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New Modulation and Control Scheme for Phase-Modular Isolated Matrix-Type Three-Phase AC/DC Converter

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***Abstract*—A phase-modular isolated three-phase AC/DC converter topology and its modulation and control scheme is proposed. The topology, denominated as IMY-Rectifier, is based on a star connection of single-phase mains frequency to high frequency AC/AC matrix converters at the input, feeding high-frequency isolation transformers. The transformer secondary windings are connected in series to the input of a diode rectifier with LC output filter. The converter provides a controlled output voltage and sinusoidal input currents in phase with the mains voltages. A description of the converter, its operating principle and an analytical calculation of the component stresses is presented.**

The proposed new control of the converter ensures a constant power flow and/or constant output voltage. Furthermore, the potential of the star point of the phase modules is actively controlled so that no connection to the mains neutral is required. Simulation results verify the operation of the new control scheme.

In addition to the proposed isolated AC/DC converter topology, alternative Boucherot network based topologies for high-frequency load independent constant AC current output and dual circuits are presented in this paper.

***Index Terms*—Power electronics, Three-phase electric power, AC-DC power converters, Matrix converters.**

I. INTRODUCTION

Three-phase power factor corrector (PFC) rectifiers offer several advantages with respect to diode rectifiers, i.e. sinusoidal input currents and controlled output voltage. In addition, some applications may require galvanic isolation of the output voltage. In order to provide the required isolation a DC/DC converter stage with a high-frequency transformer can be included, resulting in a two-stage energy conversion [1], [2].

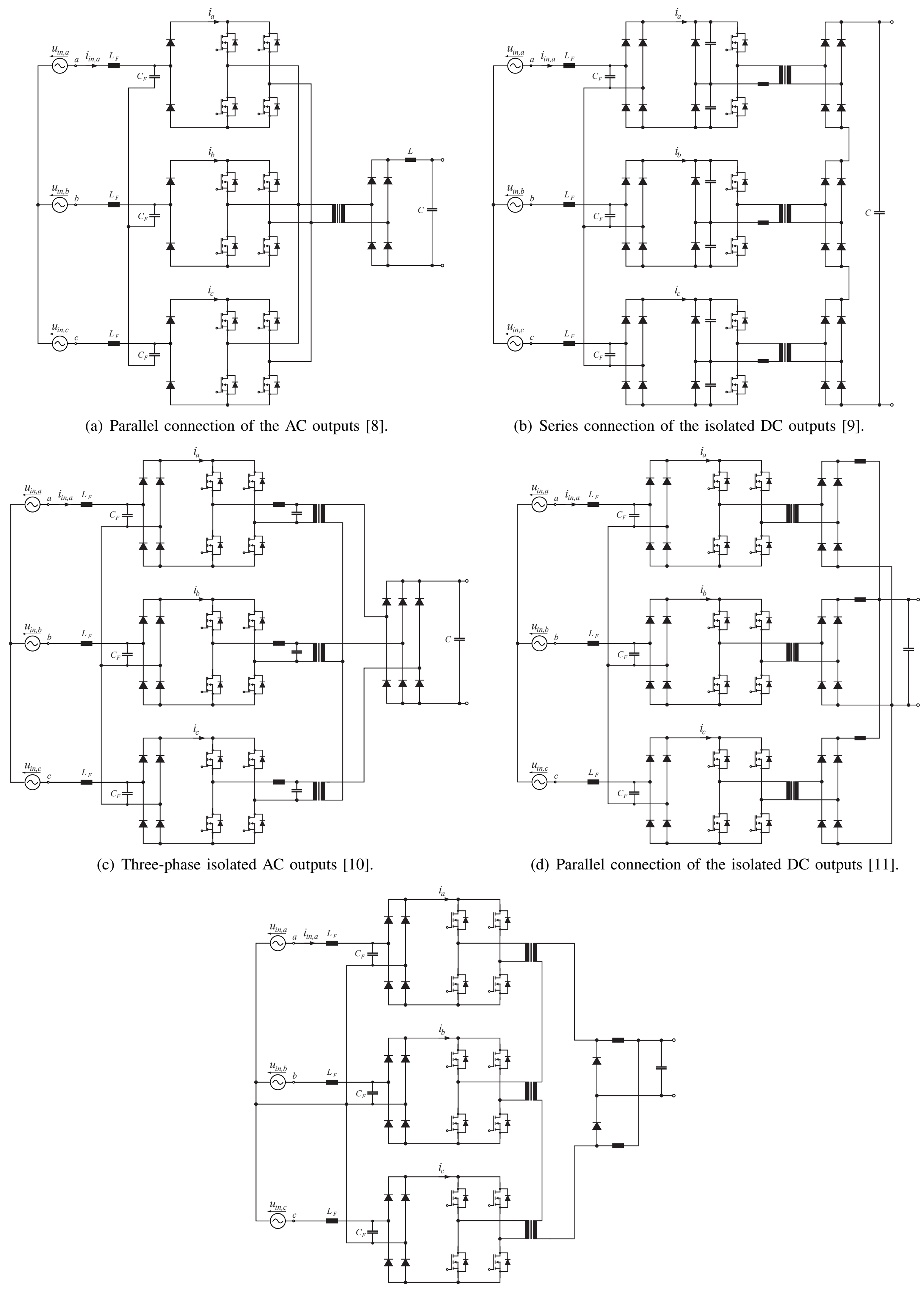
As an alternative, matrix-type [3] isolated PFC rectifiers have been proposed in [4]–[7] where a three-phase to single-phase matrix converter provides a direct conversion from mains frequency AC to high-frequency AC applied to a transformer primary; at the secondary side of the transformer a diode rectifier and a filtering stage are used for generation of the DC output voltage.

