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Topology Development of Boost-Rectifiers Providing Sinusoidal Input Current

***Abstract**. The paper presents development of three-phase boost-rectifiers based on three bidirectional switches embedded inside of a three phase diode bridge rectifier. According to the base topology of three single legs, each including two AC inputs, a numbers of topologies are provided by connection of inputs together and to DC output capacitors. The boost rectifiers' topologies have to fulfil a demand of sinusoidal AC input current without any displacement and to deliver one or two DC output voltages. The boost rectifiers are supplied from a mains or from variable speed autonomous generating systems.*

Streszczenie.** Artykuł przedstawia rozwój trójfazowych układów prostowniczych podnoszących napięcie, oparte o trzy wbudowane łączniki dwukierunkowe wewnątrz trójfazowego prostownika diodowego. Stosownie do podstawowej topologii, złożonej z trzech modułów jednofazowych, z których każdy zasilany jest z dwóch wejść AC, wiele topologii zostało opracowanych na podstawie połączenia ze sobą wejść oraz do kondensatorów wyjściowych. Prostowniki podnoszące napięcie muszą spełnić wymóg poboru sinusoidalnego prądu przy braku przesunięcia fazowego oraz wytworzeniu na wyjściu jednego lub dwóch napięć stałych. Prostowniki zasilane są z sieci lub autonomicznego systemu wytwarzania energii o zmiennej prędkości generatora. **Rozwój trójfazowych układów prostowniczych podnoszących napięcie, oparte o trzy wbudowane łączniki dwukierunkowe wewnątrz trójfazowego prostownika diodowego

Keywords: boost-rectifiers**,** AC/DC conversion, sinusoidal input current, Vienna rectifiers, pseudo Vienna rectifiers
Słowa kluczowe: prostowniki podnoszące napięcie, pobór prądu sinusoidalnego, prostownik Vienna, pseudo prostowniki Vienna

Introduction

Most of power electronics AC/AC converters consists of two sub-converters connected by an intermediate DC link voltage. So the AC source of power usually delivers AC sinusoidal voltage which is rectified to the DC voltage by a converter called rectifier. The simplest rectifier is represented by a single phase diode H-bridge or a three phase diode bridge. Most of DC/AC converters (inverters) require fixed DC voltage that is independent to the AC supply voltage variation. In this case the rectifier has to be controllable. In great number of systems stabilized DC voltage is required which is higher than amplitude of the AC voltage as is shown in Fig. 1, where the rectified voltage has to be higher t han an amplitude V_{ACmax} of the supply AC voltage i.e. $V_{dcref} > V_{ACmax}$.

The rectifier, producing the DC voltage higher than input AC voltage, is called "boost-rectifier". The other requirement of the boost-rectifier operation is low content of higher current harmonics drawn from the AC source by the controllable boost-rectifier. The demand of the DC rectified, stabilized and boosted voltage and low harmonic content is provided commonly by a two or multilevel transistor bridge converters. However, unidirectional power flow is highly demanded so the transistor converters may be replaced by simpler topologies including simple diodes and lower number of transistors. Fig. 2 shows schematic diagram of the classical three phase diode bridge rectifier *DRe* and step-up DC/DC converter *BO* producing single DC stabilized voltage [1, 2, 3, 4, 5].

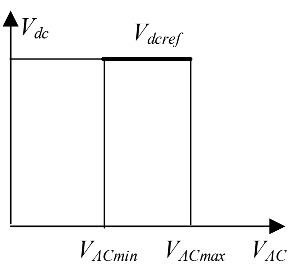

Fig.1. Boost-rectifier DC output voltage as a function of input AC amplitude voltage.

Another example of the rectifier and DC/DC converter is shown in Fig. 3 where there are two star connected sub-rectifiers *DRe1* and *DRe2* which delivers two DC voltages [2] that are stabilized by two DC/DC step-up converters [6]. The systems presented in Fig. 2 and Fig. 3 are very simple but their main disadvantage is square (or trapezoidal) AC source current waveform that contains high-order harmonics and overlapping results in displacement of the fundamental harmonic. Moreover, the two independent DC outputs may result in asymmetrical loads i.e. DC component. Therefore, such topology is not advised to use in mains systems but only to autonomous generation system supplied from low power permanent magnet generator. However, the diode rectifiers do not need any synchronization and they are very robust in accepting high overload transient current what, in comparison to transistor bridge rectifiers, is very significant feature.

A two level boost-rectifier providing single DC voltage and drawing sinusoidal AC input current without any displacement, controlled only by three active switches, was invented in 1992 by Koczara [7] and published in Power Quality Conference in Munich (1992) [8] and then in [9]. The invented boost-rectifier [7] provided the AC/DC conversion and the DC boosting in one converter called boost-rectifier. Another option of a three level boost-rectifier was patented also in 1992 [10] and published in [9]. A simplified two level boost-rectifier was also patented in 1992 [11]. The inventions [7, 10, 11] did open new family of boost-rectifiers but only the [7] and [10] development will be presented in the paper whereas topologies related to [11] will be described in the next paper.

