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| Institute: | Karlsruhe Institute of Technology (KIT)<br>Elektrotechnisches Institut (ETI) |
| Type: | Conference Proceedings |
| Published at: | Industrial Electronics Society, IECON 2016 - 42nd Annual Conference of the IEEE<br>Publisher: IEEE, Piscataway ( NJ)<br>Date: Oct. 2016<br>ISBN: 978-1-5090-3474-1 |
| Hyperlinks: | DOI: 10.1109/IECON.2016.7794010 |

# Decoupled Circulating- and Output-Current Control of Parallel Inverter Systems

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***Abstract*—Modern inverter systems often require the operation of multiple parallel inverters. When these are connected to a weak grid or a common filter, stability problems can occur. Also currents, which lead to a bottleneck of the available power, are a known problem of parallel inverter operation. In this paper a method will be presented, which allows to describe any number of parallel inverters as single virtual inverter (VI). By dividing the inverters in pairs and triplets a decoupled control of the circulating currents and the output currents will be possible. The presented control method avoids instabilities due to differing current paths of circulating and output currents. Simulation results and measurements demonstrate the performance and stability of this approach.**

## I. Introduction

There are several applications, where converters are operated in parallel, to achieve higher power capacity or system reliability. Sometimes the parallel operation is inevitable, like for offshore wind-power generation, where many inverters feed into a grid. When operating multiple inverters in parallel, the occurrence of stability problems is a known phenomenon. This can be observed especially in weak grids [1], [2]. Furthermore circulating currents can occur, leading to reduced power capacity of the whole inverter system.
Different approaches have already been presented to operate multiple converters in parallel. Coupled inductors are commonly used to suppress high frequency circulating currents between parallel inverters. The currents can be caused by desired or unwanted shifted switching of the parallel power semiconductors. In this case the circulating current path differs from the grid current path [3]. This can also be the case, when the parallel inverters have an additional common filter (e.g. LC) between their point of common coupling and the grid. When using standard control approaches for the individual converters, output and circulating currents can not be controlled independently. A difference of the circulating- and output-current paths then leads to reduced dynamics or even unstable behavior of the current controllers. A decoupled control of circulating- and output-currents is necessary [4].

This paper focuses on a solution that combines the inverters into pairs and triplets. It allows to describe the parallel inverter system as one virtual inverter (VI). The circulating active, reactive and residual currents can then be controlled decoupled from the output currents. Optimal controllers can then be designed for circulating- and output-currents.

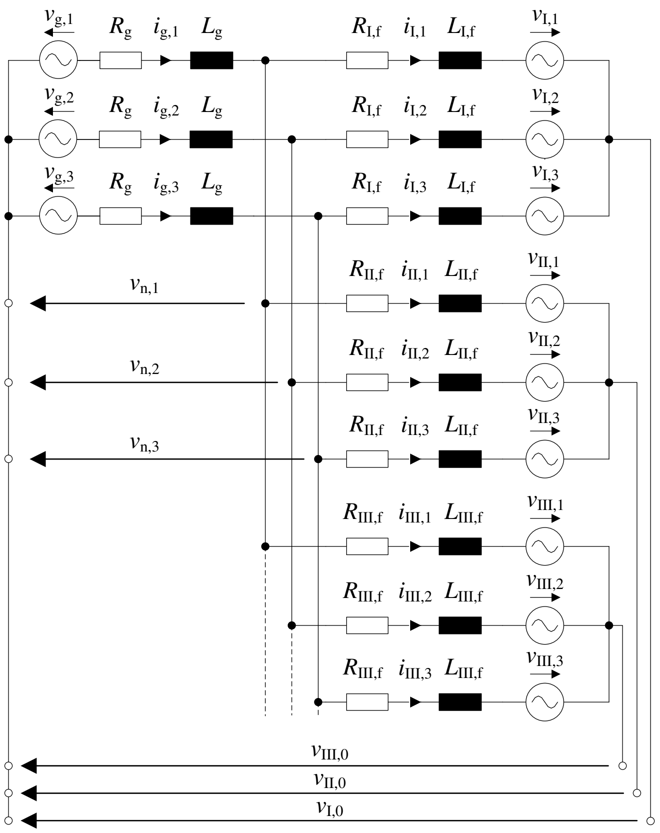


Fig. 1. Equivalent circuit of three parallel three-phase voltage-source-inverters. Each inverter is connected to the point of common coupling and has its own inductive filter. $R_g$ and $L_g$ include the grid impedance and an optional common filter between grid and point of common coupling.

