# New Boost-Type PFC MF-Vienna PWM Rectifiers with Multiplied Switching Frequency

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***Abstract*—In this paper new three-level boost-type PFC PWM rectifiers with Multiplied-switching-Frequency (MF) are presented. They can work both at high and low switching frequency for single- and for three-phase unity-power-factor applications. The proposed solutions are named MF-Vienna PWM rectifiers (M=2 or 3) and are based on classical 1F-Vienna topology (M=1), the most popular PWM boost-type PFC concept with three voltage levels. By adding auxiliary active power device(s) to 1F-Vienna circuit and through proper modulation strategies, the ripple frequency present in the input and output passive components can be doubled (M=2) or tripled (M=3). This advantage leads to the reduction of boost inductor and line filter requirements. The operation principle of the 2F-Vienna cell is validated for three-phase PWM rectifier using Voltage Oriented Control (VOC) method.**

***Index Terms*—AC-DC power converters, energy conversion, power quality, rectifiers, voltage control.**

## I. INTRODUCTION

Wind energy is one of the most economical renewable energy sources and is used widely around the world. Electricity production by means of wind energy conversion systems (WECS) is constantly growing. The international context is a challenge for all professionals involved in the generation, distribution and processing of electrical energy. According to the organization's World Wind Energy Report 2013, the renewable power installations accounted for 72% of new installations during 2013- 25GW of a total 35 GW of new power capacity, up from 70% the previous year. In EU the installations of wind turbines during the 2013 year were led by Germany (29%), the UK (17%), Poland (8%), Sweden (6%), Romania (6%) and France (6%), the other countries representing 28 % of total installed power [1].

The WECS based on permanent magnet synchronous generators (PMSG) have good prospects and potential of application, especially in the wind park. This is mainly due to high reliability and low maintenance costs. Due to these advantages, the WECS (Fig. 1) have a high degree of development in the future. For PMSG with rated power between 1.5-3MW, the most used solution is based on two voltage levels (2L) converters in a back-to-back configuration [2]. At lower powers it is possible to use other solutions, such as a diodes bridge rectifier connected in cascade with a DC-DC Boost converter [3]. For higher power applications, the use of multilevel converters presents, in recent years, an increasing interest [4].

The power converter solution is one of the key elements in building the WECS based on PMSG [5-7].

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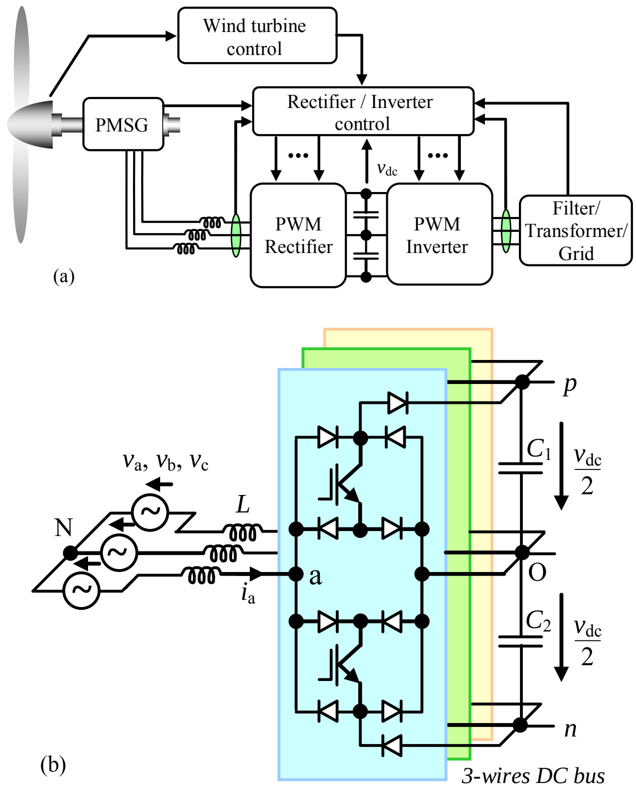


Figure 1. The WECS based on PMSG. (a) General topology with 3-wires DC bus. (b) Proposed three-phase boost-type PFC 2F-Vienna rectifier.

