Control of 3 – Phase 4 – Wire Isolated Grids

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Abstract

The generation of isolated grids by pulsed converters with characteristics close to the mains of the utility companies is a pretentious task. For generation of three-phase four-wire isolated grids are presented possible topologies and the demands on the system control are processed. For control of all conceivable load and error conditions, an extensive control technology is necessary. This must permit unsymmetrical operating conditions for an unlimited period but recognize errors simultaneously and therefore an overloading the consumer and the power semiconductors reliable may prevent. Measurement results on an experimental plant show the problems to be solved.

Introduction

The decentralized energy conversion gives the possibility to realize and to control the needed parameters of the energy on the spot. The task is to generate an isolated grid with characteristics close to the mains of the utility companies. Because of the voltage drop along the supply lines it is not effective to bridge long distances by using 3- phase 4-wire lines without any voltage stabilization.

The voltage stabilization unit for remote consumers can be avoided if a 3-phase 4-wire voltage source inverter is used to generate a local isolated AC-grid which is supplied by a DC-cable or alternative energy sources. If this isolated grid has characteristics similar to the public mains of the utility companies this is a effective and independent way to supply distributed energy consumers for instance on islands, remote plants or devices. In case of using a long cable to supply the converter it is necessary to install a voltage limitation unit to manage faults and shorts. Unbalanced or single phase loads require a fourth phase to avoid zero components. The connection of a three phase DY-transformer additional to a 3-phase inverter avoids the appearance of a zero component also. The additional expense of a transformer amounts to 30..40% of the system expense. The paper describes a control strategy for generating an isolated grid as well for unbalanced loads as current with DC-components for an unlimited period under consideration of faults and shorts.

The system is able to start up induction motors dimensioned near to the nominal power of the system.

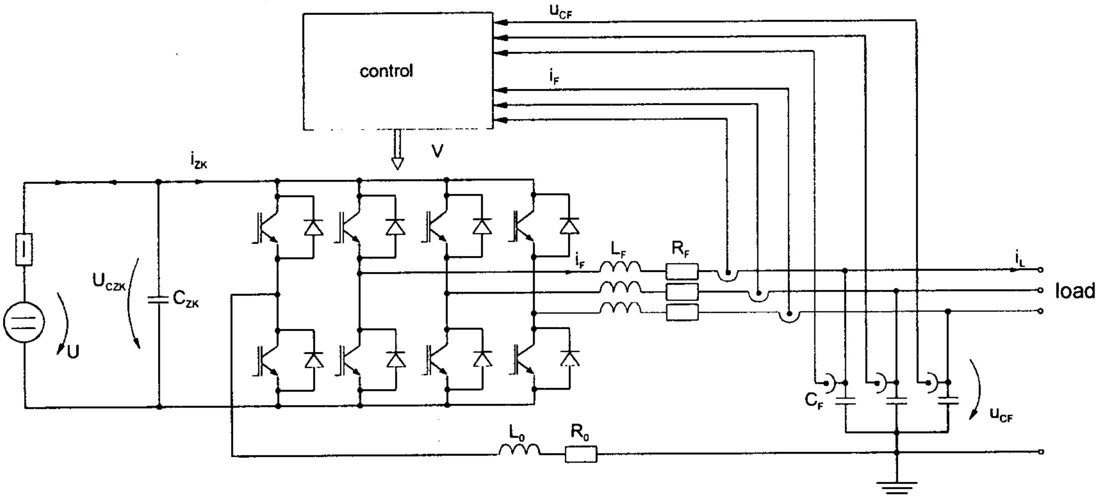

Fig. 1: simplified topology of the 4-phase VSC

Fundamental circuit topology

The power electronic part of an isolated grid consists of a voltage source converter, a supplying line and an optional voltage limitation unit. The isolated grid is rated for 100 kVA and controlled by a C167 16-bit microcontroller. Fig. 1 shows the circuit topology of the 4-phase VSC including all measuring sensors. The circuit consists of a 4-phase IGBT-bridge, a ripple filter (L_F, R_F, C_F), a zero inductance (L_0, R_0) and the DC-bus. The actual values of the state variables filter current i_F and mains voltage u_{CF} are measured in each phase and provided to the control unit. It computes the driver signals for the power electronic devices. As idealized load, the current sources were connected in parallel to the filter capacitors. The DC-link consists of the DC-bus capacity which is fed remotely by the voltage source U via a cable or an other energy source. The dynamic qualities of the system are examined subsequently using a mean-values model according to the topology shown in Fig. 1. This means that the converter is replaced by four modulated voltage sources, which inject the mean values of the converter output voltages into the electrical network.

