Evaluation of a Delta-Connection of Three Single-Phase Unity Power Factor Rectifier Systems (Δ-Rectifier) in Comparison to a Direct Three-Phase Rectifier Realization

Part I – Modulation Schemes and Input Current Ripple

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Abstract. In this paper the delta connection of three single-phase boost unity power factor rectifier units (Δ-rectifier) is analyzed based on an equivalent star connection. As the calculation of the input voltage space vectors which are associated with the combinations of the power transistor switching states of the line-to-line units shows the Δ-rectifier and a direct three-phase unity power factor (VIENNA) rectifier are characterized by equal modulation limits. Furthermore, the Δ-rectifier shows like the VIENNA Rectifier a redundancy of switching states concerning input voltage formation. This redundancy has to be employed for a control and/or suppression of a low frequency zero sequence current component circulating inside the Δ-connection of the line-to-line units. According to a digital simulation the switching frequency ripple of the sinusoidal mains current of the Δ-rectifier shows only a slightly higher normalized RMS value as resulting for the VIENNA rectifier. Therefore, in the course of further research, i.e. Part II of this paper, the stresses on the power components of the Δ-rectifier will be calculated in analytical form in order to provide a basis for a comprehensive comparative evaluation and for the dimensioning and practical realization of the system.

1 Introduction

The input stage of telecommunications power supply modules with low effects on the mains currently is frequently realized as star connection of single-phase boost unity power factor rectifier systems [1-4] (cf. **Fig.1**(a)). As a main advantage as compared to connecting the single-phase systems in delta and/or from line-to-line (cf. Fig.1(c)) this concept shows a lower voltage stress on the power semiconductors. However, for feeding the system from a three-wire mains, i.e. for missing connection of the star point *N´* to the mains neutral point *N* (cf. Fig.1(a)), a control of the partition of the mains line-to-line voltages between the inputs of the phase units and/or of the potential of *N´* has to be provided [2]. This is due to the negative incremental input impedance and/or constant input power characteristic of the individual units [1]. Alternatively, *N´* could be connected to an artificial mains star point formed by a low-frequency three-phase coupled inductor arrangement with low zero-sequence impedance as proposed in [3]. However, both concepts show drawbacks concerning control complexity and/or power density and realization costs.

Aiming for a highly reliable and compact three-phase rectifier topology, the structure of the power circuit of each phase unit could be extended by inserting

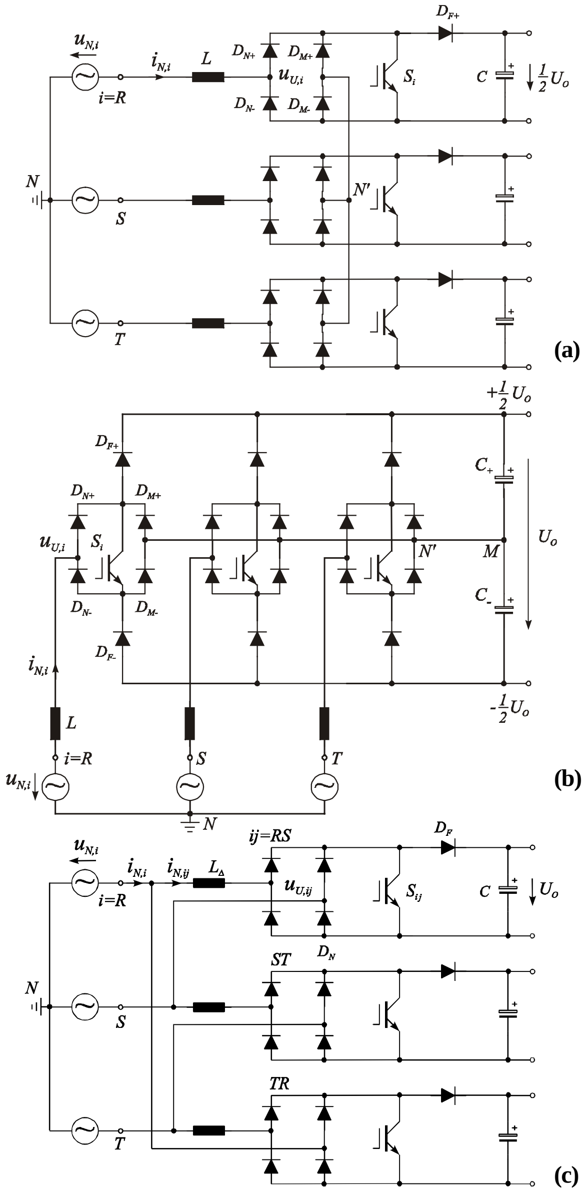

Fig.1: Realization of a three-phase boost unity power factor rectifier with low effects on the mains by combination of single-phase units in star connection (cf. **(a)**) or deltaconnection (cf. **(c)**, Δ-rectifier) or in direct three-phase form (VIENNA Rectifier, cf. **(b)**).

of an additional output diode D_{F-} in the connection to the negative output voltage terminal. The star point N' then can be connected to the center point M of a series connection of two output capacitors C_+ and C_- which are shared by all phase units (cf. Fig.1(b)). The resulting direct three-phase unity power factor rectifier topology is known as VIENNA Rectifier [5] and obviously shows an equal input current shape $i_{N,i}$ and equal stresses on the power components as the system depicted in Fig.1(a) (for equal operating and circuit parameters, i.e. equal switching frequency f_P, equal control of the power transistors S_i, equal inductance of the input inductors L, and equal output voltages $u_{C+} = u_{C-} = {}^1/_2 U_O$).

There, instead of the symmetrization of the input phase voltages as required for the star connection of the single-phase units (cf. Fig.1(a)) a control of the symmetry of the partial output voltages has to be controlled which, however, is dynamically less critical and can be performed with considerably lower circuit effort by only a minor modification of the mains current control circuit [5]. Furthermore, for the direct three-phase system for conversion and isolation of the output voltage U_0 only a single DC-to-DC converter stage has to be provided. Alternatively, also two interleaved DC/DC converter systems which are connected to the partial output voltages and which share a common output inductor and a common control circuit [6] could be employed.