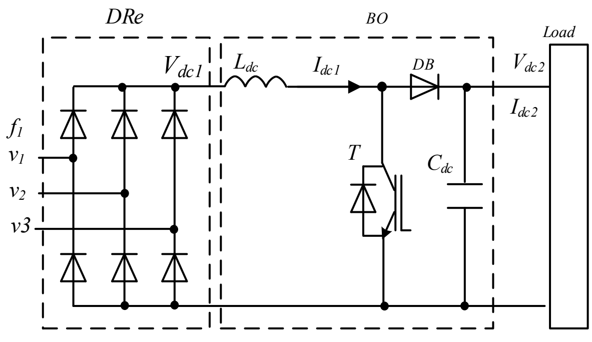

Fig.2. Schematic diagram of the three phase rectifier and step-up converter producing single DC voltage.

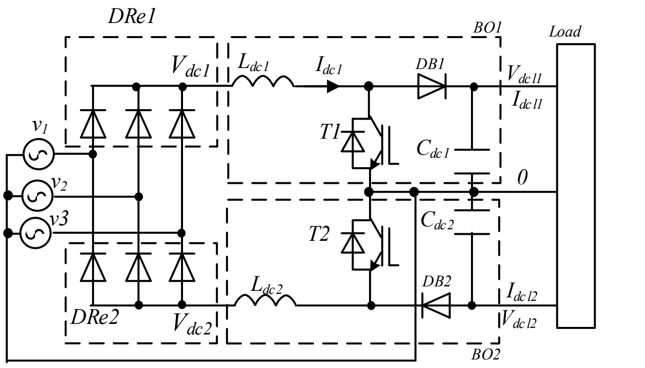

Fig.3. Three phase rectifier and step-up DC/DC converter producing two DC symmetrical voltages [6].

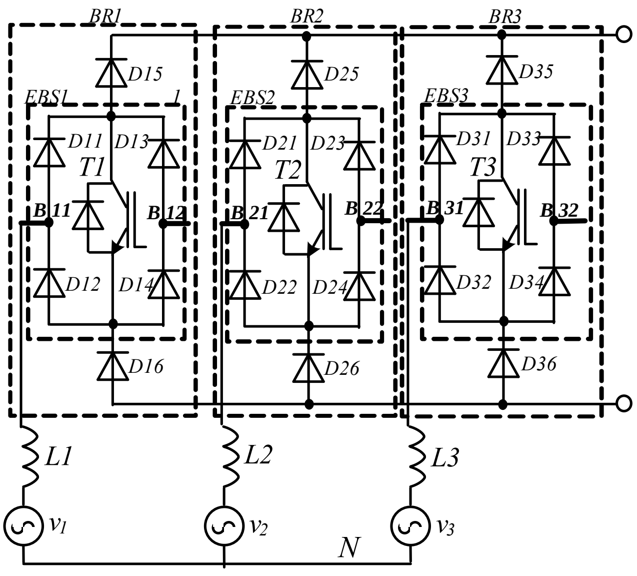

Fig. 4. Basic topology of the three phase boost-rectifier with embedded bidirectional switch.

Another simplified three level boost-rectifier was patented by Kolar [12] in 1994. The topology [12] of the boost-rectifier called by Kolar "Vienna rectifier" is based on modification of the [7] by introducing split capacitors with artificial zero potential. So the following works [7, 8] caused that great number of modifications were developed and they are presented in the paper.

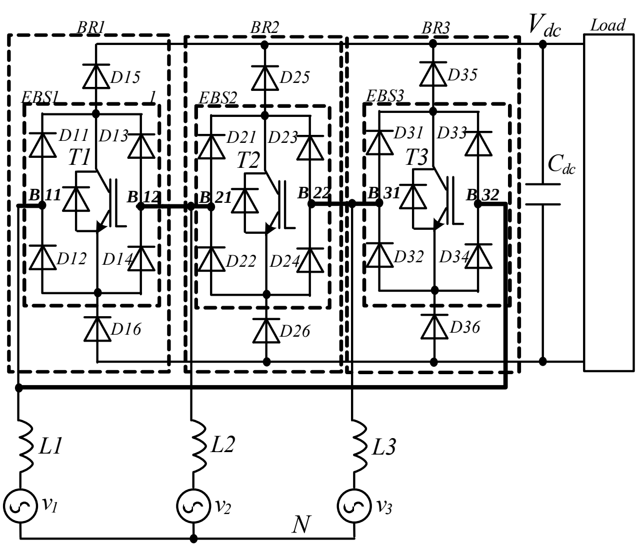

Fig. 5. Warsaw1 boost-rectifier topology [7, 8], 1992.