The switched voltage, the switched current and the Multiplied switching Frequency (MF) are important properties of power converters to achieve high efficiency. The development of direct AC-DC converters topologies was fast.

In [8] a bidirectional three-phase multilevel Pulse-Width-Modulation (PWM) rectifier to reduce harmonic components of the input current has been proposed. In order to generate three voltage levels (3L) additional power device per phase was necessary. Later, a new unidirectional boost AC-DC topology has been presented in [9]. This converter contains only one active power device per phase and was named Vienna. It is considered the most popular 3L structure of unidirectional unity-power-factor PWM rectifier and is called in this paper 1F-Vienna rectifier. This name 1F is because the ripple frequency present at the input and output components is equal to the switching frequency. Other variants of 3L unidirectional rectifiers have been proposed in [10] and [11].

Until recently, the researches have been focused on how to adjust the output voltage (buck, boost or buck-boost) and less on development of unidirectional PWM rectifiers with natural Multiplied-switching-Frequency (MF).

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Using Flying-Capacitors (FC), Stacked-FC (SFC), Coupled-Inductors (CI) Stacked-CI (SCI) and cascaded multilevel concepts, single- and three-phase PWM rectifier circuits have been developed during the last years [12-19]. All of these multilevel concepts include the MF property.

In [12-14] the Power-Factor-Correction (PFC) topologies use the CI or SCI multilevel concepts and four- or three-pole power switches. As a result, by power devices pass only a fraction of the line current. In order to reduce both the switched current and the switched voltage a new boost-type PFC multilevel concept has been proposed in [18].

In [19] a novel generalization of boost-type PFC topologies with multiple switching cells has been presented. It is based on parallel connection of two or more series PFC topologies by means of one or more coupled-inductors. Using the minimum number of active power devices as optimization criterion and SFC multilevel principle, the series PFC topologies were also generalized for more than five voltage levels.

The use of FC, SFC, CI and SCI in recent PFC multilevel concept represents a hindrance (in view of the size, weight and cost) at low switching frequency. In order to avoid the use of these multilevel concepts, new MF rectifier circuits have been developed recently [20-22].

In [20-21] the topologies are able to double or triple the ripple frequency present at the input components, without the use of known FC or CI multilevel concepts. A disadvantage of these structures is that they switch only two voltage levels on the input AC side. Another drawback derives from the fact that they can be used only for single-phase applications.

In this paper new boost-type PFC PWM rectifiers are presented. They have three voltage levels on the input AC-side and MF property, without the use of FC or CI multilevel concepts. Thus, the proposed topologies can work both at high and low switching frequency for single- and for three-phase PFC applications.

The new MF topologies are based on 1F-Vienna PWM rectifier, the most popular boost-type PFC concept with three voltage levels (3L). By adding auxiliary active power switch(es) to 1F-Vienna circuit and through proper modulation strategies, the ripple frequency present in the input and output passive components can be doubled or tripled and, thus, lead to reduced boost inductor ($L$) and line filter requirements.

The proposed solutions are named MF-Vienna PWM rectifiers (with M=2 and 3). The new three-phase 2F-Vienna topology is presented for the first time in Fig. 1. Simultaneously with doubling switching frequency, the switched voltage in power devices is reduced at half of DC output voltage and three voltage levels are obtained on the input AC side. With this, a better losses distribution is obtained and more compact/light solutions can be achieved.

The work is organized as follows. In section II two classical AC-DC boost topologies are presented. The proposed single-phase MF-Vienna PWM rectifiers (with M=2 and 3) along with the modulation patterns are explained in section III. In section IV the Voltage Oriented Control (VOC) method for proposed three-phase 2F-Vienna PWM rectifier is implemented. Finally, the main features of the proposed topologies are discussed.

## II. Classical AC-DC Boost Topologies

### A. *Classical AC-DC boost topology*

Today, there is a tendency to use PMSG at rated power converters. In such generators reactive power is not required and the active power flows through unidirectional power converter from PMSG to the DC-link. As a result, a simple diodes rectifier circuit can be connected on the side of the synchronous generator to obtain an effective solution in terms of cost (Fig. 2). However, the diode rectifiers introduce low-frequency harmonics, which can induce phenomena of resonance at the shaft. Another disadvantage is the reduction of PMSG power, as a result of the harmonics injected into it.

