A Novel Concept for Mains Voltage Proportional Input Current Shaping of a VIENNA Rectifier Eliminating Controller Multipliers

Part II: Operation for Heavily Unbalanced Mains Phase Voltages and in Wide Input Voltage Range

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II.1 Introduction

In order to achieve high reliability the VIENNA Rectifier should continue in operation also for heavily unbalanced mains phase voltages or in case of a phase loss (two-phase operation). Furthermore, for economic reasons the system should be designed for a wide input voltage range. These aspects are of major importance e.g. for telecommunications power supply systems.

In order to facilitate a comparison of the proposed control concept to a conventional control [12]which employs average current mode controllers (ramp comparison phase current controllers), the conventional control should be discussed briefly first. .

The conventional control concept depicted in Fig.II.1 provides a mains voltage proportional guidance of the input phase currents for any unbalance of the mains phase voltages and in wide input voltage range. There, for two-phase operation no changes of the control structure (in contrast to [13]) have to be performed. The partial output voltages of the VIENNA Rectifier are controlled to be of equal value and a stationary overload of the system is prevented by a limitation of the amplitude of the phase currents to a given maximum value independent of the mains voltage conditions.

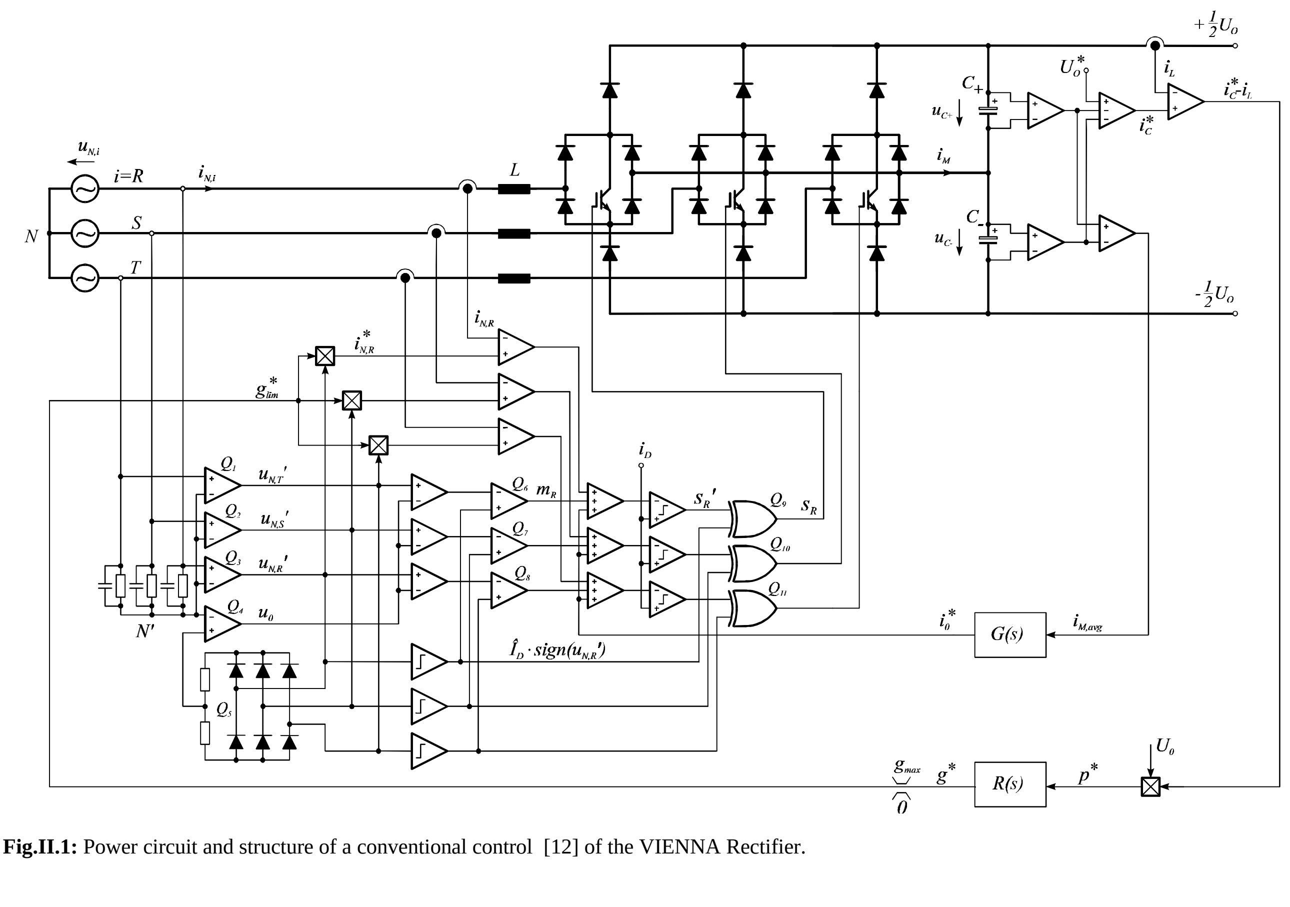

Fig.II.1: Power circuit and structure of a conventional control [12] of the VIENNA Rectifier.

II.2 Conventional Control Concept

As shown in **Fig.II.1** the control is realized in a two-loop structure where the inner current control loop employs a ramp comparison current controller for each phase; the outer control loop controls the total value of the output voltage and provides a balancing of the partial output voltages.

For the inner current control loop a mains voltage pre-control signal m_i is used which is derived from the measured mains phase voltages. Therefore, a high quality input current shape and/or a low current control error can be achieved also with purely P-type current controllers. An I-type component (which would saturate, e.g., for two phase operation without additional measures) is not required.