Development of the boost-rectifiers with embedded bidirectional switch

Basic topology of the three phase boost-rectifier with embedded bidirectional switch extracted from the [7, 8] is shown in Fig. 4. There are three parallelly connected double rectifiers *BR1, BR2, BR3*, with placed inside, embedded bidirectional switches *EBS1, EBS2, EBS3*.

Each double rectifier has an AC input. So the AC input of the *BR1* is *B11-B12*, the *BR2* is *B21-B22* and the *BR3* is *B31-B32* and to the inputs *B11, B21, B31* are connected three-phase voltage v_1, v_2, v_3 through chokes *L1, L2, L3*. When the transistors *T1, T2, T3* *are* not active then the topology shown in Fig. 4 corresponds to the classical three phase bridge with two diodes connected in series.

There are different topologies of the boost-rectifiers that are created by connection of inputs *B12, B22, B32* together or connection of the inputs *B12*, *B22, B32* to additional capacitors. So the connection (Fig. 5), marked by a thick line, i.e. *B12* to *B21, B22* to *B31*, *B32 to B11* and by placing a capacitor C_{dc} in the DC output, results in topology of the boost-rectifier [7, 8, 9]. This is a two level boost-rectifier with PWM control of the transistors *T1, T2, T3* that are working by short circuiting the AC inputs through chokes *L1, L2, L3*, shaping the input currents according to the sinusoidal reference [8, 9, 13]. This topology is called by Kolar as "Warsaw1 rectifier". As the phase current is forced by a line-to-line voltages it is possible to force the phase leading current. The topology of the boost-rectifier shown in Fig. 5 is very advantageous over a classical transistor bridge. In the boost-rectifier, made from the transistor bridge, in case of load short circuit at the DC link, all currents pass through fragile transistors whereas in the boost-rectifier short circuit load current is passing only by the robust diodes. Moreover, the transistor bridge converter requires blanking time protecting against cross short-circuit. The Warsaw1 boost-rectifier is connected to the DC link only by diodes. So it is very practical, especially when high frequency AC source is used. Hence the developed, based only on three parallel transistors, boost-rectifier is especially dedicated to high power systems supplied from high frequency sources and to high reliability systems. Another advantage of the Warsaw1 boost-rectifier is charging DC link directly from AC source via diodes. This results not only in increase of reliability but also in power losses reduction.

When the basic topology (Fig. 4) is additionally connected as shown in Fig. 6 then a three level boost-rectifier (called Warsaw2) is presented. The three level boost rectifier is created by new potential V_0, made by split DC voltage by two DC capacitors C_{dc1} and C_{dc2}. There are additional transistors *T11-T12, T21-T22, T31-T32* in each phase that are used to keep the potential V_0 balanced. So in such a boost rectifier additional transistors are used to charge output capacitors but other advantages, presented by the Warsaw1 boost rectifier are kept.

When the middle potential V_0 of the boost-rectifier, shown in Fig. 6, is connected as it is shown in Fig. 7 to a load then the artificial made potential (*0'*) may be used as neutral potential of a supply system producing AC voltage. However this neutral potential is kept only in range of maximum current of the balancing transistors (*T11 – T32*).

In 1994 Kolar patented [12] another option of connections, shown in Fig. 8. The new boost-rectifier was built by common connections of *B11, B21, B31* to the middle potential V_0, made by connection of two capacitors C_{dc1} *and* C_{dc2} placed in the DC output. So in this way it was created three level boost-rectifier with two wires DC output called by Kolar "Vienna rectifier". To balance the potential V_0 an additional special algorithm of the boost-rectifier control is required.

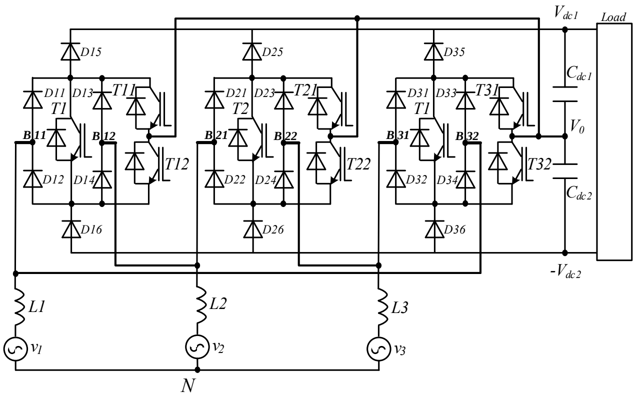

Fig.6. Warsaw2 boost-rectifier [10], 1992, [9] 1993.