In order to allow an operation at variable speed and constant voltage, a DC-DC boost converter is inserted. It is noted that, for the MW power levels, the DC-DC converter can be achieved by parallel connection of several basic switching cells type N. This connection uses one or more magnetically CI and enables the multiplied switching frequency (MF), which leads to reduction in value, volume and cost price for series inductance $L$.

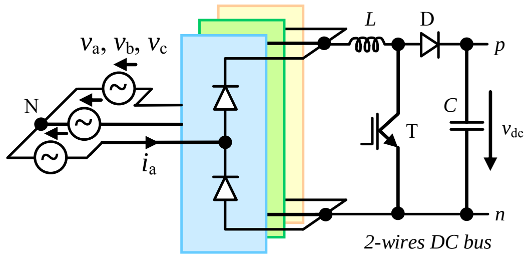


Figure 2. Classical unidirectional AC/DC boost topology.

The bidirectional Voltage-Source-Converter (VSC) with two voltage levels (2L) controlled on PWM principle is the most popular topology used in wind systems. A technical advantage of the 2L-VSC solution consists in simplicity of the structure and the small number of power devices, which gives a good robustness and reliability. However, the powers and voltages of wind turbines are growing and the 2L-VSC topology presents high switching losses and low efficiency in the MW power and Medium Voltage (MV). Also, the power devices require a parallel connection or a serial connection to get the power and voltage of the wind turbine, which would reduce the robustness and reliability of the power converter.

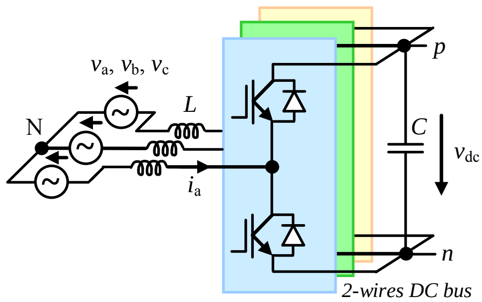


Figure 3. Classical bidirectional 2L-VSC topology.

Another problem of the 2L-VSC solution consists in obtaining on the input AC side only two voltage levels. This leads to high stress d$v$/d$t$ in the PMSG. To limit the voltage gradient and reduce the Total-Harmonic-Distortion (THD) factor, the output filters are large, bulky and expensive.

### *B. Classical Single-phase 1F-Vienna PWM Rectifier*

Recently, the unidirectional 1F-Vienna PWM rectifier with three voltage levels (3L) was proposed for connecting on the PMSG side [23-24], being a conversion solution more efficient and cheaper than 2L-VSC topology (Fig. 4).

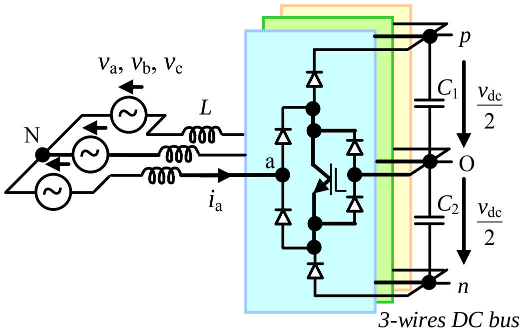


Figure 4. Classical single-phase half-bridge 1F-Vienna PWM rectifier.

Other advantages of the 1F-Vienna structure refers to: (i) 3-wires DC bus, which allows the use of multilevel inverter with two secondary DC voltage sources; (ii) eliminating the dead time, which enables the operation at high switching frequencies; (iii) the power quality is better, due to the existence of the third voltage level (the current THD factor is lower than for traditional 2L-VSC structure).

## III. PROPOSED MF-VIENNA PWM RECTIFIERS

### *A. Proposed Single-phase 2F-Vienna PWM Rectifier*

The proposed single-phase 2F-Vienna (M=2) topology is presented for the first time in Fig. 5. In order to evaluate the operating stages, the following hypotheses are made to simplify the analysis: all components are lossless, the AC-current source is purely sinusoidal and the two secondary DC-link output voltages realized by two series–connected capacitors ($C_1$ and $C_2$) are constant and equal to $v_{dc}/2$.