For the star connection of single-phase units as well as for the VIENNA rectifier in the case of a failure of a mains phase a continuation of the operation with reduced output power $P = 1/\sqrt{3}P_O \approx 0.58\,P_O$ is possible. The full rated power P_O is available for two-phase operation without overdimensioning of the power semiconductors only for a delta connection of the single-phase units (for short denoted as Δ-rectifier in the following, cf. Fig.1(c)) and for realization of the input stages of the individual line-to-line units as controlled three-phase rectifier bridges [7] (and DC side arrangement of the input inductors, not shown in Fig.1(c) for the sake of clearness). Then, in case one phase of the mains is missing, all single-phase systems can be switched over to the two remaining phases. Under consideration of the requirement of a high reliability as given, e.g. for telecommunications power supply systems this represents a major advantage and motivates a more detailed analysis of the Δ-rectifier despite the relatively high voltage stress on the power semiconductors (as compared to a star connection of the individual units and/or to the VIENNA Rectifier).

In this paper in a first step a concept for coordinated control of the line-to-line units which does provide a minimum RMS value of the mains phase current ripple is derived. There, the considerations are related to a star equivalent circuit which facilitates a direct comparison of the results with the characteristic values of a VIENNA Rectifier. For regular and/or three-phase operation, however, the placing of the inductor on the rectifier DC- or AC-side does not take influence on the formation of the ripple of the mains phase currents and/or on the stresses of the power semiconductor devices.

In **section 2** the formation of the input voltages $u_{U,ij}$ of the rectifier bridges of the line-to-line units is analyzed in dependency on the switching states of the power transistors S_{ij} (ij = RS,ST,TR) and on the signs of the line-to-line currents $i_{N,ij}$. Based on this the input voltage space vectors being available for a sinusoidal and/or mains voltage proportional guidance of the mains phase currents $i_{N,i}$ ($i=R,S,T$) and the modulation range of the system are determined. Furthermore, a switching state sequence is defined which does suppress a low frequency component of the zero sequence current circulating inside the delta connection of the line-to-line units. **Section 3** details a realization of the derived control concept by individual average current mode controllers for the line-to-line units including a mains voltage feed-forward. Furthermore, the influence of a phase displacement of the triangular carrier signals being employed by the individual line-to-line current controllers on the resulting mains phase current ripple is discussed and the possibility of extending the sinusoidal line-to-line current reference values by a third harmonic (low frequency zero sequence component) for lowering the peak current stress on the power semiconductors [8] is analyzed. In **section 4** the theoretical considerations are verified by digital simulations and the dependency of the RMS value of the mains phase current ripple on the modulation index is calculated and compared to the known characteristic values of a VIENNA Rectifier. Finally, in **section 5** a survey of the continuation of the system analysis in a Part II of this paper is given which will focus on a comparison of the utilization of the power semiconductors of the Δ-rectifier in comparison to a VIENNA Rectifier as well as on the evaluation of the realization effort under inclusion of the DC/DC converter systems for the conversion and high-frequency isolation of the output voltages of the line-to-line units. Furthermore, there a control concept which features a proper sharing of the total output power between the line-to-line units also for an asymmetry of the mains phase voltages and which is applicable in a wide input voltage range will be proposed.

2 Basic Principle of Operation

2.1 Star Connection Equivalent Circuit

An equivalent circuit of the Δ-rectifier AC side system part is shown in **Fig.2**(a). According to the input side rectification besides the switching state s_{ij} of a power transistor S_{ij} also the sign $sign(i_{N,ij})$ of the line-to-line current $i_{N,ij}$ ($ij=RS,ST,TR$) takes influence on the formation of the corrsponding input voltage

$$u_{U,ij} = sign(i_{N,ij})\,(1-s_{ij})\,U_O \qquad (1)$$

(s_{ij}=1 denotes the turn-on state of S_{ij} , s_{ij}=0 denotes the turn-off state).

The line-to-line rectifier input voltages $u_{U,ij}$ in general will contain a zero sequence system

$$u_0 = {}^1/_3\,(u_{U,RS} + u_{U,ST} + u_{U,TR}) \qquad (2)$$

which results in a zero sequence component i_0 of the line-to-line currents

$$i_{N,ij} = i_{Nij}' + i_0 \qquad (3)$$

The zero sequence current i_0 circulates inside the delta connection of the line-to-line units (cf. Figs.2(a) and (c)) and does not take influence on the formation of mains phase currents $i_{N,i}$ ($i=R,S,T$) according to

$$i_{N,R} = i_{N,RS} - i_{N,TR} = i_{N,RS}' - i_{N,TR}' \quad (4)$$

(shown for phase $i=R$).

The line-to-line current system $i_{N,ij}'$ ($j=RS,ST,TR$) is defined in connection with the (symmetrical) mains voltage by the line-to-line rectifier input voltage system remaining after subtraction of the zero sequence voltage component

$$u_{U,ij}' = u_{U,ij} - u_0\,. \quad (5)$$

The line-to-line voltage system defined by (5) can now be transformed into an equivalent phase voltage system

$$\begin{aligned} u_{U,R}' &= {}^1/_3\,(u_{U,RS}' - u_{U,TR}') \\ u_{U,S}' &= {}^1/_3\,(u_{U,ST}' - u_{U,RS}') \\ u_{U,T}' &= {}^1/_3\,(u_{U,TR}' - u_{U,ST}')\,. \end{aligned} \quad (6)$$