Due to referring the sensing $u_{N,i}$' of the mains voltages (Q_1, Q_2, Q_3 in Fig.II.1) to an artificial neutral point N' which is formed by a star connection of equal resistors (50k) with parallel connected capacitors (0.1uF) an eventually existing zero component of the input voltages $u_{N,0} = u_{N,R} + u_{N,S} + u_{N,T}$ is not measured (the actual mains phase voltages $u_{N,i}$ are referred to mains neutral point N). Therefore, the sum of the measured mains phase voltages is equal to zero

$$u'_{N,R} + u'_{N,S} + u'_{N,T} = 0 \,. \tag{II.1}$$

The zero component $u_{N,0}$ of the phase voltages $u_{N,i}$ cannot result in any current because there is no connection between the output center point M of the rectifier and the mains neutral point N. Hence, $u_{N,0}$ has not to be taken into account for the formation of the input voltage pre-control signals.

In order to attenuate the noise with pulse frequency, a filtering of the mains voltages is provided. Due to the negative influence of a phase shift of the voltage measurement on the shape of the resulting mains currents (especially in the vicinity of current zero crossing, cf. signals $\hat{I}_D$·sign($u_{N,i}$') in Fig.II.1) there advantageously a band-pass filter (BP) with zero phase shift at 50(60)Hz (low frequency cut-off at 5Hz, high frequency cut-off at 500Hz) is employed. Due to the wide pass-band the filter can be used with 50Hz or 60Hz mains frequency.

The current reference signals are derived from the voltages $u_{N,i}$'. According to Eq.(II.1) this results in

$$i^*_{N,R} + i^*_{N,S} + i^*_{N,T} = 0 \tag{II.2}$$

whereby the condition for the input currents $i_{N,R} + i_{N,S} + i_{N,T} = 0$ given due to the missing connection to the mains neutral point is considered.

Furthermore, as shown in [14], a zero component u_0 (Q_4 and Q_5 in Fig.II.1) can be derived with low effort directly from phase quantities $u_{N,i}$' and used for an extension of the mains voltage pre-control signals m_i. With this one obtains

- an equal modulation limit as given, e.g., for space-vector modulation (maximum amplitude of the rectifier input phase voltages fundamental equal to $U_0/\sqrt{3}$) and
- a significant reduction of the mains current ripple and of the 3rd harmonic of the center point current i_M as compared to purely sinusoidal modulation and/or pre-control of only $u_{N,i}'$.