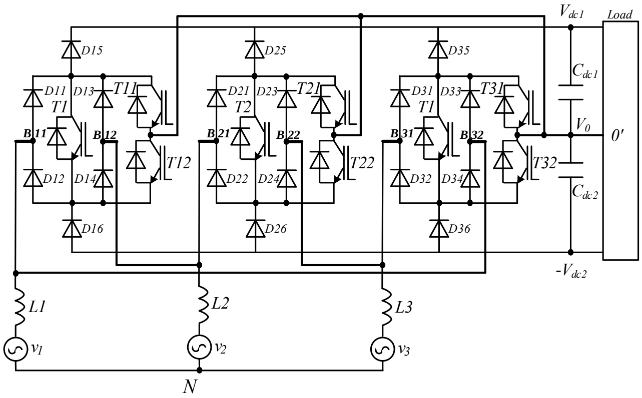

Fig.7. Boost-rectifier with three wires output including neutral (zero).

Presented results confirm the ability to provide sinusoidal input current [14, 15, 16]. Till now, the Vienna1 rectifier is the most developed and known boost-rectifier.

In 2003 Barbi connected together three inputs *B12, B22, B32* providing common potential *N'* and connects it to the neutral potential *N* of the supply system (Fig. 9) what made three single boost-rectifiers [17]. However, he stated "the presence of neutral point is undesirable" and then he did remove connection between the common point *N'* and neutral point *N* of the supply system creating in this way boost-rectifier shown in Fig. 10. Presented results confirm the ability to provide sinusoidal input current [17, 18] with cosφ = 1.

Next step of the boost-rectifier development was proposed by Tuusa [19]. In this modification inputs *B12, B22, B*32 are connected to split capacitor potential *0* and connected to the neutral potential of supply system *N* and to DC output as is shown in Fig. 11. The connection of the basic boost-rectifier are made by thick line. In this way three level boost-rectifier with three wires output was introduced. Moreover, the boost-rectifier was built as three single phase rectifier systems. Connection of the common point of the output *B12, B22, B32* to neutral potential *N* of the supply system made the output potential V_0 very stiff i.e. independent of load in case of short circuit event. In 2008 Tuusa [20] proposed an additional support to neutral potential by introducing balancing circuit as is shown in Fig. 12. The additional balancing circuit, made from transistors *TB1, TB2* and choke *LB,* assures stiffness of the neutral potential and keeps symmetry of the DC output voltages V_{dc1} *and* V_{dc2} in range of maximum current of the balancing transistors.

Boost-rectifiers shown in Fig. 5 to Fig. 12 were designed to operate as low polluting (with *cosφ* = 1) rectifiers connected to the fixed frequency and amplitude utility to supply by DC voltage drives, UPS and other equipment that requires stabilized DC voltage.

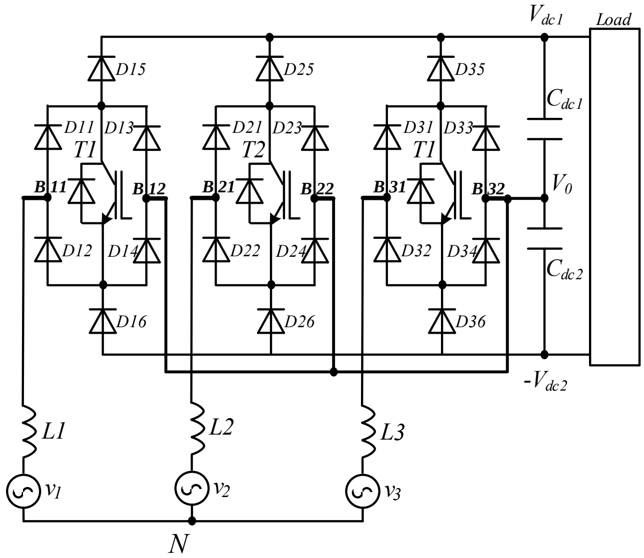

Fig.8. Vienna1 boost rectifier [10], 1994, [11, 12, 13].

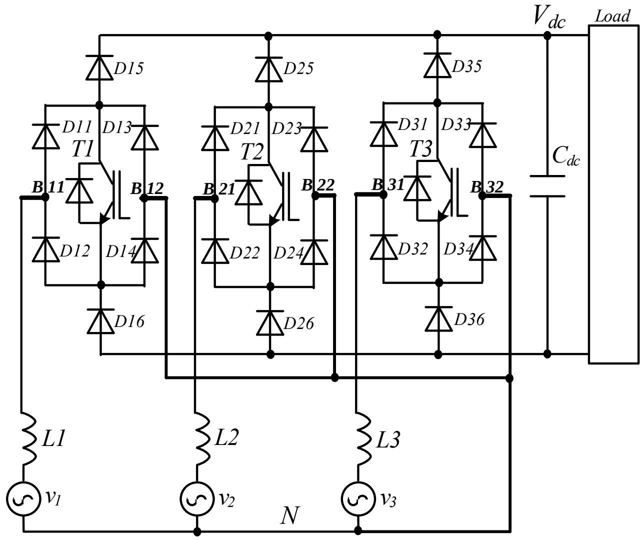

Fig.9. Boost-rectifier proposed by [17], 2003 Barbi.