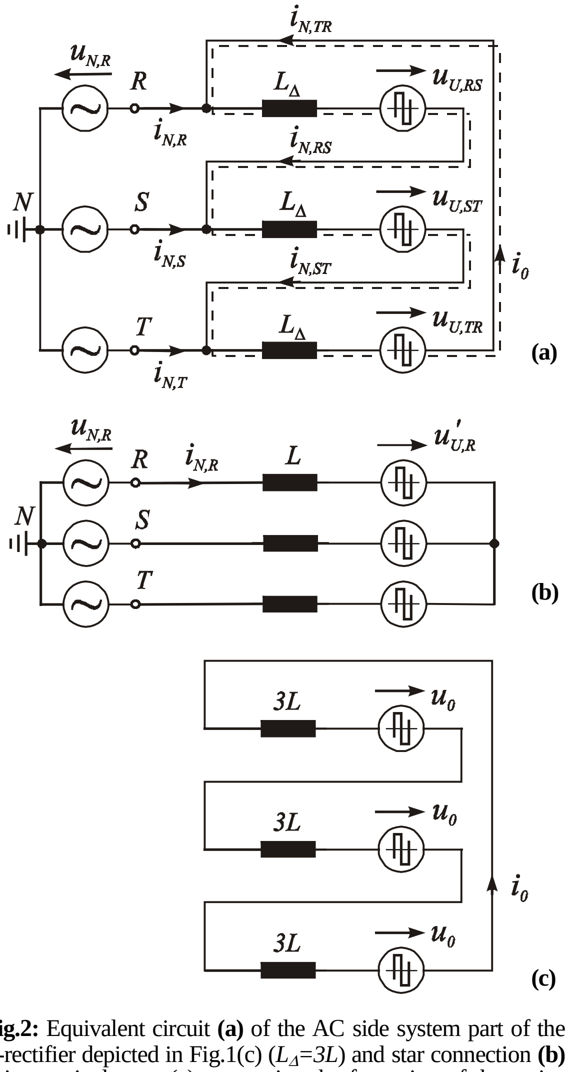

Fig.2: Equivalent circuit **(a)** of the AC side system part of the Δ-rectifier depicted in Fig.1(c) ($L_\Delta=3L$) and star connection **(b)** being equivalent to (a) concerning the formation of the mains phase currents $i_{N,i}$. Furthermore shown: equivalent circuit **(c)** for the calculation of the zero sequence component i_0 of the line-to-line currents $i_{N,ij}$ resulting due to the zero sequence component of the line-to-line rectifier input voltages $u_{U,ij}$.

Accordingly, the analysis of the system behavior could be based on an equivalent star connection as shown in Fig.2(b). There the inductance of the inductors connected in series at the AC side has to be reduced by a factor of 3,

$$L = {}^1/_3\, L_\Delta, \quad (7)$$

in order to achieve equal inner impedances of the actual delta and of the equivalent star connection.

The star equivalent circuit is valid directly also for the VIENNA Rectifier (cf. Fig.1(b), where the rectifier phase voltages without zero sequence component are defined by $u_{U,i}' = u_{U,i} - {}^1/_3(u_{U,R} + u_{U,S} + u_{U,T})$ (the total $u_{U,i}$ phase voltages could be measured with reference to, e.g., the capacitive center point M of the output voltage U_O). Therefore, referring the analysis of the Δ-rectifier to a star equivalent circuit does provide a sound basis for a comparison of the performance of both systems.

Remark: It is interesting to note that for $L = {}^1/_3\, L_\Delta$ (cf. (7)) the input inductors of the Δ-rectifier and of the VIENNA Rectifier in a first approximation show equal volumes (cf. **Fig.3**) what also does facilitate a direct comparison.

In case, e.g. a toroidal iron power core is employed for the realization the inductors, the number of turns of L_Δ could be higher by a factor of $\sqrt{3}$ for a given admissible maximum magnetic flux density. This is due to the amplitude of the line-to-line currents being lower by a factor of $1/\sqrt{3}$ as compared to the amplitude of the mains phase currents (ripple current neglected).

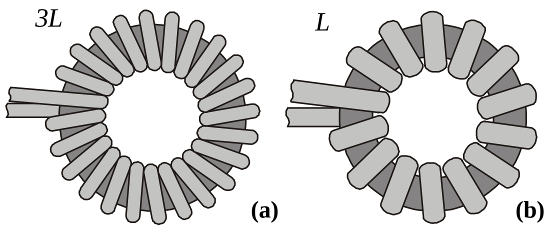

Fig.3: Practical realization of an input inductor L_Δ of a Δ-rectifier **(a)** and of an input inductor of the VIENNA Rectifier **(b)** of equal output power using equal magnetic (e.g., iron powder) cores. According to $N_\Delta = \sqrt{3}$ N, $L_\Delta = 3L$ is valid (cf. (7)).

2.2 Input Voltage Space Vectors

The space vectors of the input phase voltages $u_{U,i}'$

$$\underline{u}_{U,i}' = {}^2/_3\,(u_{U,R}' + u_{U,S}' + u_{U,T}') \quad (8)$$

resulting for $i_{N,RS} > 0$, $i_{N,ST}$, $i_{N,TR} < 0$ for the different switching state combinations $s_\Delta=(s_{RS}\; s_{ST}\; s_{TR})$ are depicted in **Fig.4**(a). There, the respective zero sequence components u_0 of the line-to-line input voltages $u_{U,ij}$ (cf. (2)) are shown as indices.

For the suppression of a low-frequency component of the zero sequence current

$$i_0 = {}^1/_3\,(i_{N,RS} + i_{N,ST} + i_{N,TR}) \quad (9)$$

being contained in the line-to-line currents $i_{N,ij}$, one has to ensure within each pulse half period ${}^1/_2T_P$ and/or within each switching state sequence (e.g., (100)-(000)-(010)-(011)) a local average value of u_0 equal to zero, i.e.,

$$u_{0,\mathrm{avg}} = {}^{1}/T_P \int u_0 \; dt_\mu = 0 \qquad (10)$$

(t_μ denotes a local time running within a pulse period T_P) by proper partition of the total on-time of the voltage space vector $\underline{u}_{U,(100)} = \underline{u}_{U,(011)}$ to the (redundant) switching states (100) and (011) which result in zero-sequence voltages of different signs and amplitudes (for s_Δ=(100) we have $u_0 = -{}^2/_3 U_O$, s_Δ=(011) results in $u_0 = +{}^1/_3 U_O$, cf. Fig.4; U_O denotes the rectifier DC output voltage, cf. Fig.1(c)).