In section II, the model for a grid-connected three-phase-inverter will be derived. In sections II-A and II-B, transformations will be introduced, which decouple the circulating- and output-current paths of two, respectively three parallel inverters. The resulting description of an arbitrary number of parallel inverters will be shown in section II-C. A possible application and the corresponding control scheme will be described in section III and validated in section IV. Measurement results of a system consisting of five parallel inverters will be presented in section V.

## II. System description

In this paper it will be assumed, that the used inverters are mains-connected three-phase voltage source inverters with an inductive filter (Fig. 1). The parallel inverters will be numbered by Roman numerals.

A simplified mathematical model of the inverters will be used, considering the inverter output to be a controllable voltage source, ignoring any switching behavior. The current control path of one inverter connected to the mains can then be described by the filter impedance of the inverter and the main impedance. The main impedance is any impedance between the point of common coupling of the examined inverters and the mains voltage source. This could for example be a common filter or just the grid impedance.

Equation (1) is the time domain representation of this system for one inverter depicted in Fig. 1.

$$
\begin{aligned}
\underbrace{\begin{pmatrix} v_{\mathrm{g},1} \\ v_{\mathrm{g},2} \\ v_{\mathrm{g},3} \end{pmatrix}}_{\underline{v}_{\mathrm{g}}} = {} & \underbrace{\begin{pmatrix} R_{\mathrm{g}} & 0 & 0 \\ 0 & R_{\mathrm{g}} & 0 \\ 0 & 0 & R_{\mathrm{g}} \end{pmatrix}}_{\underline{R}_{\mathrm{g}}} \cdot \underbrace{\begin{pmatrix} i_{\mathrm{g},1} \\ i_{\mathrm{g},2} \\ i_{\mathrm{g},3} \end{pmatrix}}_{\underline{i}_{\mathrm{g}}} \\
& + \underbrace{\begin{pmatrix} L_{\mathrm{g}} & 0 & 0 \\ 0 & L_{\mathrm{g}} & 0 \\ 0 & 0 & L_{\mathrm{g}} \end{pmatrix}}_{\underline{L}_{\mathrm{g}}} \cdot \frac{\mathrm{d}}{\mathrm{d}t} \begin{pmatrix} i_{\mathrm{g},1} \\ i_{\mathrm{g},2} \\ i_{\mathrm{g},3} \end{pmatrix} \\
& + \underbrace{\begin{pmatrix} R_{\mathrm{I,f}} & 0 & 0 \\ 0 & R_{\mathrm{I,f}} & 0 \\ 0 & 0 & R_{\mathrm{I,f}} \end{pmatrix}}_{\underline{R}_{\mathrm{I}}} \cdot \underbrace{\begin{pmatrix} i_{\mathrm{I},1} \\ i_{\mathrm{I},2} \\ i_{\mathrm{I},3} \end{pmatrix}}_{\underline{i}_{\mathrm{I}}} \\
& + \underbrace{\begin{pmatrix} L_{\mathrm{I,f}} & 0 & 0 \\ 0 & L_{\mathrm{I,f}} & 0 \\ 0 & 0 & L_{\mathrm{I,f}} \end{pmatrix}}_{\underline{L}_{\mathrm{I}}} \cdot \frac{\mathrm{d}}{\mathrm{d}t} \begin{pmatrix} i_{\mathrm{I},1} \\ i_{\mathrm{I},2} \\ i_{\mathrm{I}\,3} \end{pmatrix} \\
& + \underbrace{\begin{pmatrix} v_{\mathrm{I},1} \\ v_{\mathrm{I},2} \\ v_{\mathrm{I},3} \end{pmatrix}}_{\underline{v}_{\mathrm{I}}} + \underbrace{\begin{pmatrix} v_{\mathrm{I},0} \\ v_{\mathrm{I},0} \\ v_{\mathrm{I},0} \end{pmatrix}}_{\underline{v}_{\mathrm{I},0}}
\end{aligned} \tag{1}
$$

### A. Decoupling transformation for two inverters

A decoupled control of circulating- and output-currents for two inverters can be achieved by controlling sum- and difference currents, as shown in [3] and [5].