Phase-modular matrix-type PFC rectifiers, i.e. star-connected or delta-connected single-phase isolated rectifier modules, are an interesting alternative to phase-integrated three-phase concepts. Several approaches for the interconnection of the module outputs to generate the DC output voltage have been proposed, as shown in **Fig. 1**. In these topologies the phase modules can be considered as single-phase indirect [3] matrix converters. In this work this type of modular converters will be denominated *Isolated Indirect Matrix Y-Rectifiers* (I^2MY-Rectifiers).

The parallel connection of the high-frequency outputs of the three phase modules and a single high-frequency transformer, as shown in **Fig. 1(a)**, is proposed in [8]. In [9], each phase module has a partial series resonant converter connected at the primary of each transformer and a high-frequency rectifier on the secondary side. The converter output voltage is generated by series connection of the three DC outputs [cf. **Fig. 1(b)**]. The generation of a three-phase high-frequency AC voltage system at the secondary side of the transformers is proposed in [10], where a three-phase diode bridge rectifier is used at the output [cf. **Fig. 1(c)**]. The parallel connection of the isolated DC output voltages [cf. **Fig. 1(d)**] has been proposed in [11], but sinusoidal input currents are not achieved with this topology. The series connection of the isolated AC outputs [cf. **Fig. 1(e)**] is proposed in [12] and also described in [13]. By using a proper modulation scheme, a constant magnitude high-frequency isolated AC voltage is generated when adding the voltages of the transformer secondaries. As shown in **Fig. 1(e)**, the star point of the converter is tied to the star point of the supply voltage. This connection ensures a stable operation in case of unbalance of the voltages or currents in the converter. However, the star point of the supply voltage is not always available and it is therefore desirable to provide a control which guarantees a stable operation of the converter also for isolated converter star point.

This paper proposes a simplified phase-modular isolated PFC rectifier topology and its modulation and control scheme. The converter topology, denominated as *Isolated Matrix-type Y-Rectifier* (IMY-Rectifier), is based on single-phase direct matrix converters with series connection of the isolated AC outputs, as shown in **Fig. 2**. The converter control features sinusoidal input currents, controlled DC output voltage and a stable potential of the isolated converter star point.

The basic operation and modulation of the converter is presented in **Section II**. The output voltage control scheme, including the balancing of the star point potential, is explained in **Section III**. **Section IV** describes design considerations for the proposed topology. Alternative topologies, including



(a) Parallel connection of the AC outputs [8].

(b) Series connection of the isolated DC outputs [9].

(c) Three-phase isolated AC outputs [10].

(d) Parallel connection of the isolated DC outputs [11].

(e) Series connection of the isolated AC outputs [12].

Fig. 1 Phase-modular isolated indirect matrix-type three-phase AC/DC converter topologies.

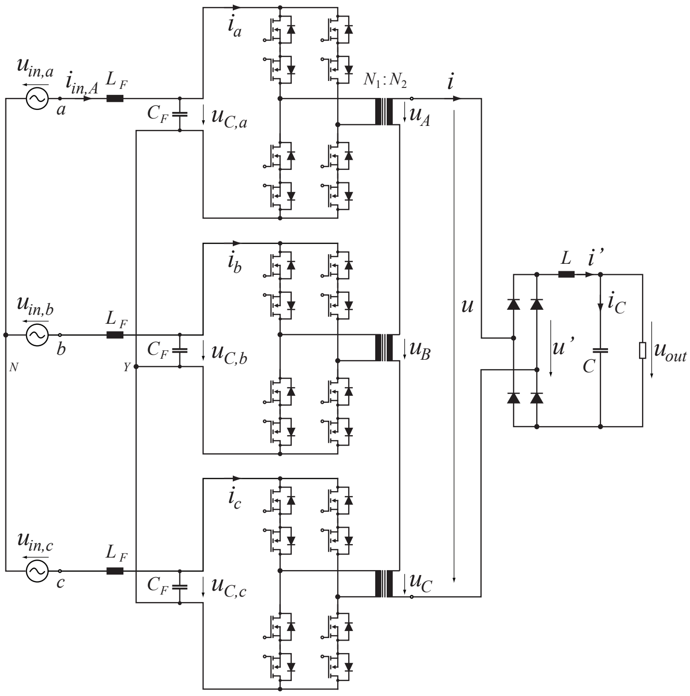


Fig. 2 Isolated Matrix-Type Y-Rectifier (IMY-Rectifier) [14].