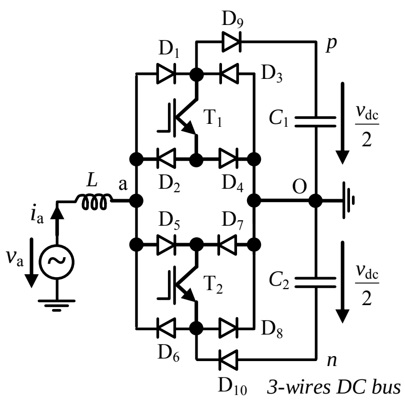


Figure 5. Proposed single-phase half-bridge 2F-Vienna PWM rectifier.

The possible operating stages during the positive half-cycle of input AC voltage ($v_a$>0) are shown in Fig. 6(a). The positive input current ($i_a$>0) flows through two diodes $D_1$ and $D_9$ if all active switches ($T_1$ and $T_2$) are turned *off*. In this case the pole voltage $v_{aO}$ is equal to half of DC output voltage ($v_{dc}/2$). If one of the power devices $T_1$ or $T_2$ is turned on, the energy is stored in the input inductor L, and the pole voltage $v_{aO}$ is equal to zero. These switching sequences are used to implement a modulation strategy responsible for doubling the effective switching frequency at the input and output currents when compared to a conventional boost-type 1F-Vienna topology.

In Fig. 6(b) the power semiconductor paths for negative half-cycle of input AC voltage ($v_a$<0) are presented. In this case the pole voltage $v_{aO}$ can be equal to zero (if $T_1$ or $T_2$ is turned *on*) or -$v_{dc}/2$ (if $T_1$ and $T_2$ are turned *off*).

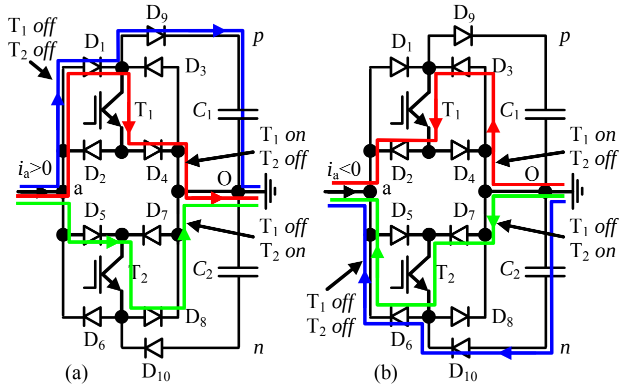


Figure 6. Operating stages of proposed single-phase 2F-Vienna rectifier.

Fig. 7 shows the proposed PWM strategy for positive input AC voltage. In order to obtain the switching sequences for $T_1$ and $T_2$ two carrier waves ($c_1$ and $c_2$), phase-shifted (PS) with half of switching period ($T_{sw}/2$), are compared with the reference duty-cycle ($d_a^*$).

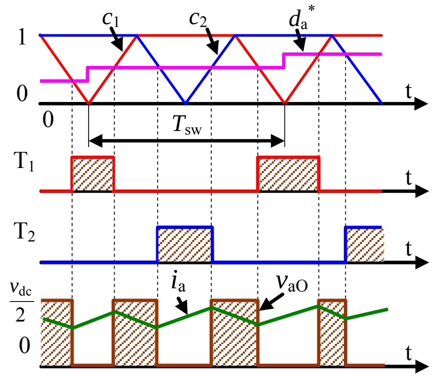


Figure 7. Proposed PWM strategy for 2F-Vienna PWM rectifier.

### *B. Proposed Single-phase 3F-Vienna PWM Rectifier*

The proposed single-phase 3F-Vienna (M=3) topology is presented for the first time in Fig. 8. By adding an auxiliary active power device ($T_3$) to the circuit 2F-Vienna and through proper modulation strategy, the ripple frequency present in the input/output passive components is tripled.