Control structure

In order to attain a deeper insight into the system dynamics of the circuit, it is useful first transform the network into a mains-fixed coordinate system (d-q-0-components). Additional to the positive-sequence control it is important to have as well control loops for the negative as zero sequence component. Otherwise these components will appear in the isolated grid voltage in case of supplying unbalanced loads.

An equivalent circuit can be computed for each of the circulating space vector components. Fig. 2 shows the equivalent circuit of the positive- and negative-sequence components of the space vectors. Fig. 3 shows the circuit for the zero-sequence component.

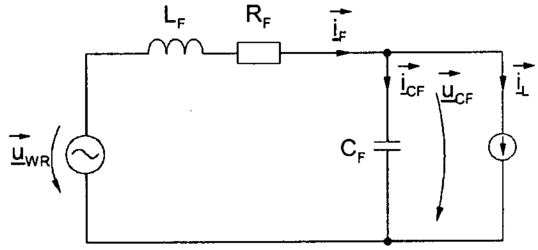

Fig. 2: Equivalent circuit of the positive- and negative-sequence components of the space phasors acc. to Fig. 1

By means of the determined equivalent circuits, it can be deduced that both, the rotating vector components of the zero-sequence component have to be controlled to a defaulted reference value. The differential equations, describing the respective state of the system which are necessary to develop the control structure of the system, can be derived from the equivalent circuits in Fig. 2 and Fig. 3.

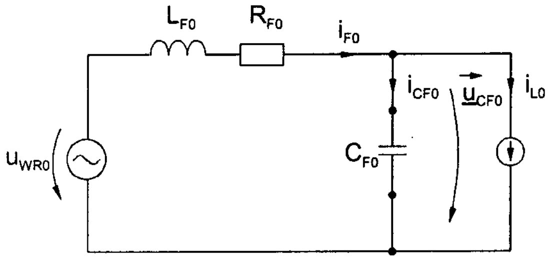

Fig. 3: Equivalent circuit of the zero-sequence component according to Fig. 1

If these differential equations of the space vectors are multiplied by the inverse unity vector of the mains voltage, the system behavior of the controlled system can be received in a coordinate system circulating synchronously with the line angle (0-d-q coordinates). In this coordinate system, the fundamental components of all space vectors of the state variables are stationary phasors. These are marked as overlined quantities. Concerning the controller design, this circumstance has positive effect, since the vector components to be controlled are idle quantities. This makes possible to use PI controllers which results in no steady-state deviation between the reference values and the actual values of the corresponding state quantities.

Description of the Feedback Control System

In Fig. 5 the block diagrams of the feedback control system, concerning the capacitor voltage's space vector is shown. It consists of the transfer matrices [S_{LF}] and [S_{CF}], which are coupled with each other. The matrix [S_{LF}] describes the system behavior of the filter choke L_F in the synchronous rotating reference frame. The system behavior of the filter capacitor is described by the transformation matrix [S_{CF}]. The control equivalent circuit of the matrices [S_{LF}] and [S_{CF}] which represent the control process can be seen in Fig. 4. The main path of the controlled system consist of components with PT_1-behavior. Besides this, the mutual coupling, having V-structure, can be seen. The V-structure is the result of coordinate-transforming the differential equations.

Since the capacitors are not being damped by parallel resistors, the main paths have pure I-behavior. In case of the filter capacitor the coupling of the two main paths result in the term $\omega \cdot C_F$.

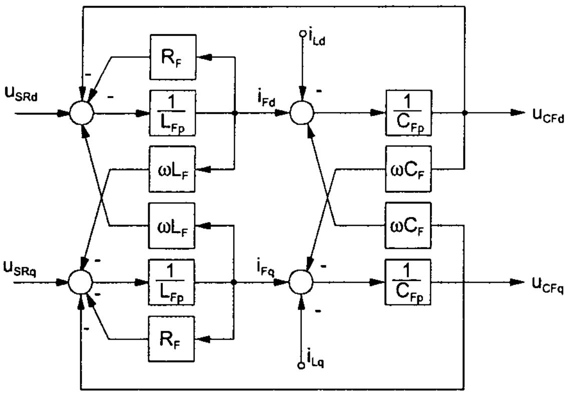

Fig. 4: Control equivalent circuit of the control process in a coordinate system rotating with mains frequency

The vector of the load current $\vec{\underline{i}}_l$ influences the controlled system as a disturbance signal.