Following from the description of a single inverter, a matrix equation for the description of two parallel, mains-connected three-phase inverters can be formed, as shown in equation (2).

$$
\begin{aligned}
\begin{pmatrix} \underline{v}_{\mathrm{g}} \\ \underline{v}_{\mathrm{g}} \end{pmatrix} = {} & \begin{pmatrix} \underline{R}_{\mathrm{g}} & 0 \\ 0 & \underline{R}_{\mathrm{g}} \end{pmatrix} \begin{pmatrix} \underline{i}_{\mathrm{g}} \\ \underline{i}_{\mathrm{g}} \end{pmatrix} + \begin{pmatrix} \underline{L}_{\mathrm{g}} & 0 \\ 0 & \underline{L}_{\mathrm{g}} \end{pmatrix} \frac{\mathrm{d}}{\mathrm{d}t} \begin{pmatrix} \underline{i}_{\mathrm{g}} \\ \underline{i}_{\mathrm{g}} \end{pmatrix} \\
& + \begin{pmatrix} \underline{R}_{\mathrm{I}} & 0 \\ 0 & \underline{R}_{\mathrm{II}} \end{pmatrix} \begin{pmatrix} \underline{i}_{\mathrm{I}} \\ \underline{i}_{\mathrm{II}} \end{pmatrix} + \begin{pmatrix} \underline{L}_{\mathrm{I}} & 0 \\ 0 & \underline{L}_{\mathrm{II}} \end{pmatrix} \frac{\mathrm{d}}{\mathrm{d}t} \begin{pmatrix} \underline{i}_{\mathrm{I}} \\ \underline{i}_{\mathrm{II}} \end{pmatrix} \\
& + \begin{pmatrix} \underline{v}_{\mathrm{I}} \\ \underline{v}_{\mathrm{II}} \end{pmatrix} + \begin{pmatrix} \underline{v}_{\mathrm{I},0} \\ \underline{v}_{\mathrm{II},0} \end{pmatrix}
\end{aligned} \tag{2}
$$

The transformation matrix (3) can be applied to this equation system.

$$\underline{T}_2 = \begin{pmatrix} \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & -\frac{1}{2} \end{pmatrix} \tag{3}$$

The result can be seen in (4), which is the system description of a virtual inverter consisting of two parallel inverters.

$$
\begin{aligned}
\begin{pmatrix} \underline{v}_{\mathrm{g}} \\ 0 \end{pmatrix} = {} & \begin{pmatrix} \underline{R}_{\Sigma} & 0 \\ 0 & \underline{R}_{\Delta} \end{pmatrix} \begin{pmatrix} \underline{i}_{\Sigma} \\ \underline{i}_{\Delta} \end{pmatrix} \\
& + \begin{pmatrix} \underline{L}_{\Sigma} & 0 \\ 0 & \underline{L}_{\Delta} \end{pmatrix} \frac{\mathrm{d}}{\mathrm{d}t} \begin{pmatrix} \underline{i}_{\Sigma} \\ \underline{i}_{\Delta} \end{pmatrix} \\
& + \begin{pmatrix} \underline{v}_{\Sigma} \\ \underline{v}_{\Delta} \end{pmatrix} + \begin{pmatrix} \underline{v}_{\Sigma,0} \\ \underline{v}_{\Delta,0} \end{pmatrix}
\end{aligned} \tag{4}
$$

The first line of this equation system describes the output-current path. The output current is defined as sum-current $\underline{i}_{\Sigma}$ and can be manipulated by the average inverter output voltage $\underline{v}_{\Sigma}$. The effective resistance $\underline{R}_{\Sigma}$ and inductance $\underline{L}_{\Sigma}$ are defined in (7) and (8). Since $\underline{i}_{\Sigma}$ corresponds to the grid current $\underline{i}_{\mathrm{g}}$, the grid impedance can be considered as part of $\underline{R}_{\Sigma}$ and $\underline{L}_{\Sigma}$. If the resistors or the inductors of the individual converters differ, the effective filter parameters contain cross-coupling terms, depending on the inverter currents. This is not part of this paper, which is why the filter parameters are assumed to be equal ($\underline{R}_{\mathrm{f}} = \underline{R}_{\mathrm{I}} = \underline{R}_{\mathrm{II}}$; $\underline{L}_{\mathrm{f}} = \underline{L}_{\mathrm{I}} = \underline{L}_{\mathrm{II}}$).