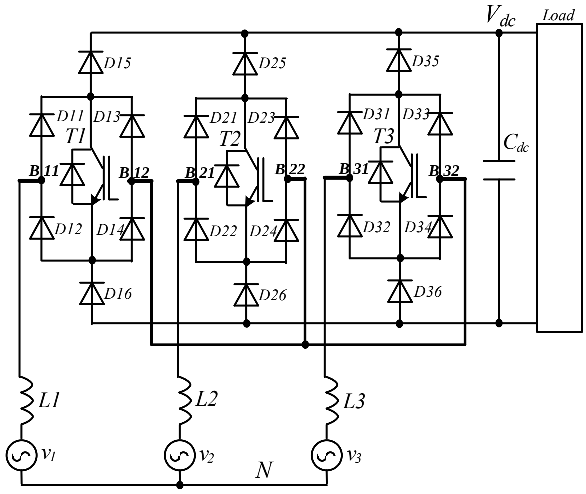

Fig. 10. Boost-rectifier without connection to neutral point of supply system proposed by [17], 2003 Barbi.

The next step of the boost-rectifiers development is application to the adjustable (variable) speed generation systems i.e. to the arrangement were the AC voltage amplitude and frequency are variable. The proposed topology had to be suitable for simple conversion DC/AC. Fig. 13 shows adjustable speed generation system in which a driving engine DE drives the permanent magnet generator PMG producing variable speed and frequency voltage that varies in very wide range. So the three phase boost-rectifier has to provide two DC voltages +V_{dc1} and $-V_{dc2}$ that are delivered to a DC/AC converter *TPIN.* The converter *TPIN* has to produce sinusoidal three single phase voltages with common neutral potential *N.* Therefore, the topology of the boost-rectifier is providing stiff neutral potential. The connections of the basic boost-rectifier are made by thick line. Such an arrangement is suitable for support of an AC microgrid.

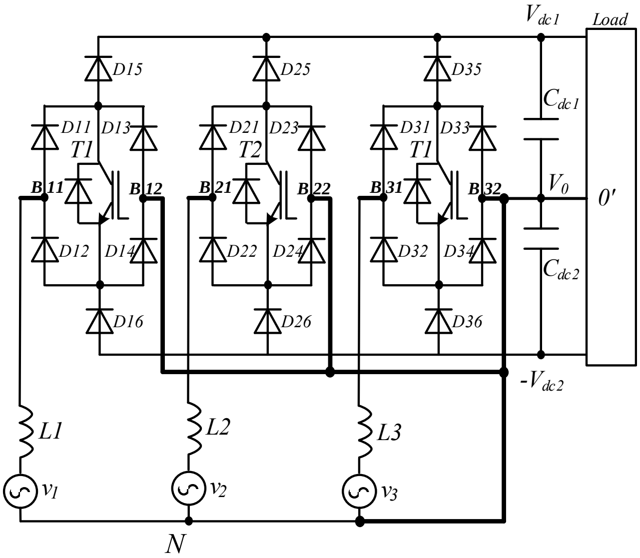

Fig.11. Boost-rectifier proposed by Tuusa [19], 2008.

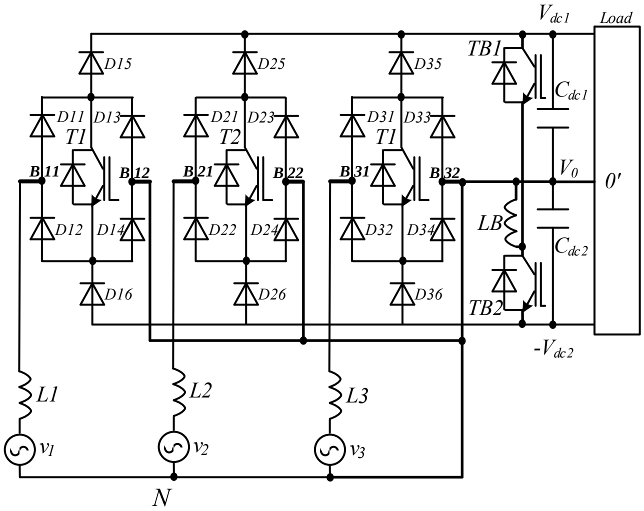

Fig.12. Boost-rectifier proposed by Tuusa [20], 2008

Another topology of the boost-rectifier, dedicated to microgrid, is shown in Fig. 14 (the connection of the basic boost-rectifier are made by thick line). This is an adjustable speed generation system providing DC microgrid. There are two battery energy storage systems for positive *BES1* and negative *BES2* parts of the microgrid. Moreover, an additional supercapacitor energy storages *SES1* and *SES2* are applied. The DC microgrid with stiff neutral wire and with two types of energy storage is very robust in overload condition. In short circuit event the load current is a sum of generator current (via rectifier), limited current delivered by battery storage and supercapacitor energy storage system. The DC three wires and three voltages system may be powered by a different additional energy sources for instance solar or wind miles. There are sets of loads LD1, LD2.