The zero-sequence control system of the capacitor voltage has the same structure as the main path of the space vector control structure. The structure for controlling the zero-sequence component is shown in Fig. 5. The load current acts as a disturbance signal also.

The parts in Fig. 5, characterized as "controller" include all components which are contribute to control the system. Due to the relatively high sampling frequency of the digital controller ($f_{sampling} = 8$ kHz), in first approximation it is permissible to model the controller with continuous gains. The processing time of the microcontroller can be considered by a dead time block.

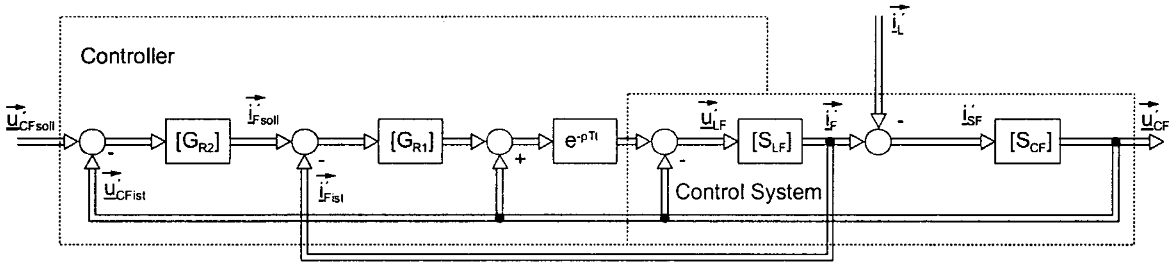

Fig. 5: Configuration for control of the space vector of the capacitor voltage

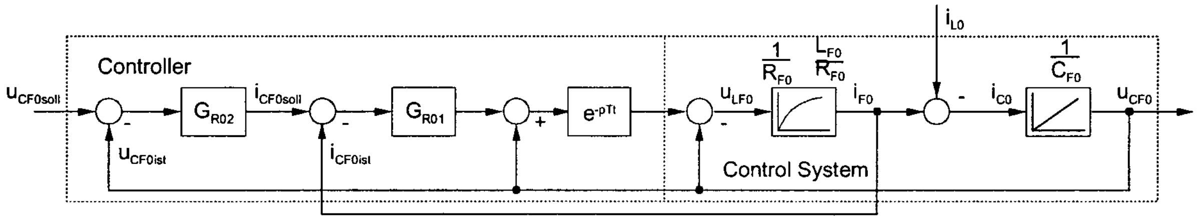

Fig. 6: Configuration for control of the zero-sequence component of the capacitor voltage

The fundamental control of the space vector of the capacitor voltage was performed with underlying control of the capacitor current (see Fig. 5).

The capacitor current is being controlled by the inner loop, consisting of the transfer matrices $[G_{R1}]$and $[S_{LF}]$. In the transfer matrix $[G_{R1}]$ the controllers for the space vector components of the capacitor current are summarized. The matrix $[G_{R1}]$ consists of proportional controllers, which fill the main diagonals. The secondary diagonals consist of zeros. The inner control loop was designed for a good disturbance signal transfer function concerning a change of the load current vector, which was achieved by a high amplification factor of the proportional controllers. Due to the use of proportional controllers, a permanent deviation occurs at the space vector of the capacitor current, which however is uncritical at this point.

The reference value of the space vector pf the capacitor current is provided by the outer control loop, which controls the voltage of the filter capacitor C_F by employment of the control matrix

$[G_{R2}]$. The main diagonal of the matrix $[G_{R2}]$ consists of transfer functions of PI-controllers. That is why in steady state no permanent deviation between reference and actual value of the space vector of the capacitor voltage is to be expected. As reference value for the d-component of the voltage vector, the line to earth voltage has to be set to 230V*√2. The reference value for the q-component is zero.