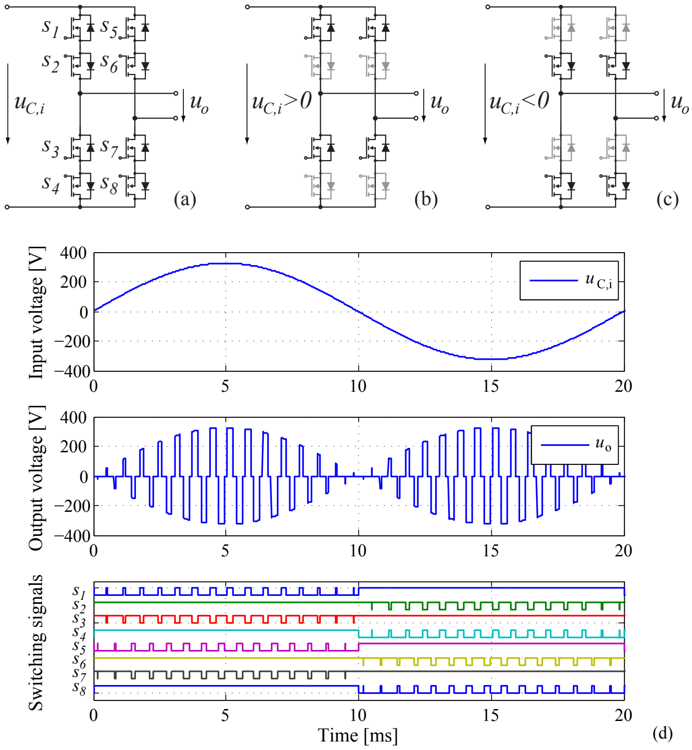


Fig. 3 Operation of one phase unit of the IMY-Rectifier. (a) Matrix converter stage. (b) Operation with positive input voltage $u_{C,i} > 0$: the switches in gray are continuously on during the positive half-cycle. (c) Operation with negative input voltage $u_{C,i} < 0$: the switches in gray are continuously on during the negative half-cycle. (d) Simulated voltages and switching signals for one cycle of the main voltage.

high frequency AC output and dual topologies, are proposed in **Section V**. Finally, conclusions and the contents of the final paper are discussed in **Section VI**.

II. Basic Operation and Modulation

The proposed IMY-Rectifier consists of three single-phase matrix converters, connected in star configuration, as shown in **Fig. 2**. The input side of each matrix converter is connected to the grid through an LC filter and the output side is connected to the primary of a high-frequency transformer. The secondaries of the transformers are connected in series and are feeding a diode bridge rectifier [14].

The operation of a phase unit is depicted in **Fig. 3**. The bidirectional switches are modulated using duty cycles that are proportional to the input voltage. During the positive half-cycle of the input voltage, only four switches are commutating at the switching frequency while the others are kept on, as shown in **Fig. 3(b)**, and the matrix converter operates as an H-bridge inverter. During the negative half-cycle, the H-bridge is inverted as shown in **Fig. 3(c)**. The simulated behavior of the output voltage and the corresponding switching signals are shown in as shown in **Fig. 3(d)**.

By using duty cycles that are proportional to the phase voltages, the voltages in the transformer secondaries can be expressed as

$$\bar{u}_A = \frac{N_2}{N_1} M \sin(\omega t + \varphi) \cdot U \sin(\omega t) \tag{1}$$

$$\bar{u}_B = \frac{N_2}{N_1} M \sin(\omega t + \varphi + \phi) \cdot U \sin(\omega t + 120°) \tag{2}$$

$$\bar{u}_C = \frac{N_2}{N_1} M \sin(\omega t + \varphi - \phi) \cdot U \sin(\omega t - 120°) \tag{3}$$

where U is the amplitude of the input voltages and M is the modulation index, defined with respect to the desired output voltage u^*_{out} as

$$M = \frac{2}{3}\frac{N_1}{N_2}\frac{u^*_{out}}{U}. \tag{4}$$

Selecting $\varphi = 0$ and $\phi = 120°$, by adding the voltages of the secondaries of the transformers, u_A, u_B and u_C, the switching frequency AC voltage u is obtained, with a constant magnitude $\hat{u}$ defined by

$$\hat{u} = \frac{N_2}{N_1} MU[\sin^2(\omega t) + \sin^2(\omega t + 120°) + \sin^2(\omega t - 120°)]$$
$$= \frac{N_2}{N_1}\frac{3}{2} MU. \tag{5}$$

This relation can be observed in **Fig. 4** where the formation of the output voltage u is depicted. The DC output voltage

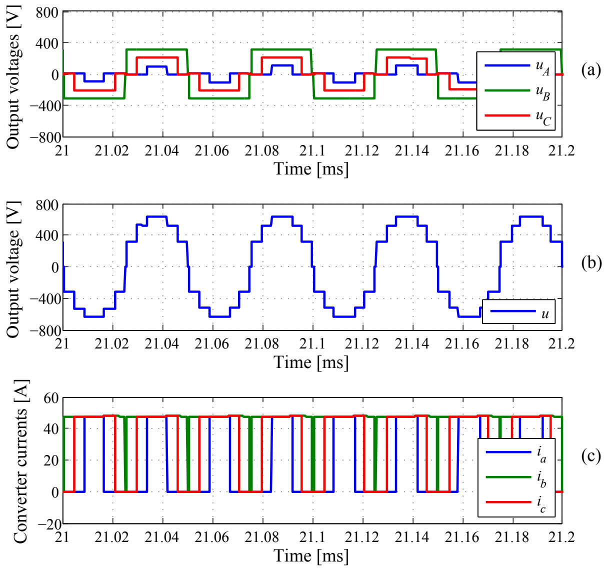


Fig. 4 Formation of the output voltage; $\frac{N_1}{N_2} = 1$.