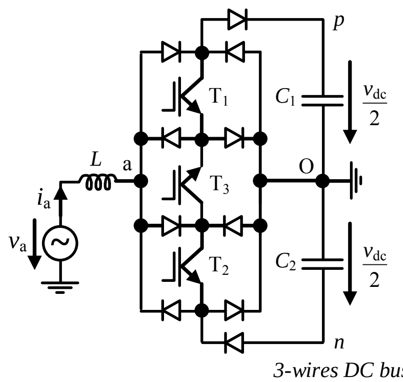


Figure 8. Proposed single-phase half-bridge 3F-Vienna PWM rectifier.

Fig. 9 presents the proposed PWM strategy for positive input AC voltage ($v_a$>0). In order to obtain the switching sequences for $T_1$, $T_2$ and $T_3$, three carrier waves ($c_1$, $c_2$ and $c_3$) phase-shifted (PS) with one third of switching period ($T_{sw}/3$), are compared with the reference duty-cycle ($d_a^*$).

Depending on the switching sequences and input AC voltage polarity, the pole voltage $v_{aO}$ can be equal to zero (if $T_1$ or $T_2$ or $T_3$ is turned *on*) or $v_{dc}/2$ (if $v_a>0$ and $T_1$ and $T_2$ and $T_3$ are turned *off*) or - $v_{dc}/2$ (if $v_a<0$ and $T_1$ and $T_2$ and $T_3$ are turned *off*).

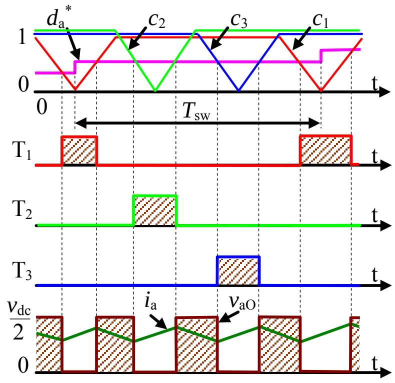


Figure 9. Proposed PWM strategy for 3F-Vienna PWM rectifier.

## IV. VOC FOR THREE-PHASE 2F-VIENNA RECTIFIER

Several methods have been proposed to control the PWM rectifiers. Voltage Oriented Control (VOC) [25-26] is one of the techniques used to control these topologies. In this work the VOC method is used to validate the good operation of the proposed 2F-Vienna topology.

The power stage is supplied from a balanced three-phase AC voltages system:

$$\begin{aligned} v_a(t) &= \sqrt{2}\cdot V\cdot cos(\omega t) \\ v_b(t) &= \sqrt{2}\cdot V\cdot cos(\omega t-2\pi/3) \\ v_c(t) &= \sqrt{2}\cdot V\cdot cos(\omega t-4\pi/3) \end{aligned} \tag{1}$$

The balanced three-phase system (sum of the AC voltages is zero at any time) can be described as a space vector, which has two components (real and imaginary respectively):

$$\vec{v}_{\alpha\beta} = v_\alpha + jv_\beta = \\ = \frac{2}{3}K\cdot\left(v_a(t)+v_b(t)\cdot e^{j\frac{2\pi}{3}}+v_c(t)\cdot e^{j\frac{4\pi}{3}}\right) \tag{2}$$

where $K=\sqrt{3/2}$ corresponds to the *invariant power*. Based on (2), the Clarke and Inverse Clarke transformations are obtained:

$$\begin{bmatrix}\alpha\\ \beta\end{bmatrix}=\sqrt{\frac{2}{3}}\cdot\begin{bmatrix}1 & -\frac{1}{2} & -\frac{1}{2}\\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2}\end{bmatrix}\cdot\begin{bmatrix}a\\ b\\ c\end{bmatrix} \tag{3}$$

$$\begin{bmatrix}a\\ b\\ c\end{bmatrix}=\sqrt{\frac{2}{3}}\cdot\begin{bmatrix}1 & 0\\ -\frac{1}{2} & \frac{\sqrt{3}}{2}\\ -\frac{1}{2} & -\frac{\sqrt{3}}{2}\end{bmatrix}\cdot\begin{bmatrix}\alpha\\ \beta\end{bmatrix} \tag{4}$$

The space vector in synchronous rotating *dq* coordinates (Fig. 10) can be written as

$$\vec{v}_{dq} = v_d + jv_q = \vec{v}_{\alpha\beta}\cdot e^{-j\vartheta} \tag{5}$$

where $\vartheta=\omega t$ and $e^{j\vartheta}=cos(\vartheta)+j\,sin(\vartheta)$.