The structure of the control system for the zero-sequence component of the system quantities is presented in Fig. 6. If only the main control path is considered, this structure is identical with the topology of the d- and/or q-component vector control of the capacitor voltage. Calculating the parameters for the capacitor current controller $[G_{R01}]$ or the capacitor voltage controller $[G_{R02}]$, parameters of the control process, different of those shown in Fig. 2 have to be taken into account.

$$R_{F0} = R_F + 3 \cdot R_0$$

$$L_{F0} = L_F + 3 \cdot L_0$$

$$C_{F0} = C_F$$

Realization of Negative sequence control

Input variables of the negative sequence control are the 3/2-transformed capacitor voltages. After rotating these values with the opposite sense of rotation of the positive sequence system, they are buffered in a ring storage. This is necessary in order to filter out the positive-sequence, appearing as a 100 Hz component. This ring buffer store has the function of a synchronous filter. In this case it has 40 storing locations in which the oldest available value is replaced by the newest one. This procedure is done in each calculation and sampling cycle. After this operation, the mean-value is generated over all the stored values. This means that in case of a sampling time of 250µs and 40 storage cells, a mean value over 10ms is generated, which results in the filtering out of a steady-state 100Hz component. These mean-values of the d- and q-components are controlled to zero by the voltage controllers. The output variables are turned back by a vector rotator operating with double frequency. Consequently they are transformed into the positive-sequence coordinate system and can be added directly to the output variables of the positive-sequence component control variables.

Realization of Zero-sequence control

It turned out that the voltage controller with subordinate current control has not enough dynamics in order to level out a possibly occurring 50Hz component in case of load unbalances. Consequently the zero- sequence control consists of two parts:

- Voltage control with underlying current control for the steady-state regulation
- Voltage regulation in a stationary d-q-coordinate system for elimination of a 50Hz component arising from unbalances

The voltage and current zero-sequence components are determined by calculation:

$$x_{Null} = \frac{1}{3}(x_1 + x_2 + x_3)$$

The DC-component of the zero-sequence component can be eliminated by a conventional control loop. To eliminate the 50Hz-component it is necessary to fall back on the control in stationary coordinates. To generate the second component with a delay of 90° regarding to the original, the actual value is buffered in a ring storage and read out again with a delay of ¼ T_{Period}.

The d- and q-components of the zero sequence system obtained this way, analogously to the positive- and negative-sequence control can be rotated and eliminated. After rotating back, merely one of the two components, is required in order to add it to the variable coming from the steady-state control and to output it to the modulator of the fourth phase.

Measurements have shown, that for effective elimination of DC-components it is necessary to have an additional measurement of the DC-component in each phase. These values are directly provided to the modulator and injected in the respective phase. This is equivalent to the addition of a DC-component per phase.

Topology with transformer feeding the zero sequence system

The use of a DY-transformer for distributing the isolated grid like shown in Fig. 7 gives the possibility to avoid a control loop for the zero-sequence component.

The control concept for the positive- and negative-sequence component for this case with transformer is identical to the control configuration without transformer. It is not necessary to consider the complex transformation ratio. The consideration of the vector group of the transformer is sufficient in case of measuring the secondary voltage. The resonance of the controlled system are excited by the strongly harmonic oscillation containing load current. Low-frequency oscillations result from the dominant low resonant frequency. Due to the fundamental control, this parallel resonance is already attenuated so strong that no resonance peak of the amplitude spectrum is detectable in the lower frequency range. If the compensation capacitor is not negligible small the system stability can be supported by realization of harmonic control loops for low frequency oscillations (5th,7th,11th and 13th).