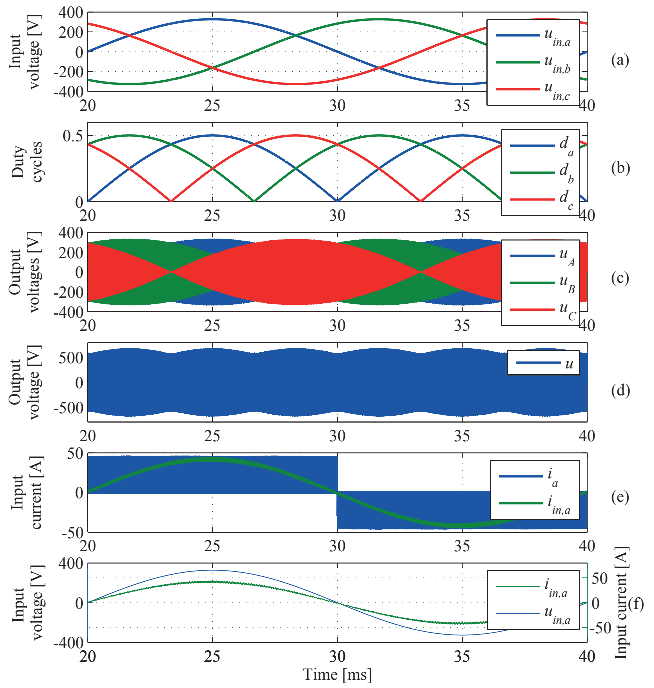


Fig. 5 Steady state operation of the IMY-Rectifier; $\frac{N_1}{N_2} = 1$.

is obtained by rectification and filtering of the high-frequency voltage u.

The steady state behavior of the IMY-Rectifier is shown in **Fig. 5**. It is observed that the input current is sinusoidal while the high-frequency output voltage u presents a constant magnitude.

An alternative modulation method that results in the same voltage and current behavior consists of operating each bridge-leg at 50 % duty cycle and to continuously adjust the phase shift between the two bridge-legs in order to generate the desired output voltage.

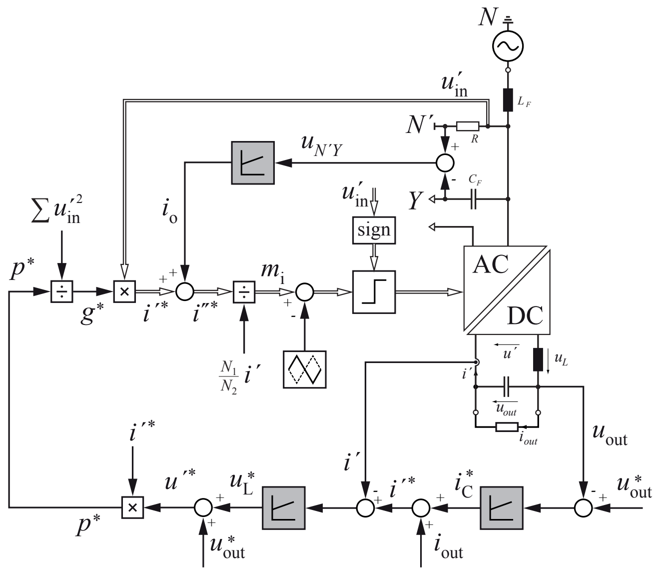


Fig. 6 Control scheme [14].

III. Control

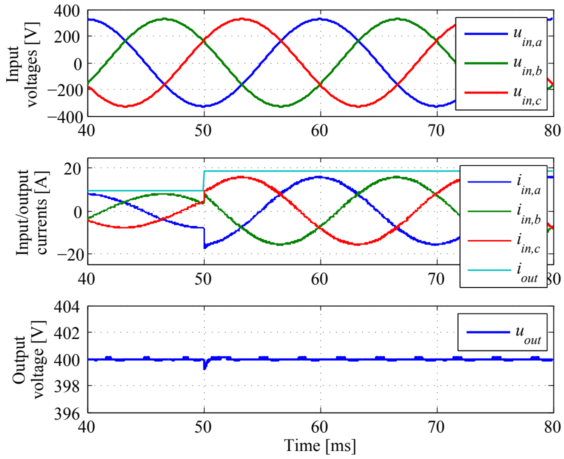
A. DC Output Voltage Control

The control of the IMY-Rectifier considers a cascaded structure with an outer control loop for the DC output voltage u_{out} and an inner control loop for the DC side inductor current i. Feedforward loops of the load current i_{out} and the reference voltage u^*_{out} are included in the outer and inner control loops, respectively. A block diagram of the control scheme is shown in **Fig. 6**.