$$\underline{i}_{\Sigma} = \underline{i}_{\mathrm{I}} + \underline{i}_{\mathrm{II}} \tag{5}$$

$$\underline{v}_{\Sigma} = \frac{1}{2}\left(\underline{v}_{\mathrm{I}} + \underline{v}_{\mathrm{II}}\right) \tag{6}$$

$$\underline{R}_{\Sigma} = \frac{1}{2}\underline{R}_{\mathrm{f}} + \underline{R}_{\mathrm{g}} \tag{7}$$

$$\underline{L}_{\Sigma} = \frac{1}{2}\underline{L}_{\mathrm{f}} + \underline{L}_{\mathrm{g}} \tag{8}$$

The second line of equation (4) describes the current path between the inverters, which is the circulating current path. The independent control of the circulating currents is also required for an equal load distribution between the inverters or for voltage balancing in the case of unconnected dc-links.

The circulating current $\underline{i}_{\Delta}$ as described in [6], the difference voltage $\underline{v}_{\Delta}$ and the effective resistance and inductance of the circulating current path, $\underline{R}_{\Delta}$ and $\underline{L}_{\Delta}$, are defined in (9)-(11). In this path, there is no influence of the mains voltage or impedance. Balancing can be done decoupled from the total output current by setting the difference voltage of the converters.

$$\underline{i}_{\Delta} = \frac{1}{2}\left(\underline{i}_{\mathrm{I}} - \underline{i}_{\mathrm{II}}\right) \tag{9}$$

$$\underline{v}_{\Delta} = \frac{1}{2}\left(\underline{v}_{\mathrm{I}} - \underline{v}_{\mathrm{II}}\right) \tag{10}$$

$$\underline{R}_{\Delta} = \underline{R}_{\mathrm{f}} \tag{11}$$

$$\underline{L}_{\Delta} = \underline{L}_{\mathrm{f}} \tag{12}$$

The equivalent circuit of the transformation can be seen in Fig. 2.

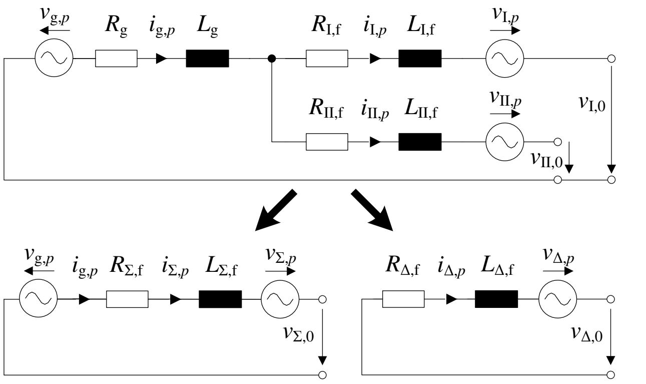


Fig. 2. Equivalent circuits of the decoupled output- and circulating-current paths of one phase $p$ of two parallel inverters. The grid impedance can be combined with the inverter filter impedance for the output-current path.

### B. Decoupling transformation for three inverters

The sum-current control can still be used for three parallel inverters. But for the description of balancing currents a linearly independent set of equations is needed. In [7] a novel control scheme for the Modular Multilevel Matrix Converter topology was presented. It allows a decoupled control of the input, output and inner system currents of the converter by applying the Clarke transformation matrix twice to the inner currents of the converter. This idea can be transferred to the situation of three parallel three-phase inverters, which also have nine arm currents in total. The Clarke transformation can be applied to the component triplets of each phase of three parallel inverters. Then the α- and β-components are a measure for the imbalances. The zero-component represents the output- or sum-values of the virtual inverter. As for two parallel inverters, the description of the three parallel inverter current control plants is written as matrix equation.