As a more detailed analysis shows with this the modulation index

$$M = \frac{\hat{U}_U'}{\frac{1}{2} U_O} \qquad (11)$$

($\hat{U}_U'$ denotes the amplitude of the fundamental of the equivalent phase voltages u_{Ui}', cf. Fig.2(b)) is limited by

$$M_{\max} = 2/\sqrt{3} \, . \qquad (10)$$

This identical to the properties of a VIENNA Rectifier of equal output voltage U_O as can be verified in Fig.4(b).

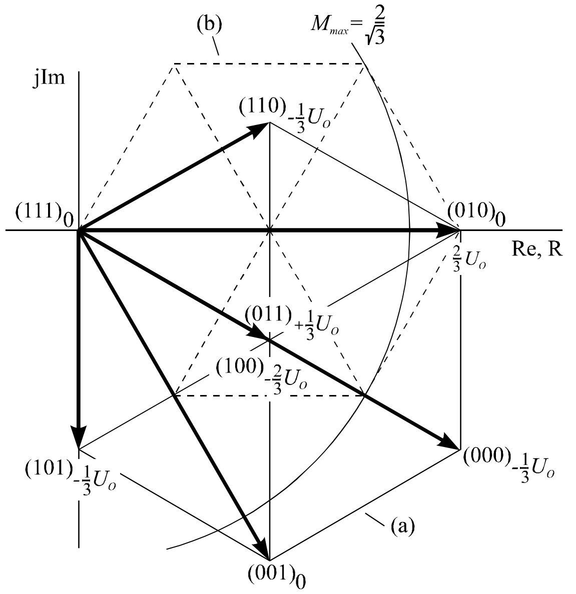

Fig.4: Space vectors of the equivalent input phase voltages $u_{U,i}'$ of the Δ-rectifier for $i_{N,RS} > 0$, $i_{N,ST}$, $i_{N,TR} < 0$ (cf. **(a)**). Denomination of the space vectors is by the corresponding combination of switching functions $s_\Delta = (s_{RS}\ s_{ST}\ s_{TR})$ of the power transistors S_{RS}, S_{ST}, S_{TR}. There, the zero sequence component u_0 of the line-to-line input voltages (cf. (2)) occurring for a combination s_Δ is given as index. Furthermore shown: Space vector hexagon of the VIENNA Rectifier for $i_{N,R} > 0$, $i_{N,S} < 0$, $i_{N,T} < 0$ and equal output voltage U_O (cf. **(b)**).

3 Input Current Control

In analogy to single-phase power factor correction for sinusoidal and/or mains proportional guidance of the input currents of the line-to-line units average current mode control is employed. This does implicitly make sure that for the formation of the line-to-line input voltages $u_{U,ij}$ the redundant switching states are incorporated in the switching state sequence in a way that no low frequency component of the zero sequence voltage u_0 does occur. A low frequency component of u_0 would result in a corresponding low-frequency distortion of the line-to-line currents $i_{N,ij}$. This is prevented by the line-to-line current controllers.

As shown in **Fig.5** the control of each line-to-line unit does refer to the absolute value of the corresponding line-to-line current which could be gained directly by measurement on the input rectifier DC side . The amplitude of the reference values $i_{N,ij}$* is determined by the output voltage controller of each unit and in dependency on the mains voltage symmetry properties in order to ensure a fundamental mains behavior of the system being equivalent to a star connection of equal resistors. By mains voltage feed-forward m_i the current control error is limited to low values also for employing a simple P-type current controller *G(s)*.

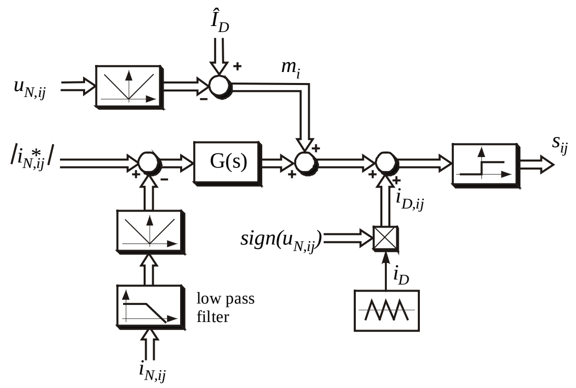

Fig.5: Impression of sinusoidal input currents of the line-to-line units in phase with the corresponding mains line-to-line voltages, i.e. $i_{N,ij}^* \sim u_{N,ij}$, by average current mode control; m_{ij} denotes the mains voltage feed-forward. Signal paths being equal for all phases are combined in double lines.

The switching of the line-to-line units is coordinated by the switching frequency carrier signals $i_{D,ij}$ of the current controllers. Aiming for a minimum ripple of the mains phase currents, always voltage space vectors lying in the immediate vicinity of the mains voltage space vector $\underline{u}_N$ should be employed for the formation of the voltages $u_{U,i}$ (for neglection of the fundamental voltage drop across the input inductors L, $\underline{u}_{U,i,avg}' \approx \underline{u}_N$ is valid, where $\underline{u}_{U,i,avg}'$ denotes the space vector to be formed in the average over a pulse period). As a more detailed analysis shows, this can be achieved by inversion of the triangular carrier signal i_D for each line-to-line current controller in dependency of the sign of the corresponding mains line-to-line voltage $u_{N,ij}$ (cf. Fig.5)

$$i_{D,ij} = sign(u_{N,ij})\, i_D \, . \qquad (13)$$

and/or in dependency on the sign of the corresponding line-to-line input current reference value $i_{N,ij}$* (showing equal phase.