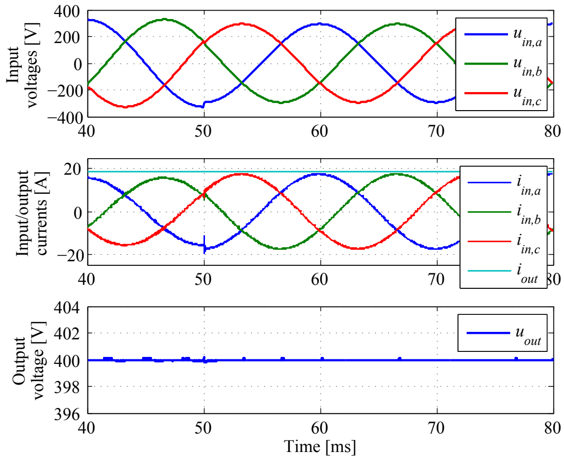
The voltage u'^* to be generated of the diode bridge is multiplied by the DC side inductor current reference i'^* to obtain a reference power p^* for the modulation stage. The modulation stage uses feedforward loops of the zero sequence free input voltages u'_{in} (measured against an artificial star point N' formed by a star connection of equal resistors) and the diode bridge DC output current i' in order to compensate variations of the input and output variables and to decouple the input and output stages of the converter.

The dynamic behavior of the IMY-Rectifier with the proposed control scheme is simulated using GeckoCIRCUITS. The response to a step change in the load resistance is shown in **Fig. 7(a)**. The load resistance is changed from 42.6 Ω (half-load) to 21.3 Ω (full-load). A voltage drop of less than 1 V is observed in the output voltage u_{out} during the transient. A fast change in the magnitude of the input currents is observed.

The effect of a step change in the input voltage amplitude is shown in **Fig. 7(b)**. A 10 % drop in the magnitude of the input voltages is applied at $t = 50\,\text{ms}$. The amplitude of the input currents is increased in order to maintain a constant power flow and the output voltage u_{out} is kept constant.

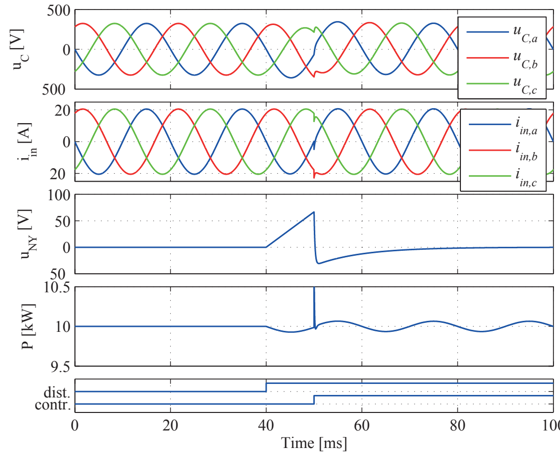


(a) Step change in the load resistance.

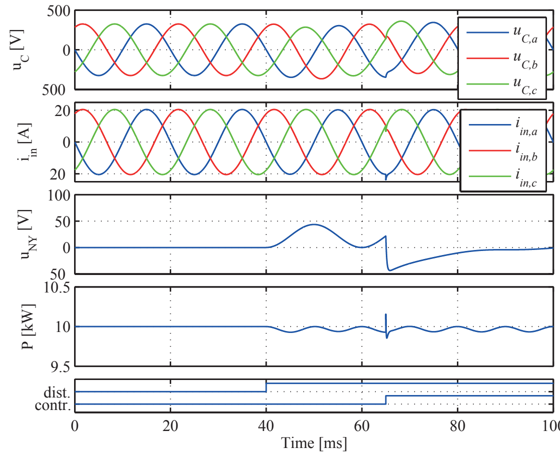


(b) Step change in the input voltage amplitude.

Fig. 7 Behavior of the control of the IMY-Rectifier during step changes in the load an in the input voltage.



(a) Offset error in a phase current reference.



(b) Gain error in a phase current reference.

Fig. 8 Behavior of the control of the star point potential.