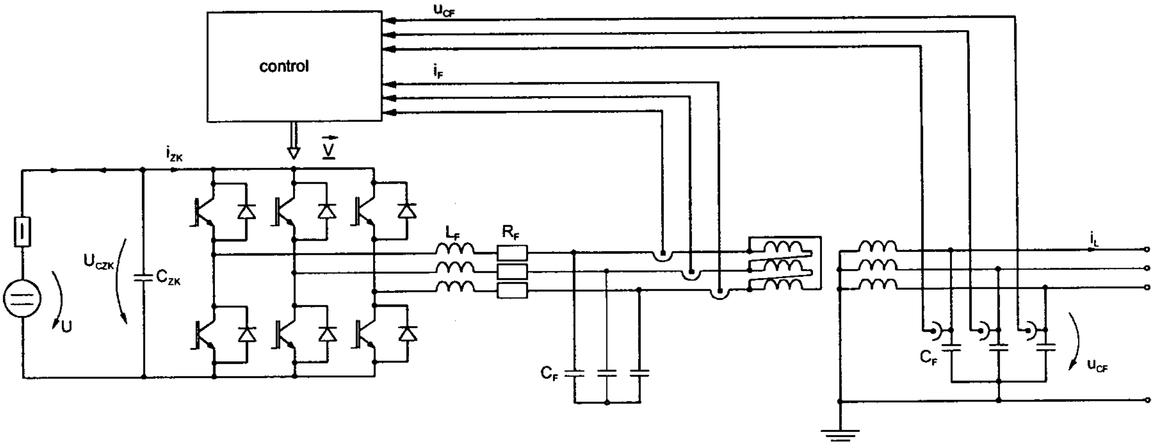

Fig. 7: Simplified topology of the 3-phase VSC with controlled transformer secondary voltage and reactive power compensation capacity C_K

Measurements

For some critical loads the next figures show the phase voltages and a phase current in continuous mode. Characteristic parameters and harmonics of the mains voltages are shown for each phase. A start up of AC-motor is also presented.

Single phase load with DC-component

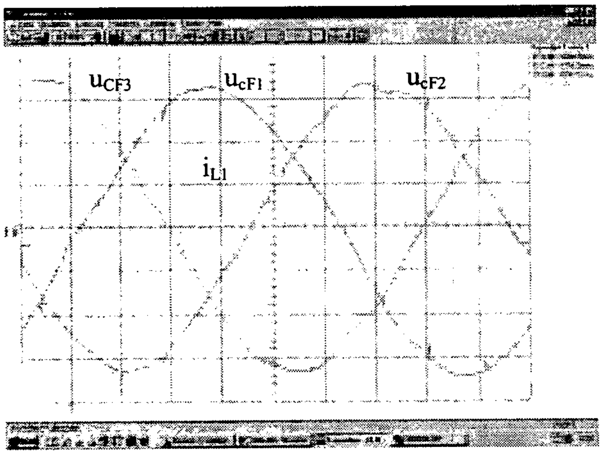

Fig. 8: single phase load with DC-component mains voltage 230V (u_c), load current(î load = 40A)

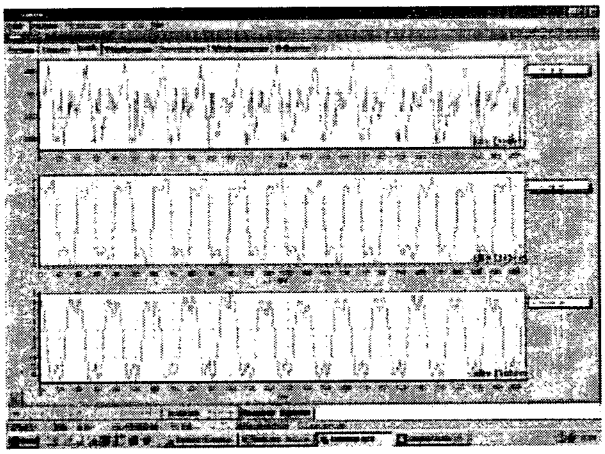

Fig. 9: single phase load with DC-component; d-component of the positive-sequence voltage, d- and q-component of the negative-sequence component of the mains voltage are shown

Measured Voltage quality:

Value	Phase 1	Phase 2	Phase 3
Volts(CF)	1,50	1,46	1,49
Volts(RMS)	232,5V	229,2V	233,0V
Volts(THD)	4,7%	2,5%	2,7%
Volts(fund)	232,3V	229,1V	232,1V
Volts(2^{nd})	2,35%	1,26%	1,50%
Volts(3^{rd})	1,95%	0,84%	1,16%
Volts(4^{th})	1,46%	0,5%	0,64%
Volts(5^{th})	0,4%	0,36%	0,45%
Volts(6^{th})	1,04%	0,83%	0,79%
Volts(7^{th})	1,37%	2,0%	1,85%

Unbalanced three phase load (ratio 1:2:3)