A detailed description of the whole control structure shown in Fig.II.1, i.e., the shifting of the pre-control signals m_i with a square-wave function $\hat{I}_D$·sign($u_{N,i}$') (cf. Q6, Q7, Q8 in Fig.II.1), the inversion of the output signals s_i' of the pulse width modulators of the phases according to the signs of the corresponding phase voltages $u_{N,i}$' (cf. XOR-gates Q9, Q10, Q11in Fig.II.1), the balancing of the partial output voltages u_{C+}, u_{C-} by an offset i_0* (added to the phase current references $i_{N,i}$*) is given in [8] and [9] and therefore shall be omitted here for the sake of brevity.

The bandwidth of the output voltage control has to be set to values as known from single-phase power factor correction (10...20 Hz) [15]. This is due to the pulsation of the total rectifier output power in case of unbalanced mains conditions (or for two-phase operation) with twice the mains frequency which results in a corresponding output voltage fluctuation and would lead to a low-frequency distortion of the input current shape (deviation from the sinusoidal and/or mains voltage proportional shape) for high output voltage controller gain. There, a high output voltage control error occurring due to small controller gain in case of load steps can be prevented by a load current feed-forward and/or by a step-like increasing the controller gain for high output voltage control error.

II.2.1 Derivation of the Reference Currents

The output signal of the output voltage controller can be interpreted as reference value of the power $p^*=(i_C^*+i_L)\cdot U_0$ to be delivered to the output (cf. Fig.II.2, i_C* is the reference value of the output capacitors charging current, i_L denotes the load current).

There a microcontroller calculates a conductivity g^* corresponding to the ohmic mains behavior of the rectifier

$$g^* = \frac{p^*}{U^2_{N,R}{}' + U^2_{N,S}{}' + U^2_{N,T}{}'} \tag{II.3}$$

($U_{N,i}'$ denotes the rms value of a mains phase voltage). Subsequently, the conductivity g^* is limited in order to keep the input current amplitude lower than the allowable maximum value $\hat{I}_{N,max}$

$$g^*_{\lim} < g_{\max} = \frac{\hat{I}_{N,\max}}{\max[\hat{U}_{N,i}']} \,. \tag{II.4}$$

Finally, the current reference values are calculated by multiplying the limited conductivity reference value g_{lim}* with the corresponding phase voltages voltage $u_{N,i}$'. Therefore, the maximum output power is proportional to the input voltage amplitude $P_I \sim \hat{U}_N$ (for symmetric mains).

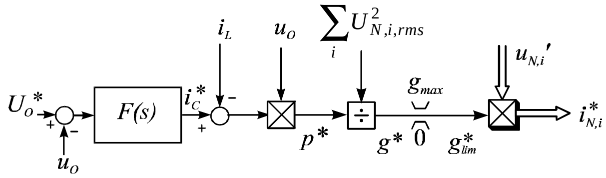

Fig.II.2: Block diagram of the derivation of the mains phase current reference values $i_{N,i}$* from the output p* of the output voltage controller.

For two-phase operation or for heavily unbalanced mains voltage the maximum value of the output power is limited automatically according to a current amplitude of $\hat{I}_{N,max}$ (in the phase with the highest voltage amplitude). The input currents are proportional to the corresponding mains phase voltages $u_{N,i}$', i.e., a phase with a lower input voltage is loaded by a lower current. This symmetric ohmic loading of the phases of the mains could help to prevent overloading (and/or tripping of a fuse located, e.g., at the output of a distribution transformer) of an already heavily loaded phase and/or result in a higher power being available from the mains as compared to two-phase operation after tripping of the fuse.

II.3 Multiplier Free Control Scheme

As shown in Eq.(I.5) (cf. part I) for the multiplier free current control the carrier signal amplitude $\hat{I}_D$ can be interpreted as input conductivity g of the system for constant output voltage U_0, i.e.

$$\hat{I}_D = g \cdot U_0 \ . \tag{II.5}$$

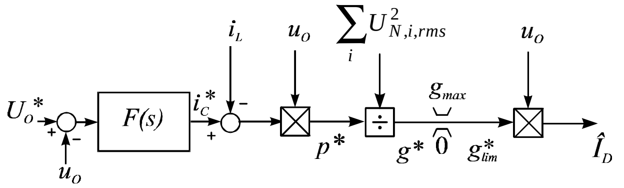

Fig.II.3: Block diagram of the derivation of the carrier amplitude $\hat{I}_D$ from the output p^* of the output voltage controller.