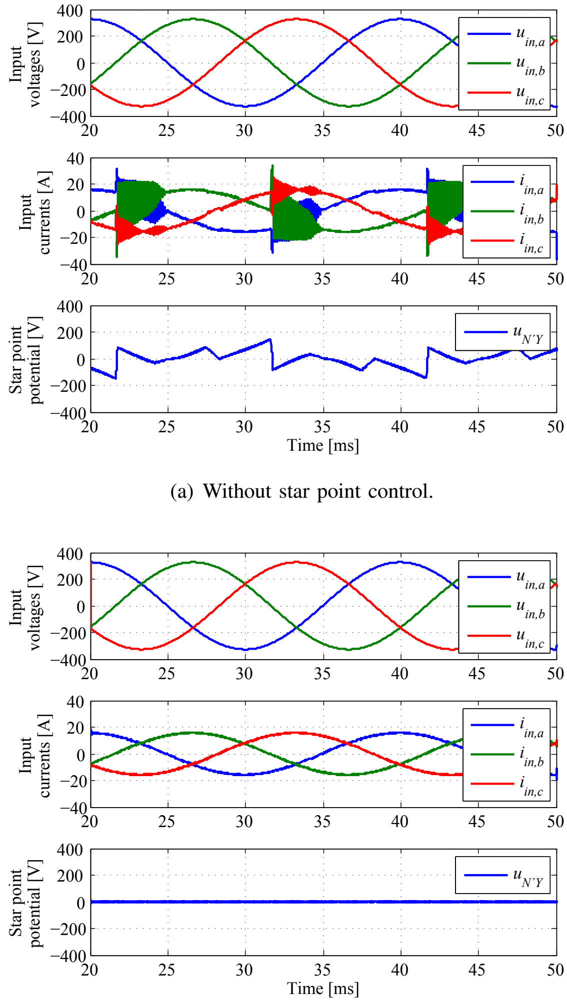
B. Control of the Star Point Potential

Due to the possible unbalance of the input voltages as well as gain and offset errors in the current and voltage measurements, the potential of the star point Y of the phase modules, with respect to an artificial star point N' of the grid, can present variations that may introduce distortion of the currents or problems in the control of the converter.

In order to mitigate these kind of problems, a star point potential controller has been included into the control scheme shown in **Fig. 6**. By using a star connection of equal resistors R for the voltage measurements, any zero sequence component is removed from the measurements. In addition, the potential difference of the star point Y against the star point N' of the resistors is controlled to zero using a proportional-integral (PI) controller that adds a zero sequence current i_o to the reference currents used in the modulation stage.

The behavior of the star point potential control is shown in **Fig. 8** for constant power operation of the converter. A simplified model of the converter is used for these results. The effect of a 0.2 A offset error in the reference of the phase A current is shown in **Fig. 8(a)**. When the error is introduced, at $t_1 = 40\,\mathrm{ms}$, the star point potential $u_{N'Y}$ presents a fast increase until the control is activated at $t_2 = 50\,\mathrm{ms}$ and $u_{N'Y}$ returns to zero. The effect of a $1\,\%$ lower amplitude in the reference current of phase A is shown in **Fig. 8(b)**. The introduction of this gain error generates an oscillation of $u_{N'Y}$, which is eliminated when the control is activated.

In order to further verify the behavior of the proposed star point potential control, the full IMY-Rectifier is simulated using GeckoCIRCUITS. As shown in **Fig. 9(a)**, a $5\,\%$ gain error in the input voltage measurement is enough to generate large deviations in the star point potential $u_{N'Y}$ and distortions in the input currents when the IMY-Rectifier operates without the star point control. Simulation results using the star point control under the same conditions are shown in **Fig. 9(b)**. The



(a) Without star point control.

(b) With star point control.

Fig. 9 Behavior of the IMY-Rectifier with a 5 % gain error in the voltage measurements (one phase voltage is measured with a higher gain).

star point potential is kept equal to zero and the input currents present no distortion.

IV. Design

A. Stresses on the Power Semiconductors

The maximum voltage stress in the switches of the matrix converters is defined by the amplitude of the phase-to-neutral input voltages

$$u_{S,max} = U = \sqrt{2} \cdot 230 \text{ V} = 325 \text{ V}. \tag{6}$$

Compared to a phase-integrated three-phase converter, where the voltage stress on the switches is defined by the line-to-line voltage, a lower voltage stress is applied to the power semiconductors in the phase-modular system and 600 V devices can be used with a 45 % safety margin.

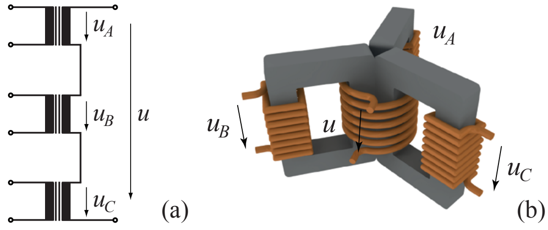


Fig. 10 Integration of the phase transformers.

For the calculations of the current stresses, sinusoidal input currents and constant output current $i_{out} = I_{DC}$ are assumed. For a given modulation index M, defined in (4), the rms current in each switch of the matrix converter is defined by

$$I_{T,rms} = I_{DC} \frac{N_2}{N_1} \sqrt{\frac{3M}{2}}, \tag{7}$$

and the average current is given by

$$I_{T,avg} = I_{DC} \frac{N_2}{N_1} \frac{3M}{2}. \tag{8}$$

In the output diode bridge rectifier, the voltage stresses are defined by the amplitude of the voltage u in the secondary side of the transformer

$$u_{D,max} = \frac{3}{2} \frac{N_2}{N_1} U. \tag{9}$$

The rms current in the diodes can be calculated in terms of the modulation index M and the output current I_{DC}

$$I_{D,rms} = \frac{I_{DC}}{2} \sqrt{1 + \frac{3M}{\pi}}, \tag{10}$$

while the average current depends only on the output current:

$$I_{D,avg} = \frac{I_{DC}}{2}. \tag{11}$$

B. Transformer Construction

The high-frequency isolation transformer can be optimized by integrating the three phase transformers as shown in **Fig. 10**; the primary windings are arranged on the outer legs of the cores and a single secondary winding is placed around the remaining legs of the three cores.