$$\begin{pmatrix}\underline{v}_g\\ \underline{v}_g\\ \underline{v}_g\end{pmatrix} = \begin{pmatrix}\underline{R}_g & 0 & 0\\ 0 & \underline{R}_g & 0\\ 0 & 0 & \underline{R}_g\end{pmatrix} \cdot \begin{pmatrix}\underline{i}_g\\ \underline{i}_g\\ \underline{i}_g\end{pmatrix} + \begin{pmatrix}\underline{L}_g & 0 & 0\\ 0 & \underline{L}_g & 0\\ 0 & 0 & \underline{L}_g\end{pmatrix} \cdot \frac{\mathrm{d}}{\mathrm{d}t} \begin{pmatrix}\underline{i}_g\\ \underline{i}_g\\ \underline{i}_g\end{pmatrix} + \begin{pmatrix}\underline{R}_I & 0 & 0\\ 0 & \underline{R}_{II} & 0\\ 0 & 0 & \underline{R}_{III}\end{pmatrix} \cdot \begin{pmatrix}\underline{i}_I\\ \underline{i}_{II}\\ \underline{i}_{III}\end{pmatrix} + \begin{pmatrix}\underline{L}_I & 0 & 0\\ 0 & \underline{L}_{II} & 0\\ 0 & 0 & \underline{L}_{III}\end{pmatrix} \cdot \frac{\mathrm{d}}{\mathrm{d}t} \begin{pmatrix}\underline{i}_I\\ \underline{i}_{II}\\ \underline{i}_{III}\end{pmatrix} + \begin{pmatrix}\underline{v}_I\\ \underline{v}_{II}\\ \underline{v}_{III}\end{pmatrix} + \begin{pmatrix}\underline{v}_{I,0}\\ \underline{v}_{II,0}\\ \underline{v}_{III,0}\end{pmatrix} \quad (13)$$

Equation (13) can then be multiplied with the Clarke transformation matrix (14).

$$\underline{T}_3 = \begin{pmatrix}\frac{2}{3} & -\frac{1}{3} & -\frac{1}{3}\\ 0 & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{3}}\\ \frac{1}{3} & \frac{1}{3} & \frac{1}{3}\end{pmatrix} \quad (14)$$

The resulting equation system (15) describes the circulating current paths between the inverters and a zero-component, which is the actual output current path.

$$\begin{pmatrix}0\\ 0\\ \underline{v}_g\end{pmatrix} = \begin{pmatrix}\underline{R}_\alpha & 0 & 0\\ 0 & \underline{R}_\beta & 0\\ 0 & 0 & \underline{R}_0\end{pmatrix} \cdot \begin{pmatrix}\underline{i}_\alpha\\ \underline{i}_\beta\\ \underline{i}_0\end{pmatrix} + \begin{pmatrix}\underline{L}_\alpha & 0 & 0\\ 0 & \underline{L}_\beta & 0\\ 0 & 0 & \underline{L}_0\end{pmatrix} \cdot \frac{\mathrm{d}}{\mathrm{d}t} \begin{pmatrix}\underline{i}_\alpha\\ \underline{i}_\beta\\ \underline{i}_0\end{pmatrix} + \begin{pmatrix}\underline{v}_\alpha\\ \underline{v}_\beta\\ \underline{v}_0\end{pmatrix} + \begin{pmatrix}\underline{v}_{\alpha,0}\\ \underline{v}_{\beta,0}\\ \underline{v}_{0,0}\end{pmatrix} \quad (15)$$

The first two lines are a linearly independent description of the current unbalance $\underline{i}_\alpha$ and $\underline{i}_\beta$, which can be used to control the circulating current of the inverter system. The third line describes the output current $\underline{i}_0$, which is equal to the grid current. The resulting filter resistances and inductances are defined in (19)-(22).

