bridge with 6,5kV transistors, but then will be reduced switching frequency and efficiency would be also decreased. Such a solution would imply increasing the values of elements in the filters and increase the size of the transformer core.

Use of three-level NPC (3L-NPC) converter in MV side shown in Fig. 5b allows to use transistors of not only the same voltage class, but also of the same current class as on LV side. This ensures that all semiconductors will be used in an optimal way, working at high frequency.

Use of half-bridge topology, instead of the full-bridge, reduces by half voltage on terminals applied to transformer on the MV side, which reduce the volume of the transformer core. Such a solution significantly reduces the cost of the entire device, despite the additional capacitor branches in half bridges.

The main advantage of the 3L-NPC (Fig. 5b) is that all of the switching devices in a leg withstand only half of the dc bus voltage during commutation between states, which also yields lower in comparison to the two-level inverter.

To obtain high DC-link voltage for full-bridges of MVC, 3L-NPC have to be connected in series. Using topology presented in Fig. 5b, we need as much transistors on MV

side of DAB as on LV-side. To minimize number of transistors on LV-side, there is presented in Fig. 8 new topology of three-phase dual active bridge (DAB3). Instead of 12 transistors on LV-side in previous solution, there is only 6 required.

Topology presented in Fig. 8 is a combination of DAB3 (Fig. 7) and 3L-NPC DAB (Fig. 5b). Three-phase full bridge on the left side of transformer, can be replaced with three modules of 3L-NPC. Connection of 3L-NPC modules in series allows to obtain a high DC-link voltage for MV modules of NPC full-bridges. Topology presented in Fig. 8 provides the lowest number of switches achieving very high DC-gain.

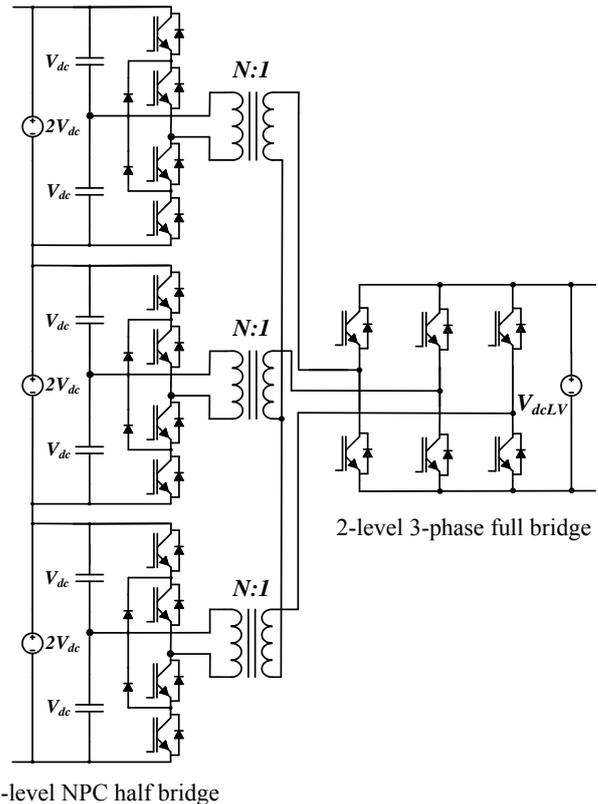


Fig. 8. Mixed topology of DAB3 to obtain high DC ratio

### Low Voltage Converter

On the low voltage side the simplest solution is to use two-level inverter. This solution is not free of drawbacks. Three-level NPC topology shown in Fig. 9 allows the use of transistors of the voltage class of 600V, which allows switching at a high frequency, while maintaining high efficiency.

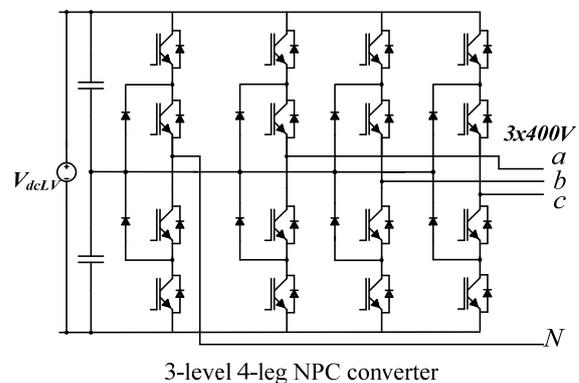


Fig. 9. Three-level four-leg topology proposed for LVC

Thanks to a three-level topology, emitted electromagnetic interference remains low, it is possible to apply a grid filter with elements of small values, which has a direct impact on size and price of the device [20].

The LVC requires possibility to operate with LV four-wire network and operate correctly under unbalanced conditions. It has been shown, that three-level, four-leg topology can fulfil these requirements [21]. Research mentioned is verified with three-level flying capacitor topology, however NPC topology can provide the same functionality and performance.

## Summary

Solid state transformers provide attractive alternative to conventional distribution transformers. This solution has a number of advantages hard to find in a traditional power transformer such as flexible, bidirectional control of active and reactive power, robustness against voltage disturbances, reduced volume and ability to integrate with Smart Grid.

Widespread application of SSTs is dependent on development of reliable technology of MVC and DC-DC converters, that constitute the system. With present semiconductor technology these requirements can be met with modular converters with multiple building blocks connected in series at MV side and in parallel at LV side. Multilevel converter topologies provide attractive solution for SST building blocks.

A review of possible topologies presented in this paper shows, that three-level NPC converter branches built with 3,3kV IGBTs pose a promising solution both for MVC and DC-DC converter blocks. In the MVC full-bridge solution is proposed to maximize operating AC voltage, while at MV side of DC-DC converter half-bridge is preferred, as it decreases transformer voltage with respect to DC voltage by a factor of two. Three-phase DAB with 3L-NPC half bridges ensures the lowest part number and allows to achieve very high DC-gain.