V. Alternative Topologies

A. High Frequency AC Output

In addition to rectifier applications, the proposed converter can be also used as a high frequency AC source. An interesting alternative topology can be obtained replacing the output rectifier by a Boucherot circuit, in order to provide a constant-current supply to the load independent of the load resistance [15]. An LC filter tuned in resonance with the frequency of the transformer output voltage u is connected at the terminals of the secondary side of the transformer as shown in **Fig. 11**. A constant-current supply i_{out} is provided to the load across the terminals of the resonant capacitor.

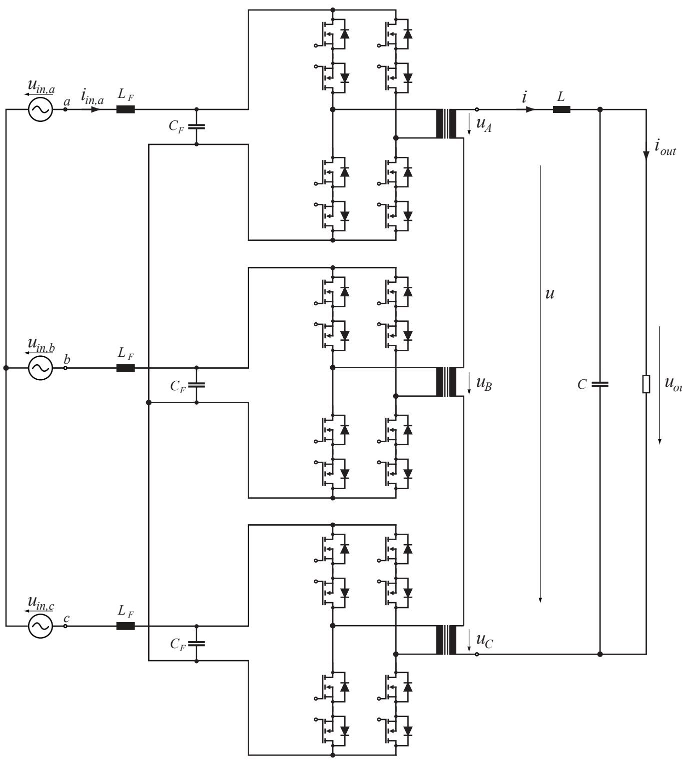


Fig. 11 New circuit topology with HF constant AC current output "Boucherot-IMY-AC/AC-Converter".

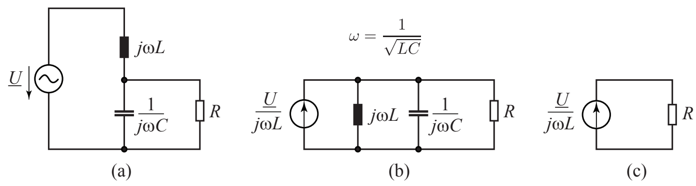


Fig. 12 Operation of the Boucherot circuit. (a) Circuit with voltage source. (b) Equivalent circuit with a current source. (c) Equivalent circuit when the resonance of the LC circuit is tuned to the source frequency.

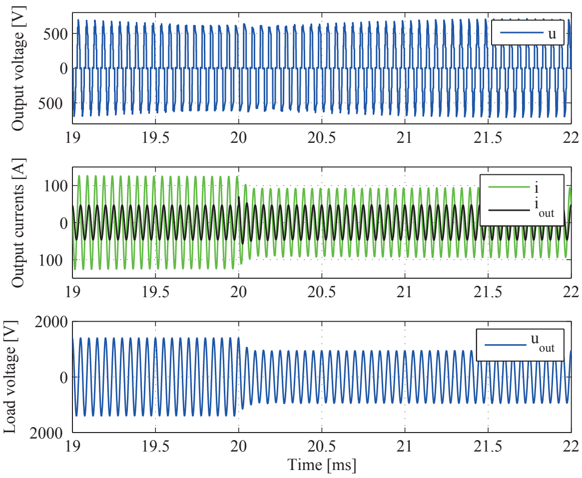


Fig. 13 Automatic control behavior of the Boucherot-IMY-AC/AC-Converter. Simulation results for a step change in the load resistance; the load resistance is changed from 40 Ω to 20 Ω. The converter operates in open loop.

The basic principle of the Boucherot circuit is described in **Fig. 12.(a)**, with a voltage source $\underline{U}$, an LC series resonant circuit and a resistive load in parallel to the capacitor. The voltage source with a series inductor can be replaced by an equivalent current source with a parallel inductor as inner impedance, as shown in **Fig. 12.(b)**. When the resonant frequency of the LC circuit is tuned to the frequency of the voltage source ω_s, the parallel LC circuit shows infinite impedance and can therefore be neglected; accordingly a constant current is impressed to the load, independently of the value of R, as shown in **Fig. 12.(c)**. The load current magnitude is defined by the value of the inductance L, the frequency and magnitude of the voltage u or by the modulation index m.

The current regulation capability of this circuit is shown in **Fig. 13** for a step change in the load resistance and operation in open loop with predefined duty cycles of the phase units and no feedback loops. The LC output circuit is tuned to a resonant frequency equal to the switching frequency and the inductance and capacitance values are selected for a constant output current magnitude of 40 A. It is observed that after the load resistance is changed the load voltage is automatically adjusted and the load current magnitude is kept nearly constant.