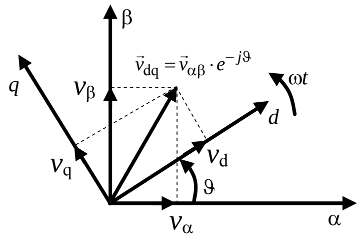


Figure 10. Synchronous rotating dq coordinates representation.

Using (5), the Park and Inverse Park transformations are obtained:

$$\begin{bmatrix}d\\ q\end{bmatrix}=\begin{bmatrix}cos(\vartheta) & sin(\vartheta)\\ -sin(\vartheta) & cos(\vartheta)\end{bmatrix}\cdot\begin{bmatrix}\alpha\\ \beta\end{bmatrix} \tag{6}$$

$$\begin{bmatrix}\alpha\\ \beta\end{bmatrix}=\begin{bmatrix}cos(\vartheta) & -sin(\vartheta)\\ sin(\vartheta) & cos(\vartheta)\end{bmatrix}\cdot\begin{bmatrix}d\\ q\end{bmatrix} \tag{7}$$

The voltage equations describing the converter in the *abc* reference frame are

$$\begin{bmatrix}v_a\\ v_b\\ v_c\end{bmatrix}=R\cdot\begin{bmatrix}i_a\\ i_b\\ i_c\end{bmatrix}+L\cdot\frac{d}{dt}\begin{bmatrix}i_a\\ i_b\\ i_c\end{bmatrix}+\begin{bmatrix}v_{aN}\\ v_{bN}\\ v_{cN}\end{bmatrix} \tag{8}$$

In $\alpha\beta$ reference frame the voltage equations of the converter are as follows

$$\begin{bmatrix}v_\alpha\\ v_\beta\end{bmatrix}=R\cdot\begin{bmatrix}i_\alpha\\ i_\beta\end{bmatrix}+L\cdot\frac{d}{dt}\begin{bmatrix}i_\alpha\\ i_\beta\end{bmatrix}+\begin{bmatrix}v_{\alpha N}\\ v_{\beta N}\end{bmatrix} \tag{9}$$

Equations (9) can be expressed in complex variables as

$$\vec{v}_{\alpha\beta}=R\cdot\vec{i}_{\alpha\beta}+L\cdot\frac{d}{dt}\vec{i}_{\alpha\beta}+\vec{v}_{\alpha\beta N} \tag{10}$$

Considering (5), the complex voltages (10) are transformed as

$$\vec{v}_{dq}\cdot e^{j\vartheta}=R\cdot\vec{i}_{dq}\cdot e^{j\vartheta}+ \\ +L\cdot\frac{d}{dt}\left(\vec{i}_{dq}\cdot e^{j\vartheta}\right)+\vec{v}_{dqN}\cdot e^{j\vartheta} \tag{11}$$

After simplification with $e^{j\vartheta}$ is obtained:

$$\vec{v}_{dq}=R\cdot\vec{i}_{dq}+L\cdot\frac{d\vec{i}_{dq}}{dt}+j\omega L\cdot\vec{i}_{dq}+\vec{v}_{dqN} \tag{12}$$

Taking into account that

$$\begin{aligned}\vec{v}_{dq} &= v_d + jv_q\\ \vec{i}_{dq} &= i_d + ji_q\end{aligned} \tag{13}$$

the voltage equations in the *dq* reference frame are:

$$\begin{aligned}v_d &= R\cdot i_d+L\cdot\frac{di_d}{dt}-\omega L\cdot i_q+v_{dN}\\ v_q &= R\cdot i_q+L\cdot\frac{di_q}{dt}+\omega L\cdot i_d+v_{qN}\end{aligned} \tag{14}$$

Using (14), the *dq* reference voltages ($v_{dN}^*$ and $v_{qN}^*$) are presented in (15). These references are limited at $v_{dc}/2$.

$$\begin{aligned}v_{dN}^* &= v_d - v_{RLd}^* + \omega L\cdot i_q\\ v_{qN}^* &= v_q - v_{RLq}^* - \omega L\cdot i_d\end{aligned} \tag{15}$$

The VOC control is implemented in Fig. 11 and is based on equations (15). The outer loop is for the DC bus voltage regulation.