Therefore, the calculation of the carrier signal amplitude $\hat{I}_D$ has to be performed in an analog way as the calculation of the input conductivity g_{lim}^* (cf. Eq.(II.4)) for the conventional control in order to ensure $\hat{I}_N < \hat{I}_{N,max}$ in a wide input voltage range and for unbalanced mains phase voltages.

In the case at hand a low cost microcontroller (ATMEL AT90S8535, which is US$ 6.00 in single pieces) is employed for performing the calculation of $\hat{I}_D$. The microcontroller handles also the control of the total output voltage, the symmetry of both partial output voltages, the automatic start-up, the input voltage supervisory, the converter output current feed-forward (cf. i_L in Fig.II.3), the hick-up mode at light load, the signalization of failures and could provide a digital or analog interface to a central supervising unit in case of paralleling of a higher number of converters. So the costs of the microcontroller in comparison to a discrete realization of equal functionality are comparably low.

II.4 Experimental Results

The experimental investigation was performed in connection with a prototype of the VIENNA Rectifier with the following ratings:

Output power:	P_O	=	5kW
Input voltage rms line to line:	U_N	=	400V
Input current maximum:	$\hat{I}_{N,max}$	=	12A
Output voltage:	U_0	=	675V
Switching frequency:	f_s	=	25kHz.

In order not to exceed the maximum input current value of the rectifier the output power was decreased to 3.2kW (approx. 60% of nominal output power) in order to showing the behavior of the system for balanced mains and under heavily unbalanced mains voltage conditions for equal output power.

In **Fig.II.6** the experimental results under the following four mains voltages conditions are shown for the conventional control (cf. Fig.II.6, left hand side) and for the multiplier free control (cf. Fig.II.6, right hand side):

(a) symmetric mains
(b) phase R is disconnected from the mains
(c) phase R is disconnected from the mains and connected to mains phase S
(d) phase R is disconnected from the mains and connected to the neutral N.

As shown in Fig.II.6 both control concepts provide a high quality of the input current, the input currents do not show any significant differences and are guided proportional to the zero sequence free input voltages $u_{N,i}$'.

The dependency of the total harmonic distortion of the input currents (*THD A*) and of the power factor l on the output power is given in **Fig.II.4**. There the performance of the multiplier free control concept (cf. Part I Fig.I.6) is higher as compared to the conventional control for low output power levels (P_O<1.6kW). The opposite is true for higher output power, but, considering the limited accuracy of the measurement equipment the performance can be considered about equal for both concepts.

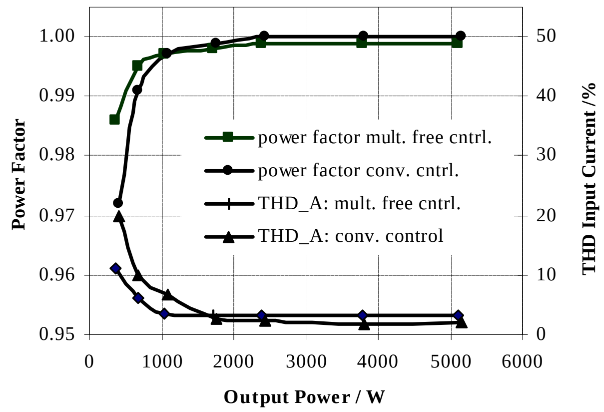

Fig.II.4: Total harmonic distortion of the input currents (*THD* A) and of the power factor l for the conventional and for the multiplier free control concept (cf. Part I Fig.I.6) in dependency on the rectifier output power.