The resulting equivalent circuit of this transformation can be seen in Fig. 3.

$$\underline{i}_\alpha = \frac{2}{3}\left(\underline{i}_I - \frac{1}{2}\underline{i}_{II} - \frac{1}{2}\underline{i}_{III}\right) \quad (16)$$

$$\underline{i}_\beta = \frac{2}{3}\left(\frac{\sqrt{3}}{2}\underline{i}_{II} - \frac{\sqrt{3}}{2}\underline{i}_{III}\right) \quad (17)$$

$$\underline{i}_0 = \underline{i}_I + \underline{i}_{II} + \underline{i}_{III} \quad (18)$$

$$\underline{R}_\alpha = \underline{R}_\beta = \underline{R}_f \quad (19)$$

$$\underline{L}_\alpha = \underline{L}_\beta = \underline{L}_f \quad (20)$$

$$\underline{R}_0 = \frac{1}{3}\underline{R}_f + \underline{R}_g \quad (21)$$

$$\underline{L}_0 = \frac{1}{3}\underline{L}_f + \underline{L}_g \quad (22)$$

### C. Expansion of the description for $n$ inverters

Since any natural number greater than 3 can be calculated as $n = 2\cdot r + 3\cdot s$ for $r, s \in \mathbb{N}^+$, an arbitrary amount of parallel inverters can be grouped to $r$ pairs and $s$ triplets. This way, several VIs will result. These VIs, which on their output ports behave like autonomous inverters, can be grouped in pairs and triplets by applying the above described approach to their sum-current path models. This leads to a tree structure of inverters with one root VI that forms the interface to the mains or the connected load (Fig. 4). So in each case only one controller for the output current remains. The amount of controllers needed for the circulating currents depends on the number

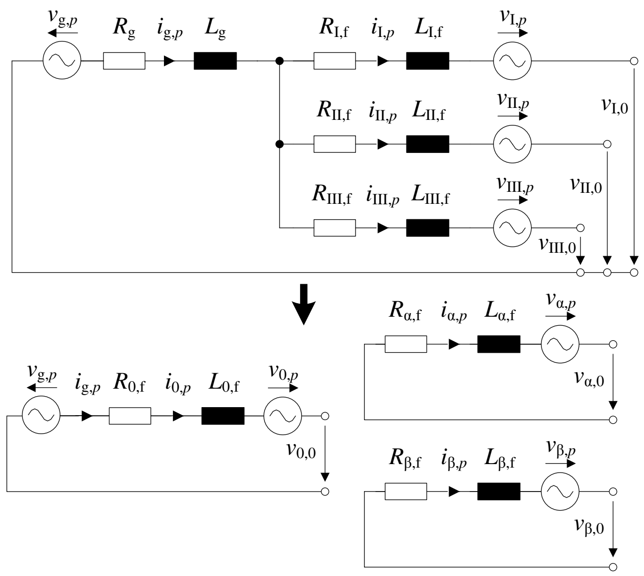


Fig. 3. Equivalent circuits of the decoupled output- and circulating-current paths of one phase $p$ of three parallel inverters. The circulating currents are described in the two-dimensional αβ-plane. The grid impedance can be combined with the inverter filter impedance for the output-current path.

of parallel inverters. When the controllers are distributed on multiple devices, the measured currents of one VI has only to be known by the overlaid controller. This is a large benefit for the communication structure, which can also be built up in a tree structure. In this way the failure of one branch does not lead to a total outage.

## III. Control scheme

### A. Current control

The current controllers of one VI can be designed independently for the output currents and the circulating currents. Each controller can be derived from the system descriptions above. Any control system can be used, e.g. PI-controllers or state-space based controllers.
For a three-phase system, it makes sense to control the αβ- respectively the dq-components of the currents. For this purpose, the Clarke transformation can be applied one more time on each component of the system and a dq-transformation allows the decoupled control of active and reactive currents.

The investigated control scheme according to this description is shown in Fig. 5.

### B. DC link voltage control

In the case of a voltage source inverter, DC-link voltages $u_{\mathrm{DC}}$ have to be controlled. The classic approach for controlling the dc-link voltage is a cascade of voltage and current control. Since in the novel approach transformed currents are controlled, the same transformation has to be applied to the dc-link voltages. For two converters, the transformation $\underline{T}_2$