The PI voltage regulation sets the reference value for the *d* current component ($i_d^*$) that controls the power. Two independent PI controllers have also been used to generate the *dq* reference voltages imposed at the terminals of the series inductances $L$ ($v^*_{\mathrm{LRd}}$ and $v^*_{\mathrm{LRq}}$). The feedforward terms -ωL$i_q$ and ωL$i_d$, together with the supply voltages ($v_d$ and $v_q$) are added to these references of the decoupled system to improve the system performance. The two PI current controllers and the PI voltage controller are common dimensioning [26].

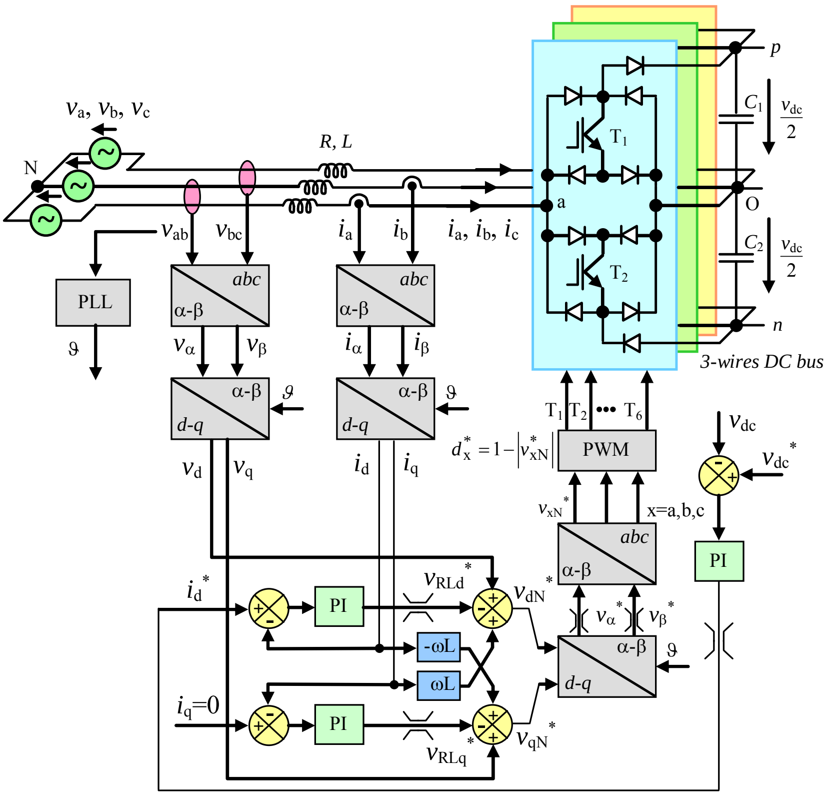


Figure 11. Voltage oriented control for proposed three-phase 2F-Vienna PWM rectifier.

The VOC method is based on a three-phase Phase-Locked-Loop (PLL) structure (Fig. 12). It is an important part of the system and its aim is to give the voltage angle ϑ of the three-phase system ($v_a$, $v_b$ and $v_c$). This angle is represented in *rad* and is used in the model for all the *dq* transformations.

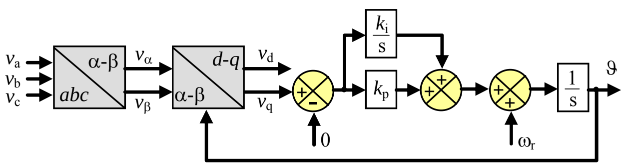


Figure 12. Three-phase PLL topology.