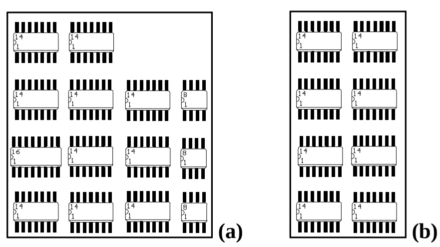

Fig.II.5: Comparison of the realization effort of the control concepts based on the number of integrated circuits being required for the practical realization of the conventional (a) and of the multiplier free control concept (b). Integrated circuits which have to be provided in equal function for both concepts (i.e. for the calculation of the conductivity g^*_{lim} and/or of the carrier amplitude $\hat{I}_D$ (cf. Fig.II.3) and or for protection) are not shown.

A comparison of the realization effort of the control concepts (cf. **Fig.II.5**) concerning the number of integrated circuits yields about half of the size of the printed circuit board area in case parts being necessary for both types of control in equal function (microcontroller, input current measurement, protection functions etc.) are not considered.

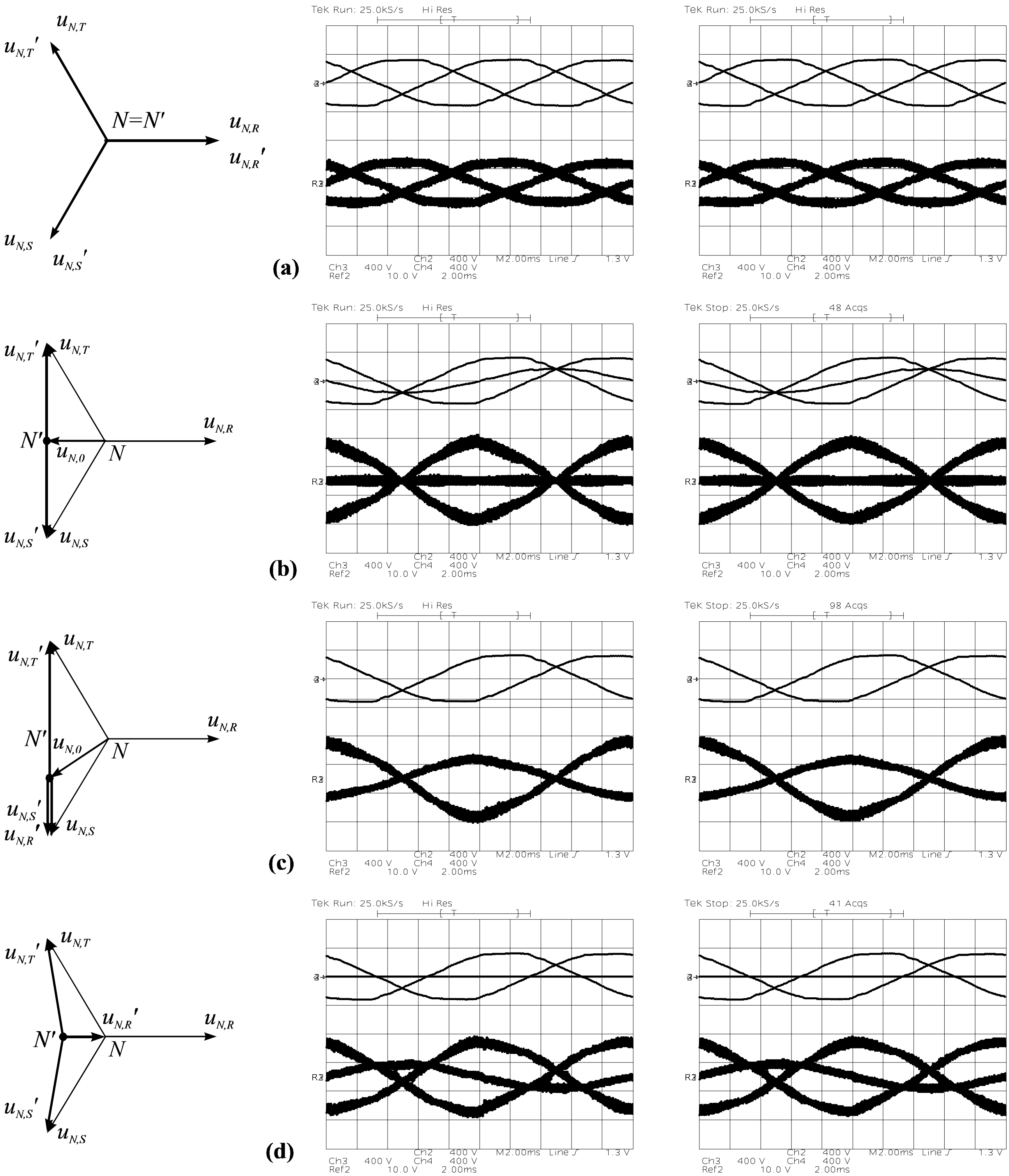

Fig.II.5: Time behavior of the phase voltages $u_{N,i}$ and of the input phase currents $i_{N,i}$ of the VIENNA Rectifier for four different mains voltage conditions (shown by phasor diagram) as resulting for the conventional current control concept (left hand side) and for the multiplier free current control (right side), cf. Part I, Fig.I.6; **(a)**: symmetric mains, **(b)**: phase *R* disconnected, **(c)**: phase *R* disconnected from the mains and connected to phase *S* and **(d)**: phase *R* disconnected from the mains and connected to the neutral.

II.5 Conclusions

Part II of this paper shows the operation of a three phase PWM (VIENNA) Rectifier operating with symmetric and heavily unbalanced mains voltage for application of a conventional phase current control and for the novel multiplier free current control concept (cf. Part I, Fig.I.6). The difference in performance of both concepts is minor but the multiplier free control concept does allow to save about 40% of board space for the realization of the basic controller function. Taking into consideration the additional parts which are required in equal form for both concepts (input current measurement, output voltage measurement and control, supervisory functions and microcontroller), the