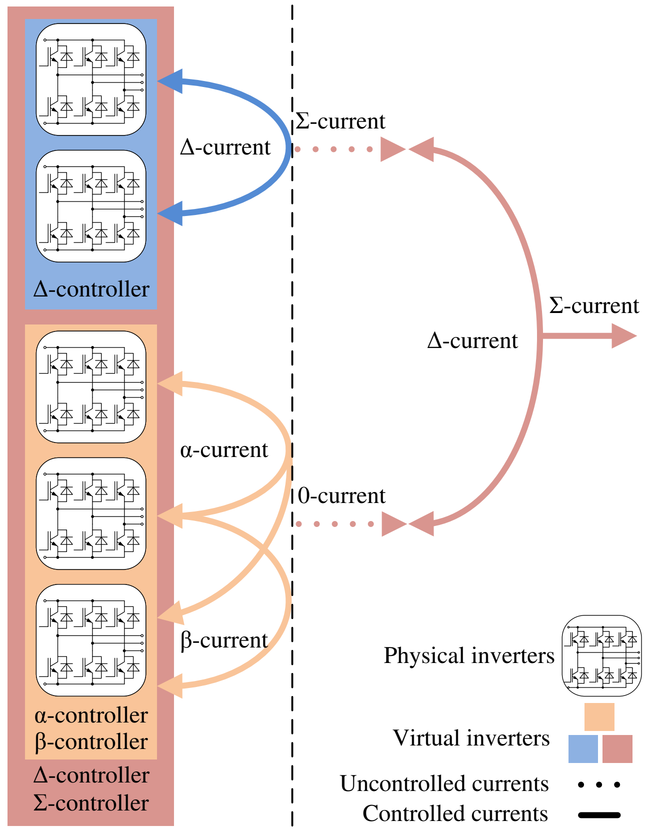


Fig. 4. Schematic example of five parallel inverters and the partitioning of the inverters into a pair and a triplet. The inverter pair and triplet are treated as virtual inverters. This virtual inverter pair can again be combined to a virtual inverter.

must be used, resulting in equations (23) and (24).

$$v_{\Sigma,\mathrm{DC}} = \frac{1}{2} \cdot (v_{\mathrm{I,DC}} + v_{\mathrm{II,DC}}) \quad (23)$$

$$v_{\Delta,\mathrm{DC}} = \frac{1}{2} \cdot (v_{\mathrm{I,DC}} - v_{\mathrm{II,DC}}) \quad (24)$$

For three inverters, the transformation $\underline{T}_3$ leads to the αβ0-components of the voltages.

$$v_{\alpha,\mathrm{DC}} = \frac{2}{3} \cdot \left( v_{\mathrm{I,DC}} - \frac{1}{2} v_{\mathrm{II,DC}} - \frac{1}{2} v_{\mathrm{III,DC}} \right) \quad (25)$$

$$v_{\beta,\mathrm{DC}} = \frac{2}{3} \cdot \left( \frac{\sqrt{3}}{2} v_{\mathrm{II,DC}} - \frac{\sqrt{3}}{2} v_{\mathrm{III,DC}} \right) \quad (26)$$

$$v_{0,\mathrm{DC}} = \frac{1}{3} \cdot (v_{\mathrm{I,DC}} + v_{\mathrm{II,DC}} + v_{\mathrm{III,DC}}) \quad (27)$$

If the DC-link capacitors of the parallel inverters are interconnected, the Δ- respectively αβ-components of the voltages can not occur. Then only the Σ- or 0-component of the dc-link voltage has to be controlled.

The outputs of the voltage controllers can directly be fed as references to the particular current controllers, as depicted in Fig. 5.