B. Dual Topologies

It is also possible to build dual topologies of the converter concepts proposed in **Fig. 2** and **Fig. 11**. A boost-type IMY-Converter, in which the inductor of the rectifier is moved to the AC side of the matrix converters, is shown in **Fig. 14(a)**. In this topology, the secondary sides of the transformers are connected in parallel and operate as high-frequency current sources. Then, the supplied current i is rectified by the diode bridge and filtered by a capacitor, providing a DC voltage u_{out} to the load [cf. **Fig. 14(b)**].

By replacing the output diode rectifier by a dual Boucherot circuit, shown in **Fig. 14(c)**, a high-frequency constant-magnitude voltage u_{out} is impressed in the load, independent of the load resistance value. The converter topology can be represented by the simplified model as shown in **Fig. 15(a)**. In this model, the current source with the parallel capacitor can be replaced by an equivalent voltage source with an inner series capacitor, as shown in **Fig. 15(b)**. By tuning the frequency of the resonance between the capacitor and inductor to be equal to the equivalent voltage source frequency, the impedances of the capacitor and inductor cancel each other, resulting in the equivalent circuit shown in **Fig. 15(c)**. In this way, a voltage with a constant magnitude is impressed to the load, independent of the value of the load resistor R.

VI. Conclusions

A new modulation and control of a three-phase phase-modular isolated matrix-type Y-rectifier is presented. The con-

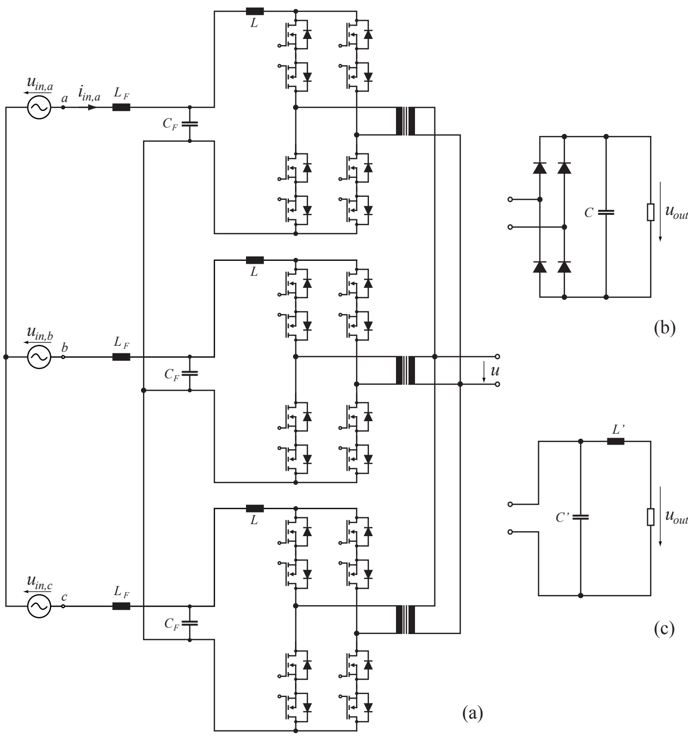


Fig. 14 Boost-type dual topologies with inductors in the AC side. (a) Boost-type IMY-Converter. (b) Output stage of the dual IMY-Rectifier. (c) Output stage for the dual HF constant AC output voltage Boucherot-IMY-AC/AC-Converter.

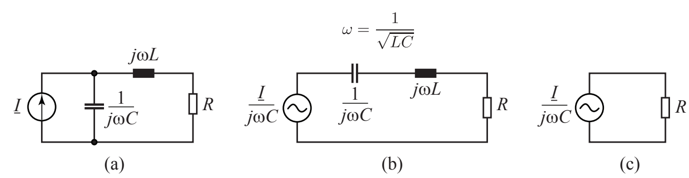


Fig. 15 Operation of the Boucherot circuit dual. (a) Circuit with current source. (b) Equivalent circuit with a voltage source and inner impedance $\frac{1}{j\omega C}$. (c) Equivalent circuit when the resonance of the LC circuit is tuned to the frequency ω_s of the feeding current source.

verter operates with sinusoidal input currents and controlled output voltage. The control scheme also considers the control of the star point potential for safe operation under unbalance and errors in the reference currents.

The proposed control scheme achieves a fast dynamic response in the compensation of disturbances, as shown in simulation results for step changes in the load resistance and in the amplitude if the input voltages.

Compared to a phase-integrated three-phase rectifier, the phase-modular approach requires a larger number of semiconductor devices. However, the voltage stress of these devices is lower by a factor of $\sqrt{3}$, allowing the use of power switches with lower voltage rating. Accordingly, for a 400 V_{l-l} mains, 600 V instead of 1200 V semiconductor devices can be used, i.e. 650 V CoolMOS instead of IGBTs, featuring operation at significantly higher switching frequencies.

In addition to the IMY-Rectifier, alternative topologies are presented, considering a high-frequency AC output, denominated the Boucherot-IMY-AC/AC-Converter, and the dual boost-type alternatives to both converters.

Future work consider the verification of the proposed concepts on a 7.5 kW laboratory prototype, designed for 400 V_{l-l} mains voltage, 400 V DC output voltage and 72 kHz switching frequency.

Acknowledgment

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