The operation of the units showing positive input currents and of the units showing negative input currents then is in opposite phase; accordingly for e.g. $i_{N,RS} > 0$, $i_{N,ST}$, $i_{N,TR} < 0$ the switching state s_Δ= (100) will appear at the beginning and at the end of a pulse period and switching state s_Δ= (011) will be employed in the vicinity of the center of a pulse period (e.g. a switching state sequence within a pulse period there could be (100)-(000)-(001)-(011)-(011)-(001)-(000)-(100), cf. Fig.4). According to (2) and Fig.4 this does result in the formation of a pronounced zero sequence voltage u_0 with switching frequency (for $i_{N,RS} > 0$, $i_{N,ST}$, $i_{N,TR} < 0$ we have $u_0 = -{}^2/_3 U_O$ for s_Δ= (100) and $u_0 = +{}^1/_3 U_O$ for s_Δ=(011)) and/or in a relatively high zero sequence component of the ripple $\Delta i_{N,ij}$ of the input currents $i_{N,ij}$ of the line-to-line units.

The envelope of the ripple of the line-to-line rectifier input currents is independent of the coordination of the action of the line-to-line current controllers and can be formulated by a simple analytical calculation in normalized form as

$$\Delta \hat{i}_{N,ij,n} = \Delta i_n \, \tfrac{2}{\sqrt{3}} M \sin \omega_N t \, (1 - \tfrac{\sqrt{3}}{2} M \, \sin \omega_N t) \qquad (14)$$

(ω_N denotes the mains angular frequency) where

$$\Delta i_n = U_O T_P / 8L \, . \qquad (15)$$

(For the derivation of (15) $u_{N,ij} = \hat{U}_N \sin(\omega_N t)$ has been assumed and the fundamental voltage drop across L_Δ has been neglected, i.e. $u_{N,ij} \approx u'_{U,ij,avg}$ has been assumed; $u'_{U,ij,avg}$ denotes the (local) average value of $u'_{U,ij}$ related to a pulse period). Therefore, the coordination of the individual units according to (13) does make sure that a mximum share of the $\Delta i_{N,ij}$ ($\Delta i_{N,ij}$ shows an envelope which is independent of the coordination concept employed, cf. (14)) does form a zero sequence component circulating inside the delta connection. For the formation of a ripple of the mains phase currents therefore there remains only a small share of $\Delta i_{N,ij}$, accordingly the phase currents will show a low ripple and/or a largely sinusoidal shape.

The theoretical considerations have been verified by digital simulations (cf. **Fig.6**(c)). There the following system operating parameters have been assumed:

Mains line-to-line voltage	$U_{N,ij}$	=	480V_{rms}
Output voltage	U_0	=	800V
Mains current amplitude	$\hat{I}_{N,ij}$	=	10A
Mains side inductance	L_Δ	=	2.1mH
Switching frequency	f_P	=	25kHz
P-Type current control	$G(s)$	=	5
Carrier signal amplitude	$\hat{I}_D$	=	10A
Time constant of the controller first order filtering of the input current	τ	=	100μs

(for Δi_n as defined by (15) we therefore have Δi_n =5.71A).

The advantage of a coordination of the line-to-line units according to (11) is shown clearly by a comparison to alternative concepts in Fig.6(a). The time behavior of the line-to-line input current ripple components is shown for using identical carriers for all individual line-to-line current controllers

$$i_{D,ij} = i_D \qquad (16)$$

and in Fig.6(b) for a symmetric phase displacement of the triangular carrier signals of

$$\begin{aligned} i_{D,RS} &= i_D\{t\} \\ i_{D,ST} &= i_D\{t + {}^1/_3 T_P\} \\ i_{D,TR} &= i_D\{t - {}^1/_3 T_P\}. \end{aligned} \qquad (17)$$