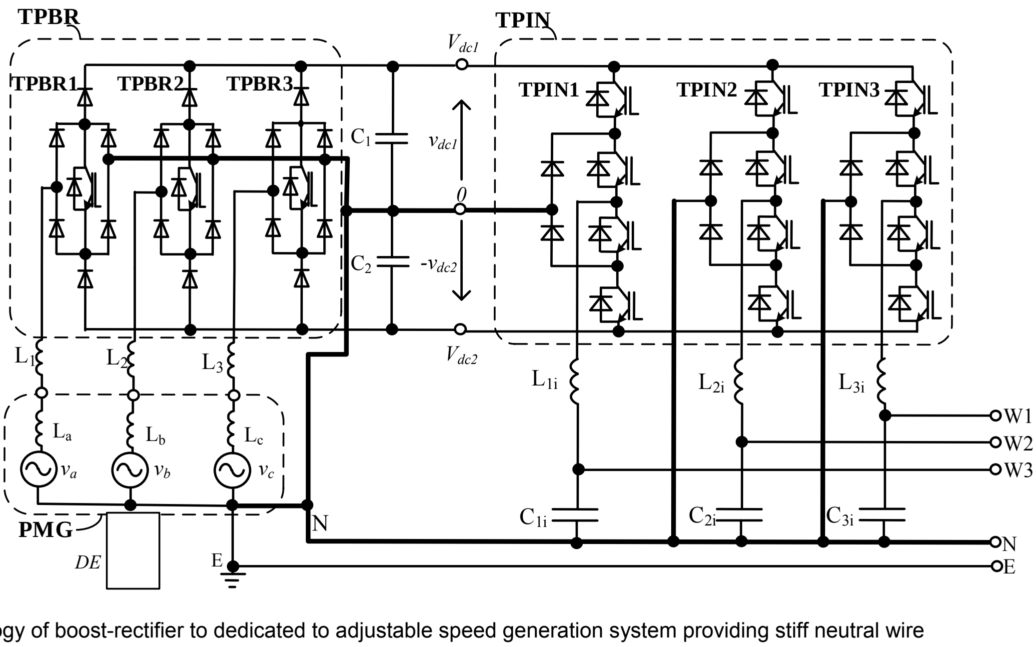

Fig.13. Topology of boost-rectifier to dedicated to adjustable speed generation system providing stiff neutral wire

Another type of boost rectifier (Fig. 15) was patented in 1992 [21]. This is a two level rectifier with delta connected switches DCBS and its topology and concept is partly similar to boost rectifier shown in Fig. 5. The boost rectifier from Fig. 15 was dedicated to drives so this is only two wires output. A modification of the topology (Fig. 15) leading to three level boost rectifier is patented, 2 years later in 1994, by Kolar [12]. The modified topology developed by Kolar is shown in Fig. 16. The star connected switches SCBS have common connection of the AC input that is connected additionally to “neutral” potential made by two capacitors CD1 and CD2. This type of the boost rectifiers will be presented in next papers.