saving in board space will be, however, only in the range of about 10%. A further advantage of the multiplier free control concept is that no information about the sign or magnitude of the input phase voltages is required for performing the control function. Furthermore, in contrast to the conventional control concept there is no requirement of an adjustment of the amplitude of the triangular shaped carrier signal and of the amplitude of rectangular shaped pre-control signal m_i to the rectifier voltage transfer ratio. This would be especially advantageous for applications where the output voltage level is considered as a degree of freedom for maximizing the efficiency of the rectifier in combination with a DC-to-DC converter connected in series at the output. A drawback of the multiplier free control concept is the requirement of generating two unipolar triangular shaped carrier signals with adjustable amplitude and high accuracy (equal amplitudes of both carrier signals and minimum and/or maximum value equal to 0).

Finally, we would like to point out that for medium performance applications the derivation of the carrier amplitudes $\hat{I}_D$ could be performed without a microcontroller (cf. Fig.II.7). There, the ripple of the peak value of the input currents has to be low pass filtered in order not to distort the shape of the input currents and/or the partition of the output voltage.

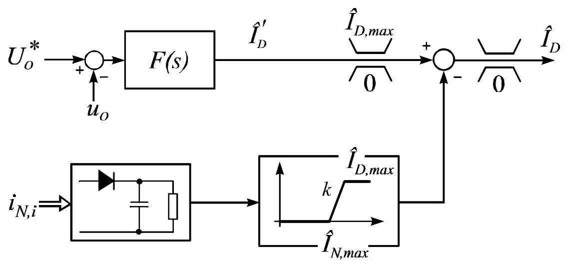

Fig.II.7: Concept providing a stationary and a dynamic input current amplitude limitation without a microcontroller.

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References

[1] **Maksimovic, D., Yungtaek, J., and Erickson, R.:** *Nonlinear Carrier Control for High Power Boost Rectifiers.* Proceedings of the 10th IEEE Applied Power Electronics Conference, Dallas, March 5-9, Vol. 2, pp. 635-641 (1995).

[2] **Gegner, J. P., and Lee, C. Q.:** *Linear Peak Current Mode Control: A Simple Active Power Factor Correction Control Technique For Continuous Conduction Mode.* Record of the 27th IEEE Power Electronics Specialists Conference, Baveno, Italy, June 23-27, Vol. 1, pp. 196-202 (1996).