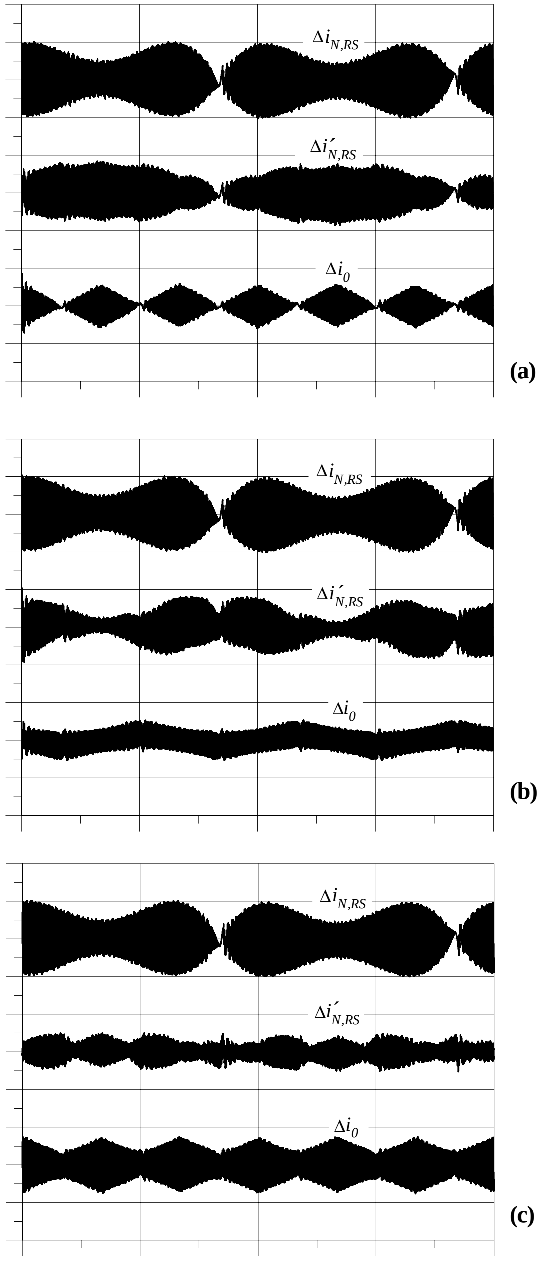

Fig.6: Time behavior of the ripple $\Delta i_{N,RS}$ of a line-to-line current $i_{N,RS}$ within a mains period for control of the Δ-rectifier according to (16) (cf.**(a)**), (17) (cf. **(b)**) and (13) (cf.**(c)**). Furthermore shown: zero sequence component Δi_0 of $\Delta i_{N,RS}$ circulating inside the delta connection (cf. Fig.2(a)) and component $\Delta i_{N,RS}' = \Delta i_{N,RS} - \Delta i_0$ which in connection with $\Delta i_{N,TR}'$ and $\Delta i_{N,ST}'$ determines the ripple of the mains phase currents $i_{N,R}$ and $i_{N,S}$.

In both cases a significantly lower zero sequence component Δi_0 of the ripple currents $\Delta i_{N,ij}$ is formed, accordingly there results a higher amplitude of the ripple component $\Delta i_{N,ij}'$ contributing to the ripple $\Delta i_{N,i}$ of the mains phase currents $i_{N,i}$.

The difference in the performance of the control methods according to (13), (16) and (17) is confirmed for the whole modulation range also by the calculation of the RMS value of the ripple components (cf. Fig.7). For the normalized (index n) RMS value of $\Delta i_{N,ij}$ we have for any coordination ((13), (16), or (17)) of the carrier signals $i_{D,ij}$

$$\Delta I^2_{N,ij,rms,n} = \tfrac{1}{3} M^2 \left(\tfrac{3}{8} M^2 - \tfrac{16}{3\sqrt{3}\pi} M + \tfrac{2}{3}\right) \qquad (18)$$

(valid for M=0...1, cf. **(f)** in Fig.7).

As is immediately clear by considering the different spectral composition of the ripple current components ΔiN,ij´ and Δi0 we have for the RMS values of the ripple components

$$\Delta I^2_{N,ij,rms} = \Delta I'^2_{N,ij,rms} + \Delta I^2_{0,rms} \qquad (19)$$

where ΔIN,ij,rms under consideration of the symmetry of the feeding mains and of the symmetry of the rectifier

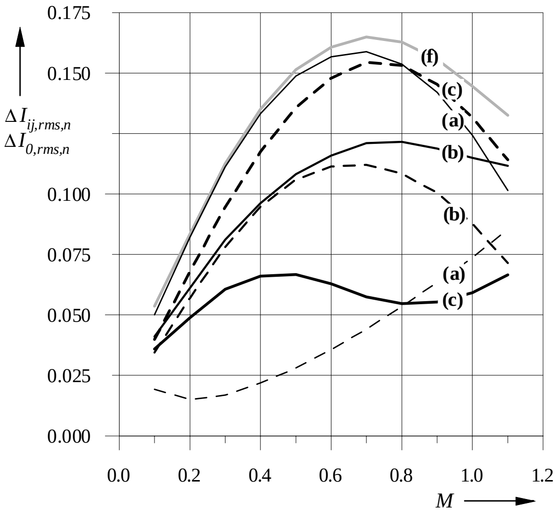

Fig.7: Dependency of the RMS value of the ripple components on the modulation index for control of the line-to-line currents according to (16) (cf.**(a)**), (17) (cf. **(b)**) or (13) (cf. **(c)**). RMS values of the zero sequence ripple components are shown by broken lines; **(f)**: RMS value of the total ripple of a line-to-line current.

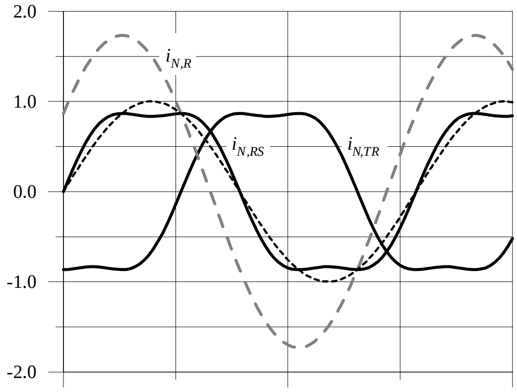

Fig.8: Reduction of the amplitude of the line-to-line rectifier input currents $i_{N,ij}$ and/or of the maximum current stress on the power transistors S_{ij} by a factor of $\sqrt{3}/2 \approx 0.87$ by a third harmonic $i_{0,(3)}$ of amplitude $\hat{I}_{0,(3)} = {}^{1}/_{6}\, I_{N,ij,(1)}$ ($I_{N,ij,(1)}$ denotes the amplitude of the line-to-line current fundamental which is shown by a dotted line); i_0 does not take influence on the shape of the mains phase current $i_{N,i}$, shown for $i=R$; line-to-line current $i_{N,ST}$ not shown.