Recent studies show, that three-level topologies are also an attractive solution for LVC [20], [21].

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## REFERENCES

- [1] Nabae, A., Takahashi, I., Akagi, H., A New Neutral-Point-Clamped PWM Inverter, *IEEE Transactions On Industrial Electronics*, Vol. IA-17, No. 5, (1981), 518 - 523
- [2] Benysek G., Kazmierkowski M.P., Popczyk J., Strzelecki R., Power electronic systems as a crucial part of Smart Grid infrastructure – a survey, *Bulletin Of The Polish Academy Of Sciences* Vol. 59, No. 4, (2011), 455 – 473
- [3] Marquardt R., "Modular Multilevel Converter: An universal concept for HVDC-Networks and extended DC-Bus-applications," International Power Electronics Conference (IPEC), 21-24 June 2010, 502-507,
- [4] Nami A., Liang J., Dijkhuizen F., and. Demetriades G. D., Modular Multilevel Converters for HVDC Applications: Review on Converter Cells and Functionalities, *IEEE Transactions On Industrial Electronics*, VOL. 30, NO. 1, [2015], 18 - 36
- [5] Kolar J., Oritz G., "Solid State Transformer Concepts in Traction and Smart Grid Applications", *Conference for Power Conversion and Intelligent Motion (PCIM Europe 2015)*, Nuremberg, Germany, May 19-21, 2015
- [6] Aggeler D., Biela J., Kolar J. W., Solid-State Transformer based on SiC JFETs for Future Energy Distribution Systems, (online, cit. 2015-01-05), Available from: [www.pes.ee.ethz.ch](http://www.pes.ee.ethz.ch)
- [7] Claus M., Retzmann D., Uecker K. Zenker A., Improvement in Voltage Quality for Power Systems – with SVC PLUS, Internationaler ETG Kongress 2009, Available from: [http://www.ptd.siemens.de/ETG1009\\_SVCPLUS.pdf](http://www.ptd.siemens.de/ETG1009_SVCPLUS.pdf)
- [8] Solas, E., Abad, G., Barrena, J.A., Aurtenetxea, S., Carcar, A., Zajac, L., Modular Multilevel Converter With Different Submodule Concepts — Part II: Experimental Validation and Comparison for HVDC Application, *IEEE Transactions On Industrial Electronics*, VOL. 60, No. 10, (2013), 4536 - 4545
- [9] Malinowski M., Styński S., Simulation of Single Phase Cascade Multilevel PWM Converters, *The International Conference on "Computer as a Tool"*, EUROCON [2007], 1524 - 1529
- [10] Lai J-S., Peng F. Z., Multilevel Converters - A New Breed of Power Converters, *IEEE Transactions On Industrial Electronics*, VOL. 32, NO. 3, [1996], 509 - 517
- [11] Malinowski M., Gopakumar K., Rodriguez J., Perez M. A., A Survey on Cascaded Multilevel Inverters, *IEEE Transactions On Industrial Electronics*, Vol. 57, No. 7, (2010), 2197 - 2206
- [12] Hoosh B. M., Zaimedidine R., Undeland T. M., Comparison of Harmonics and Common Mode Voltage in NPC and FLC Multilevel Converters, *14th International Power Electronics and Motion Control Conference, EPE-PEMC (2010)*
- [13] Rech, C., Pinheiro, J.R., Hybrid Multilevel Converters: Unified Analysis and Design Considerations, *IEEE Transactions On Industrial Electronics*, VOL. 54, NO. 2, [2007], 1092 – 1104
- [14] de Oliveira, T.H., Roncalio, J.G.P., Rech, C., Costa, M.A.D., Performance analysis of modular converter for solid state transformers, *Power Electronics Conference COBEP*, [2013], 1060 - 1066
- [15] Everts J., Krismer F., Van den Keybus J., Driesen J., Kolar J. W., Optimal ZVS Modulation of Single-Phase Single-Stage Bidirectional DAB AC-DC Converters, *IEEE Transactions On Power Electronics*, VOL. 29, NO. 8, [2014], 3954 - 3970
- [16] Jing P., Wang C., Analysis of Isolated Three-level Half-bridge Bidirectional DC/DC Converter based on series resonant, *International Symposium on Industrial Electronics ISIE* [2012], 194 - 199
- [17] Gajowik T., Rafał K., Bobrowska-Rafał M., Bi-directional DC-DC converter in three-phase Dual Active Bridge Topology, *Przegląd Elektrotechniczny*, Vol. 90, No. 5, (2014), 14-19
- [18] De Doncker, R.W.A.A. Divan, D.M. Kheraluwala, M.H., "A three-phase soft-switched high-power-density DC/DC converter for high-power applications", *Industry Applications*, IEEE Transactions on , vol.27, no.1, Jan/Feb 1991, 63-73
- [19] Boillat D., Roy S. Tripathi, A.; Bhattacharya, S., "Design considerations of a three phase dual active bridge based on reactive power flow," *Energy Conversion Congress and Exposition (ECCE)* 15-20 Sept. 2012, 424-430
- [20] Teichmann R., Malinowski M., Bernet S., Evaluation of Three-Level Rectifiers for Low Voltage Utility Applications, *IEEE Transactions On Industrial Electronics*, VOL. 52, NO. 2, (2005), 471 – 482
- [21] Sedlak M., Stynski S., Kazmierkowski M.P., Malinowski M., Operation of four-leg three-level flying capacitor grid-connected converter for RES, *Industrial Electronics Society, IECON* (2013), 1100 – 1105