[3] **Rajagopalan, J., Lee, F. C., and Nora, P.:** A Generalized Technique for Derivation of Average Current Mode Control Laws for Power Factor Correction without Input Voltage Sensing. Proceedings of the 12th Applied Power Electronics Conference, Atlanta, February 23-27, Vol.1, pp. 81-87 (1997)

[4] **Ben-Yaakov, S., and Zeltser, I.:** *PWM Converters with Resistive Input*. Proceedings of the 37th International Power Conversion Conference, Nuremberg, Germany, May 26-28, pp. 87-95 (1998).

[5] **Qiao, C., and Smedley, K. M.:** *A General Three-Phase PFC Controller. Part II for Rectifiers with a Series-Connected Dual-Boost Topology.* Record of the 34th IEEE Industry Applications Conference, Phoenix, Oct. 3-7, Vol. 4, pp. 2512-2519 (1999).

[6] **Qiao, C., and Smedley, K. M.:** *Three-phase Unity-Power-Factor VIENNA Rectifier with Unified Constant-frequency Integration Control.* Proceedings of the IEEE International Power Electronics Congress, Acapulco, Mexico, Oct. 15-19, pp. 125-130 (2000).

[7] **Kolar, J. W.:** Selbsttätige Einprägung sinusförmiger Netzphasenströme bei Dreiphasen-Pulsgleichrichtersystemen. Austrian Patent Application; filed: May 28, 1999.

[8] **Kolar, J. W., and Zach, F. C.:** *A Novel Three-Phase Utility Interface Minimizing Line Current Harmonics of High-Power Telecommunications Rectifier Modules.* Proceedings of the 16th IEEE International Telecommunications Energy Conference, Vancouver, Canada, Oct. 30-Nov. 3, pp. 367-374 (1994).

[9] **Drofenik, U., and Kolar, J.W.:** Comparison of Not Synchronized Sawtooth Carrier and Synchronized Triangular Carrier Phase Current Control of the VIENNA Rectifier I. Record of the IEEE International Symposium on Industrial Electronics, Bled, Slovenia, June 12-16, Vol. 1, pp. 13-19 (1999).

[10] **Kolar, J.W., Miniboeck, J., and Stoegerer, F.:** *Multipliziererfreie Phasenstromregelung für unidirektionale Dreiphasen-Dreipunkt-Pulsgleichrichtersysteme mit weitem Aussteuerbereich.* Austrian Patent Application, filed: 10/2000.

[11] **Ide, P., Froehleke, N., Grotstollen, H., Korb, W., and Margaritis, B.:** *Analysis of Three/Phase/Three/Level Rectifiers at Low Load and Discontinuous Contuction Mode***.** Proceedings of the 15th IEEE Applied Power Electronics Conference, New Orleans, Feb. 6-10, Vol. 1, pp. 197-204 (2000).

[12] **Kolar, J.W.:** *Vorrichtung zum zuverlässigen Betrieb dreiphasiger Pulsgleichrichtersysteme an stark unsymmetrischen Netzen.* Austrian Patent Application, filed: 08/2000.

[13] **Ide, P., Froehleke, N., Grotstollen, H., Korb, W., and Margaritis, B.:** *Operation of a Three-Phase/Three-Level-Rectifier in Wide Range and Single-Phase Applications*. 25th Annual Conference of the IEEE Industrial Electronics Society, San Jose (CA), USA, Nov. 29-Dec. 3, pp. 577-582 (1999).

[14] **Blasko, V.:** *Analysis of a Hybrid PWM Based on Modified Space Vector and Triangle Comparison Methods.* IEEE Transactions on Industry Applications, Vol. 33, No. 3, pp. 756-764 (1997).

[15] **Noon, J.P., and Dalal, D.:** *Practical Design Issues for PFC Circuits.* Proceedings of the 12th IEEE Applied Power Electronics Conference, Atlanta, Feb. 23-27, Vol. 1, pp. 51-58 (1997).