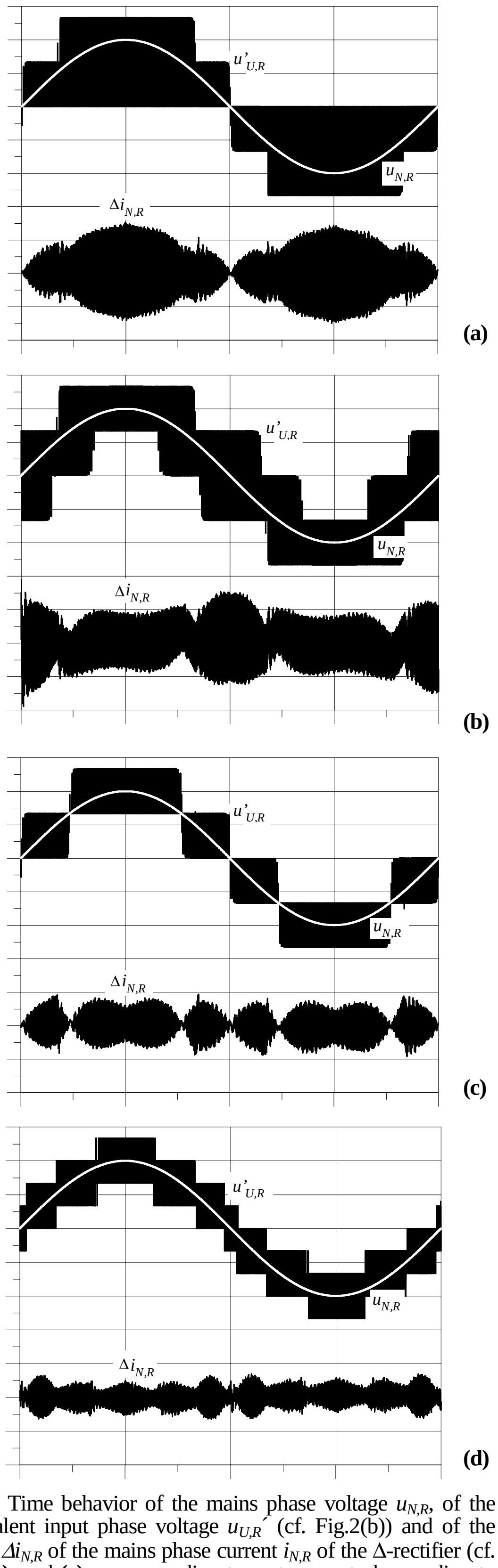

Fig.9: Time behavior of the mains phase voltage $u_{N,R}$, of the equivalent input phase voltage $u_{U,R}{}'$ (cf. Fig.2(b)) and of the ripple $\Delta i_{N,R}$ of the mains phase current $i_{N,R}$ of the Δ-rectifier (cf. **(a)**, **(b)**, and **(c)**, corresponding to system control according to (16), (17) and (13)); furthermore shown: time behavior of the characteristic quantities for the VIENNA Rectifier (cf. **(d)**) within a mains period; scales: 200V/div, 2A/div.

topology directly defines the RMS value of the ripple of the mains phase current

$$\Delta I_{N,i,rms} = \sqrt{3}\Delta I'_{N,ij,rms} \quad (20)$$

A reduction of $\Delta I'_{N,ij,rms}$ by a high zero sequence component $\Delta I_{0,rms}$ therefore directly translates into a higher quality of the mains phase currents (cf. (a),(b) and (c) in Figs.7 and 9).

A zero sequence component of the line-to-line currents does not take influence on the formation of the mains phase currents and therefore constitutes a degree of freedom of the line-to-line current control. As proposed in [7] one therefore could extend the purely sinusoidal shape of the line-to-line current reference values by adding a third harmonic $i_{0,(3)}$. For a relation of the amplitude of the third harmonic and of the current fundamental amplitude of

$$\hat{I}_{0,(3)} = {}^{1}/_{6}\, I_{N,ij,(1)} \quad (21)$$

this does result in a reduction line-to-line current peak value by a factor of $\sqrt{3}/2 \approx 0.87$ as compared to the fundamental and in a corresponding reduction of the peak current stress of the power transistors and on the input inductors L_Δ (for a given number of turns and a maximum admissible magnetic flux density the inductor peak current is determining the magnetic core volume and/or inductor size). Advantageously, the RMS value of the line-to-line currents thereby is only increased marginally, i.e. by a factor of $1.014 \cdot \sqrt{2}\ I_{N,ij,(1),rms}$ as compared to the purely sinusoidal case (denoted by the index (1)). As more detailed analysis shows this is true also for the average and RMS values of the currents in the power semiconductors.

4 Comparative Evaluation

In **Fig.10** the time behavior of the equivalent phase voltage $u_{U,i}'$, of the corresponding mains phase voltage $u_{N,i}$ and of a ripple $\Delta i_{N,i}$ of the mains phase current $i_{N,i}$ is shown for the different control concepts of the Δ-rectifier and for the VIENNA Rectifier (for details of the input current control employed for the VIENNA Rectifier see Fig.II.1 in [8]). The average phase current ripple amplitude resulting for the optimum, i.e. minimum mains current ripple control of the Δ-rectifiers (cf. (13)) is about comparable to the performance of the VIENNA rectifier. This is verified in **Fig.10** for the whole modulation range for equal rated power of the AC side inductors ($L_\Delta = 3L$, cf. (7)), equal switching frequency $f_P = 1/T_P$ and equal output voltage U_0 and does give motivation for a further analysis of the system (the analytical calculation of the stresses on the power components will be published in a Part II of this paper).

Concerning a comparison of the Δ-rectifier and of the VIENNA Rectifier also the amplitude spectrum of the input current ripple components is of interest. As shown in **Fig.11**, harmonics with ordinal numbers $n \approx 500$ (switching frequency) are pronounced in the spectrum of of the VIENNA Rectifier show only minor differences, however, for the VIENNA Rectifier a more even distribution of the main part of the spectral power to harmonics with single and double switching frequency is