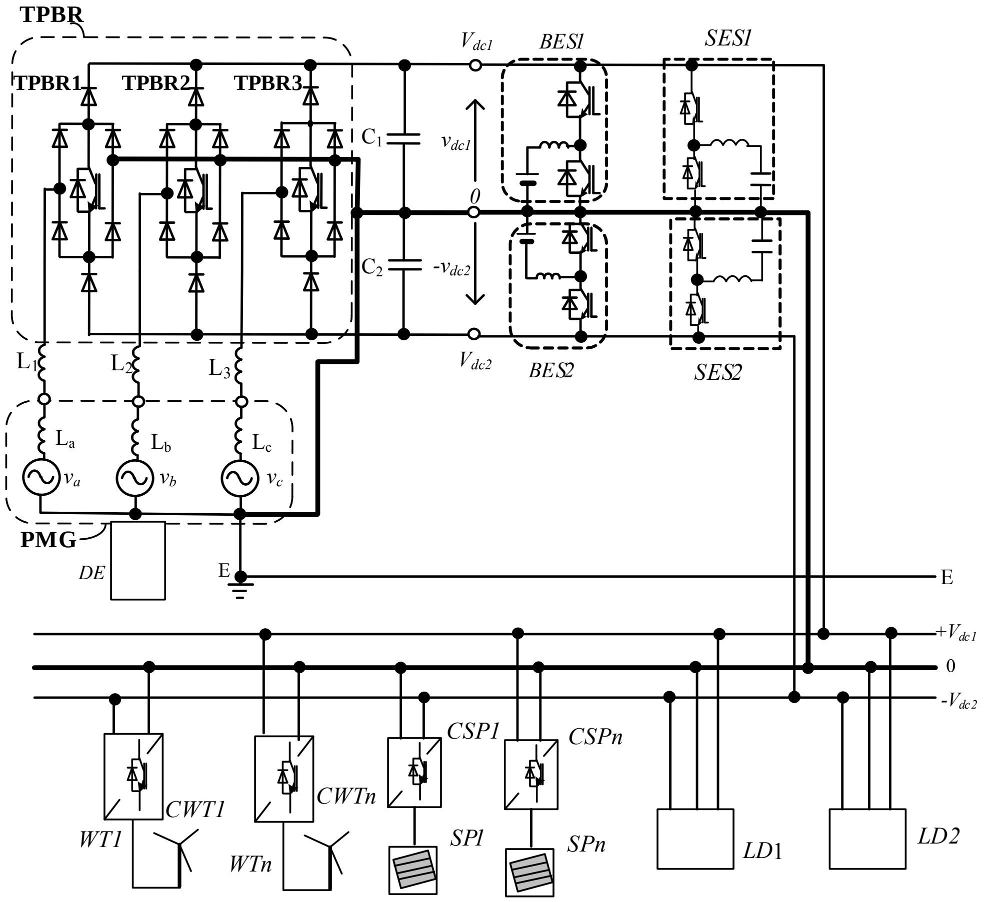

Fig. 14. The boost-rectifier topology dedicated to DC microgrid.

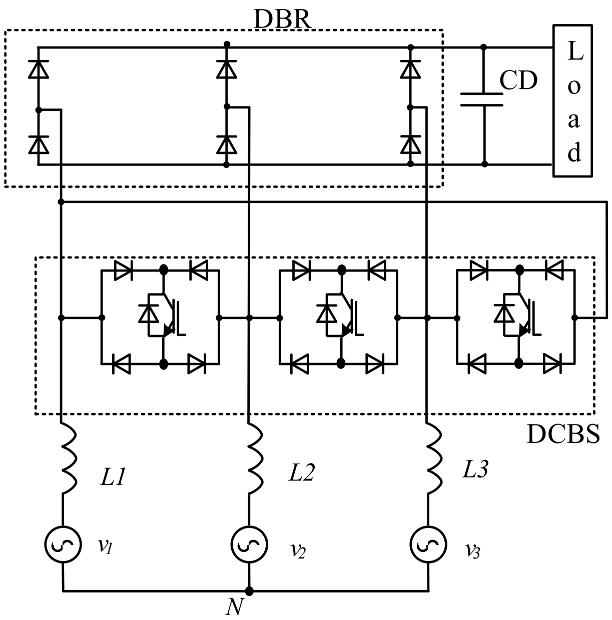

Fig.15. Simplified two level delta boost rectifier [21].

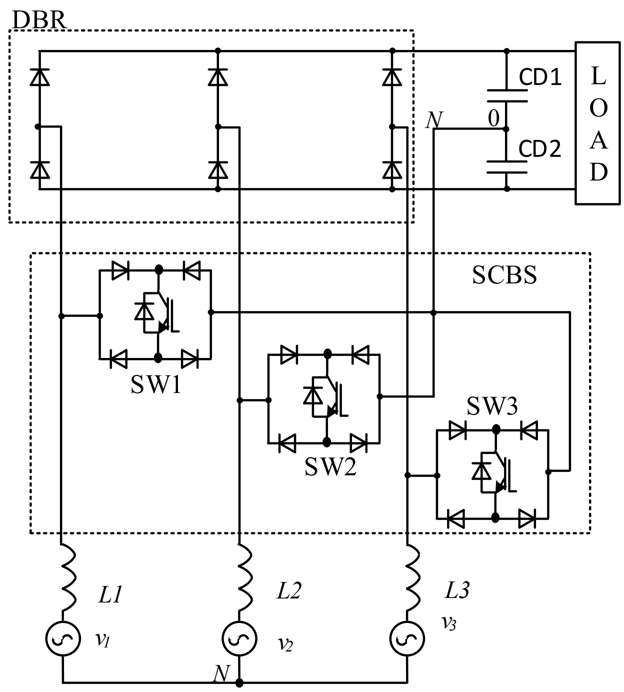

Fig.16. Simplified three level boost rectifier [22].

Conclusions

The paper presents topologies and part of history of development of the three phase boost-rectifiers based on embedded bidirectional switch placed inside three phase diodes bridge rectifier. There are two and three level converters with two or three DC output wires. The two wires DC output (microgrid) is dedicated mostly to supply drives whereas the three output including stiff neutral wire (stiff potential) is used to supply DC/AC converters providing AC sinusoidal supply system (AC microgrid).