The PI controller constants ($k_p$ and $k_i$) can be determined using the following relations:

$$k_p = \frac{b_w^2}{\sqrt{2}\cdot V}\,;\; k_i = \frac{2\cdot b_w}{\sqrt{2}\cdot V} \tag{16}$$

where $b_w$ represents the bandwidth of the PLL structure (it is considered 2π *rad/s* for this implementation); $\omega_r$ is the reference value (*rad/s*) and $V$ is the effective (*rms*) value of AC supply voltage.

The VOC method provides the PWM control signals for the proposed 2F-Vienna rectifier. The DC output voltage reference ($v^*_{dc}$) is 700V and a resistive load is connected between the two DC output terminals *p* and *n*.

Fig. 13 shows the simulated results. The load resistance is changed suddenly at 0.2s from 150Ω to 30Ω, corresponding to a load of 16.3kW (30Ω) instead of 3.3kW (150Ω).

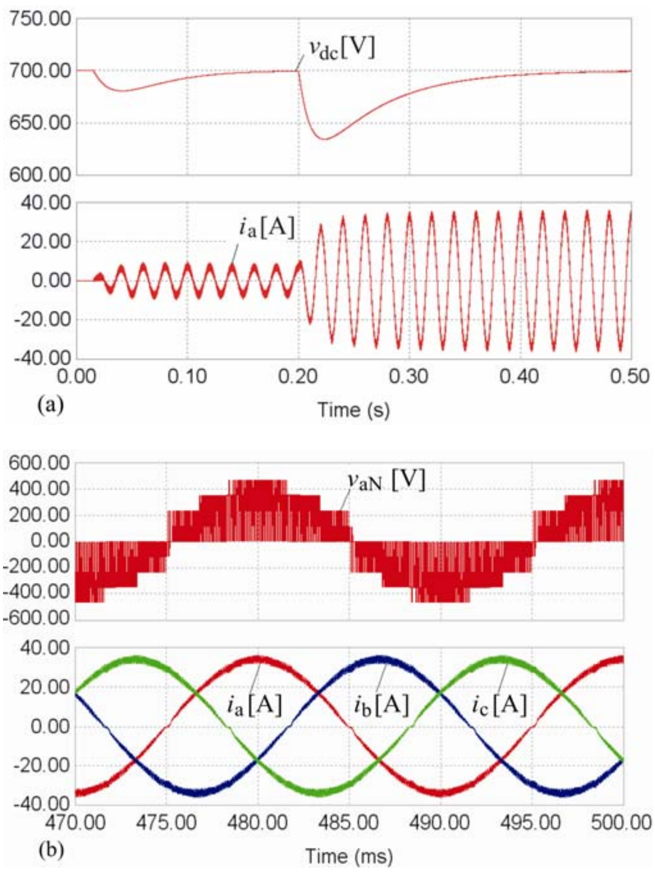


Figure 13. Simulated results for proposed three-phase 2F-Vienna rectifier ($V$=230V, $R$=0.05Ω, $L$=1mH, $f_{sw}$=8kHz). (a) $v_{dc}$ – output DC voltage and $i_a$ – line AC current. (b) $v_{aN}$ – input voltage converter and line AC currents.

It is observed that the three proposed objectives were achieved: (i) the proper operation of the new topology is validated; (ii) the output voltage is kept constant and (iii) the absorbed currents are sinusoidal and are in phase with the AC supply voltages.

## V. CONCLUSION

In this paper new boost-type PFC three-level PWM rectifiers with Multiplied-switching-Frequency (MF) are presented. These circuits have the advantage of natural doubling or tripling the switching frequency in the input and output passive components, without using Flying-Capacitor (FC) or Coupled-Inductor (CI) multilevel concepts.

The proposed solutions are named MF-Vienna PWM rectifier (M=2 and 3), and are based on classical three-level 1F-Vienna topology. They can work both at high and low switching frequency for single- and for three-phase unity-power-factor applications. Thus, the MF-Vienna topology (M=2 and 3) is suitable for compact PFC designs.

The disadvantages of the proposed circuits are related to the increased number of power devices with additional isolated gate driver(s) and the need for a more complex modulation that leads to increase the computation efforts.

The operation principle of the 2F-Vienna topology is validated for three-phase boost-type PFC PWM rectifier, using Voltage Oriented Control (VOC) method.

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