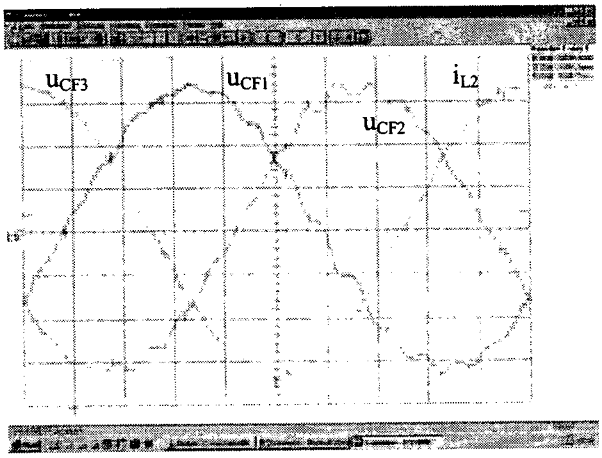

Fig. 10: unbalanced three phase load (load ratio 1:2:3) mains voltage 230V (u_c), load current(î load = 75A)

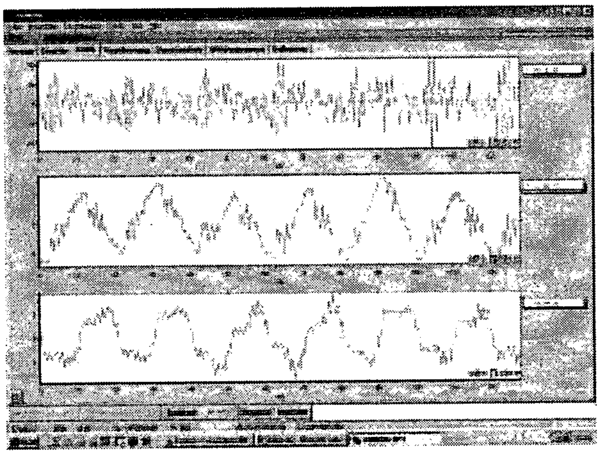

Fig. 11: unbalanced three phase load (load ratio 1:2:3) q-component of the positive sequence voltage, d- and q-component of the negative sequence component of the mains voltage are shown

Measured Voltage quality:

Value	Phase L1	Phase L2	Phase L3
Volts(CF)	1,46	1,45	1,47
Volts(RMS)	231,8 V	229,6 V	233,4 V
Volts(THD)	5,3%	3,9%	4,8%
Volts(fund)	231,4 V	229,4 V	233,1 V
Volts(2nd)	0,21%	0,22%	0,19%
Volts(3rd)	2,7%	2,3%	3,16%
Volts(4th)	0,05%	0,04%	0,1%
Volts(5th)	1,61%	0,96%	1,51%
Volts(6th)	0,13%	0,09%	0,05%
Volts(7th)	2,52%	1,41%	2,54%

Start up of an AC-Motor 22kW

Fig. 12 shows the mains voltage, the load current and the ref. value of the d-component of the filter current during a start up of an AC-motor. The limitation of the start up current (approx. 400-500A) leads to a voltage sag for nearly 2 sec. A voltage lowering is the sole solution to start up loads with a high inrush current, if the inverter can not manage such high overcurrents for the needed time. The current is limited to150A and the mains voltage amounts 100V during start up.

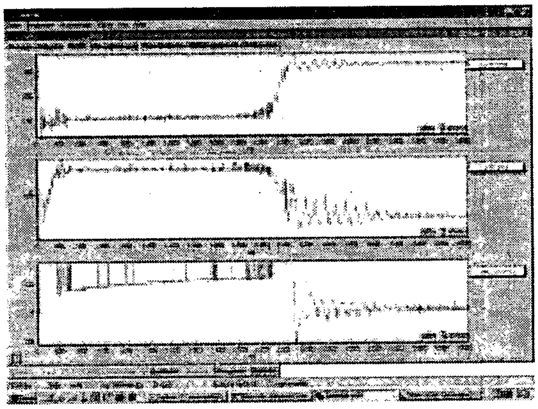

Fig. 12: start up of a AC-motor 22kW using a current limitation control

Summary

The presented system for generating isolated grids can supply balanced, unbalanced or DC-loads under maintaining the voltage quality parameters. A control loop for the negative-sequence and zero-sequence of the mains voltage is necessary. The used 4-phase inverter is able to manage the negative- and zero-sequence system with a lower expense according to the use of a 3-phase inverter and an additional DY-transformer.

A connection of loads with high inrush currents like motors or transformers are only possible if the inverter can be overloaded or a voltage sag have to be accepted for the respective time.

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