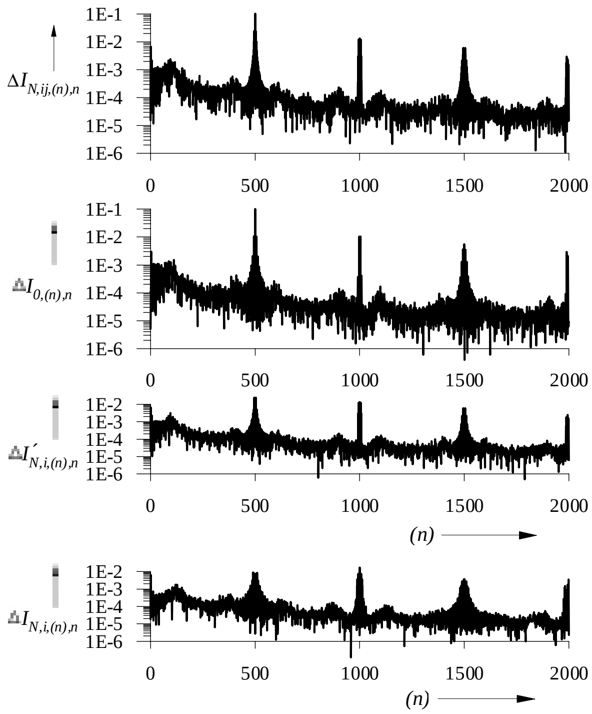

Fig.11: Normalized amplitude spectrum of the ripple components ripple components of the Δ-rectifier (control according to (13)) and of the phase current ripple of a VIENNA Rectifier of equal output power; (*n*) denotes the ordinal number of the harmonics; the normalization is with reference to the amplitude of the mains current fundamental $\hat{I}_{N,(1)}$; simulation parameters as given in section 3.

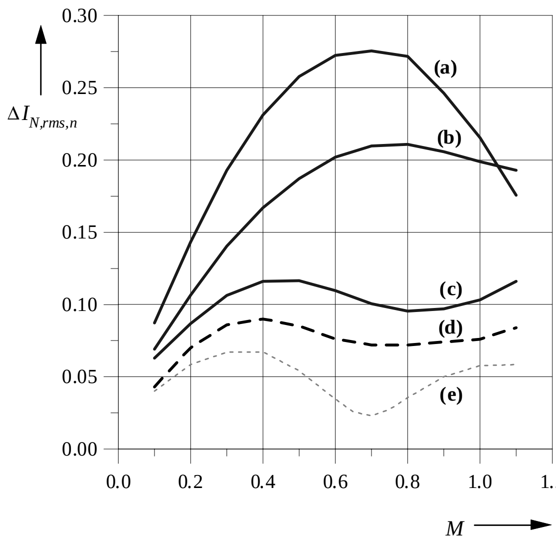

Fig.11: Normalized RMS value $\Delta I_{N,rms,n}$ of the phase current ripple $\Delta i_{N,i}$ (basis of the normalization: $\Delta i_n = U_O T_P / 8L$) in dependency on the modulation index *M* for identical triangular carrier signals of the ramp-comparison current controllers of the individual line-to-line units of the Δ-rectifier (cf. **(a)** and (16)); **(b)**: symmetric phase displacement of the carrier signals of the partial systems by ${}^{1}/_{3}T_P$ (cf. (17)); **(c)**: as (a) but inversion of a carrier signal of a line-to-line current controller for negative sign, i.e. $i_{N,ij} < 0$, of the corresponding phase current (cf. (13)). Furthermore shown: Input current ripple characteristic of the VIENNA Rectifier (cf. **(d)**) and of the three-level Δ-rectifier shown in Fig. 11 (cf. **(e)**).

$\Delta i_{N,ij}$ which is mainly due to zero sequence ripple components (cf. $\Delta I_{0,(n),n}$ in Fig. 11). The spectra $\Delta I_{N,i,(n),n}{}'$ of the mains phase current ripples of the Δ-rectifier and given. As a comparison of the average amplitude of $\Delta i_{N,i}$ (cf. Fig.9(d)) and of $\Delta i_{N,ij}$ (cf. Fig.6(c)) indicates higher core losses of the input inductors will occur for the Δ-rectifier. This finally is a consequence of the delta connection of the individual units which does allow the formation of a zero sequence current ripple in contrast to a star connection as given for the VIENNA Rectifier.

5 Conclusions

As this paper shows a delta connection of single-phase boost-type unity power factor rectifiers (Δ-rectifier) does provide a low level of harmonics with switching frequency of the mains phase currents comparable to direct three-phase concepts (VIENNA Rectifier).

A main advantage of the (Δ-rectifier is its high modularity, however, one has to accept the disadvantage of a high blocking voltage stress on the power transistors and free-wheeling diodes which (without additional means) results in a relatively low system efficiency. This weakness however can be eliminated in case three-level boost converters are employed for realizing the line-to-line units. The resulting system structure is depicted in **Fig.12** and is characterized by a very low RMS value of the mains current ripple as has been verified by first digital simulations (cf. (e) in Fig.11). Furthermore, for replacement of the input single-phase diode bridges of the conventional approach by three-phase thyristor bridges a change over of all line-to-line systems to the two phases remaining in the case of a mains phase loss could be performed and/or a high system reliability could be achieved.

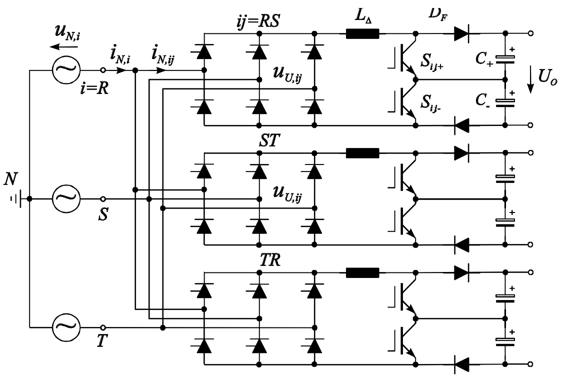

Fig.12: Basic structure of the power circuit of a three-level Δ-rectifier. In contrast to a system employing input diode bridge rectifiers the connection of the line-to-line units to the mains can be selected by proper firing of the thyristor bridges, i.e. all units could be connected to only two mains phases in case of a mains phase loss.

In the course of the continuation of the research, therefore, the system shown in Fig.12 should be analyzed in detail concerning the stress on the power components, the electromagnetic compatibility and the input current control in case of an unbalance of the mains phase voltages. A compilation of the results of the analysis to be carried out at the ETH Zurich and a comparison to the characteristics of the VIENNA Rectifier will be presented in part II of this paper to be published at the IEEE International Telecommunications Conference 2001.

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