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REFERENCES

[1] Da Ponte M., Grzesiak L., Koczara W., Pospiech P., Niedzialkowski A., Hybrid Generator Apparatus, *U.S. Patent 6175217 (B1)*, 1996
[2]. Al -Khayat N., Koczara W., Krasnodebski A., Electrical Power supply System and a Permanent Magnet Generator for Such a System, *Patent US 2007/0008741 A1*, Jan. 11, 2007
[3] Chakraborty S., Kramer W. E., Simoes M. G., Power Electronics for Renewable and Distributed Energy Systems, *A Sourcebook of Topologies, Control and Integration,* London, England: Springer Verlag, 2013, ch. 7, 235-265
[4] Strzelecki R., Benysek G., Power Electronics in Smart Electrical Energy Networks, London, England: Springer, 2008, 303-325
[5] Bhende C.N., Misra S., Siva Ganesh Malta, Permanent Magnet Synchronous Generator-Based Standalone Wind Energy Supply System, *IEEE Transaction on Sustainable Energy*, 2 (2011), n.4, 361-373
[6] Koczara W., Current waveform shaping, *Polish Patent PL 168999*, Warsaw, 30.10.1992
[7] Koczara W., Controlled Rectifier, *Polish Patent PL 167855*, Warsaw, 17.04.1992
[8] Koczara W., Unity factor three phase rectifier, Power Quality '92 Conference Europe, Munich, Germany, October 14-15, (1992), 79-88
[9] Bialoskorski P., Koczara W., Unity Power Factor Three Phase Rectifiers, PESC'93 24th Annual IEEE Power Electronics Specialists Conf., Seattle, (1993), 669-674
[10] Koczara W., Multiphase Controlled Rectifier, *Polish Patent PL 168997*, Warsaw, 30.10.1992
[11] Koczara W., Controlled Rectifier, *Polish Patent PL 169874*, Warsaw, 18.12.1992
[12] Kolar J.W., Vorrichtung und Verfaren zur Umformung von Drehstrom in Gleichstrom, European Patent Office EP 0660498 *A2*, 20.12.1994
[13] Koczara W., Bialoskorski P., Controllability of the Three Phase Rectifier Operating with Unity Power Factor, Fifth European Conference on Power Electronics and Application, Brighton, UK 13-16 September 1993, Vol. 7, 183-187
[14] Kolar J.W., Zach F.C., A novel three phase utility interface minimizing line current harmonics of high power telecommunications rectifier modules, 16th International Telecommunications Energy Conference, (1994), 367-374
[15] Kolar J.W., Zach F., Analysis of a New Three-Phases Forced Commutated High Power Factor Boost -Type AC/DC Converter, PEMC September 1994 Conference, Warsaw, (1994), 735-741
[16] Hartmann M., Miniboeck J., Kolar J. W., A Three-Phase Delta Switch Rectifier for More Electric Aircraft Applications Employing a Novel PWM Current Control Concept, Applied Power Electronics Conference and Exposition, (2009), 1633-1640
[17] Borgonovo, D., de Novaes, Y.R., Barbi, I., A three-phase three-switch two-level PWM rectifier, Power Electronics Specialist Conference 2003, vol. 3, 1075-1079
[18] Batista F.A.B., Barbi I., Space vector modulation applied to three-phase three-switch two-level unidirectional PWM rectifier, Applied Power Electronics Conference and Exposition, (2006), 944-950
[19] Ahuhtala J., Tuusa H., Space Vector Modulation Method for Unidirectional Four-Wire Three-Phase/Level/Switch (Vienna) Rectifier, 7th International Conference on Power Electronics, October 22-26, 2007 Daegu, Korea, 742-748
[20] Ahuhtala J., Tuusa H., Space vector modulated four-wire unidirectional three-phase/level/switch (VIENNA) rectifier with an additional leg for DC link voltage balancing, Applied Power Electronics Conference and Exposition, (2008), 238-244
[21] Koczara W., Controlled Rectifier, *Polish Patent PL 169874*, Warsaw, 18.12.1992
[22] Koczara W., Bialoskorski P., Multilevel Boost rectifiers as a Unity Power Factor Supply For Power Electronics Drive and Battery Charger, Proceedings of Industrial Electronics Conference ISIE, 1993, Budapest, 477-481
[23] Koczara W., Bialoskorski P., Modified Rectifiers with Unity Power Factor, PEMC 1994 Conf., Warsaw, 1994, pp. 309-314
[24] Koczara W., Balkowiec T., High Power PERFECTGEN for Three-Wire DC Microgrid Application, 5th International Conference on Power Engineering, Energy and Electrical Drives, May 11-13, (2015), 458-464
[25] Koczara W. Balkowiec T., Three phase boost rectifier dedicated to PERFECTGEN - Adjustable speed generation system, *EVER 2015*, Mar. 31-Apr, 2, (2015), 1-6