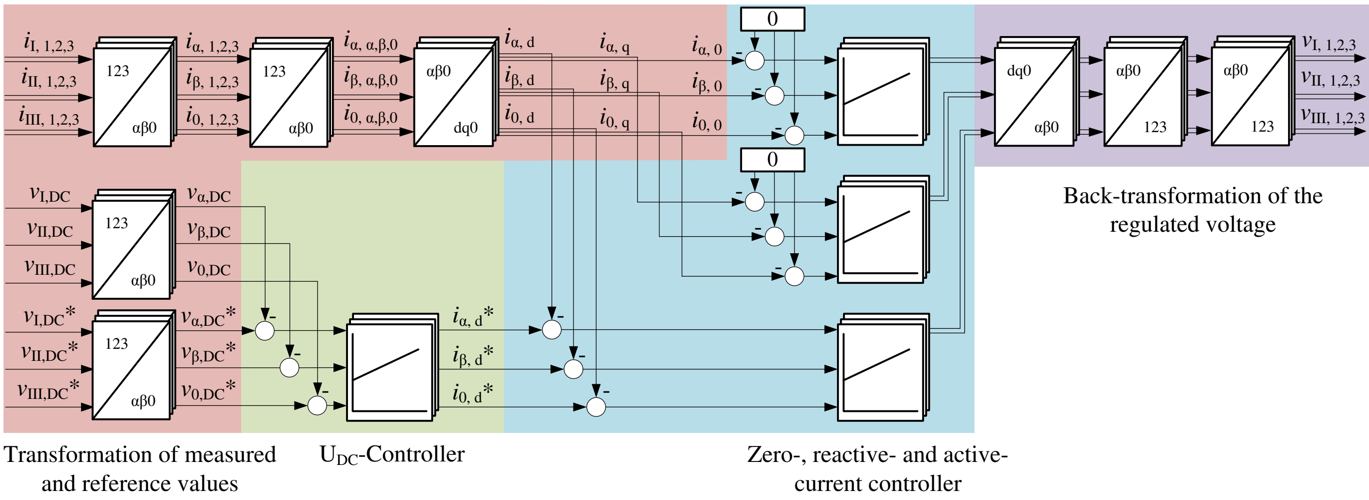


Fig. 5. Current control scheme with superimposed dc-link voltage control of three parallel operated three-phase voltage source inverters. The used dq-transformations are fed with the momentary node voltage angle, which is not depicted. They are used to decouple active and reactive currents. The reference values for zero- and reactive-currents are set to zero. The regulated voltages can be directly applied to a modulator.

## IV. Simulation

Three parallel dc-link voltage-source-inverters have been modeled in Simulink, according to Fig. 1. The main benefit of the presented description is the ability to use different control parameters for the circulating current control and the output current control. Different parameters are imaginable for example when using individual L-filters for the single inverters and a common LC-filter for node voltage quality means. To keep the simulation clear, only L-filters are being used. Every converter has a filter with the parameters $L_{\mathrm{I/II/III,f}} = 612\,\mu\mathrm{H}$ and $R_{\mathrm{I/II/III,f}} = 4\,\mathrm{m}\Omega$ connected to its output. At the point of common coupling, the main filter inductance and the grid inductance are combined to $L_{\mathrm{g}} = 1.1\,\mathrm{mH}$ and $R_{\mathrm{g}} = 7.1\,\mathrm{m}\Omega$.

A simulation is carried out to compare the presented control strategy to a standard approach. The novel control scheme is depicted in Fig. 5. For the classic approach, each inverter is controlled separately with a superposed dc-link voltage controller. The parameters of the current controllers are in both cases selected according to the absolute optimum of a cancellation controller. For the classic approach, the series connection of the small filter and the main filter is considered as current control path. In the simulation, two things shall be demonstrated. First, the assumption that an evenly distributed output current can be controlled by both, the classic and the novel approach with the same quality. Second, a circulating current between inverter II and III will be set, to demonstrate the benefit of the presented control method.

The simulation results can be seen in Fig. 6. The DC-link voltage reference is $v_{\mathrm{DC,I/II/III}}* = 700\,\mathrm{V}$. At $t = 20\,\mathrm{ms}$ the reference of the reactive current of each inverter is set to $i_{\mathrm{I/II/III,q}}* = 10\,\mathrm{A}$. In both cases, the current is adjusted correctly. The single current controllers of the standard approach are rated for the grid current path and thus behave exactly like the sum-current controller in the presented approach. At $t = 50\,\mathrm{ms}$ the reference for a circulating reactive current between inverter II and inverter III is set ($i_{\mathrm{II,q}}* = 20\,\mathrm{A}$, $i_{\mathrm{III,q}}* = -20\,\mathrm{A}$). On the right side of Fig. 6 stability problems can be seen with the classic control method, while the presented controller shows a robust behavior (left side).

Finally, at $t = 100\,\mathrm{ms}$, the reference values of the dc-link voltages are changed to generate a circulating active-current ($v_{\mathrm{DC,II}}* = 750\,\mathrm{V}$, $v_{\mathrm{DC,III}}* = 650\,\mathrm{V}$). Again the presented controller shows a stable reaction.

## V. Measurements

Measurements were taken on a system consisting of five parallel grid-connected three-phase voltage source inverters with coupled dc-links. The controller is set up in a tree-structure, as described in section II-C and depicted in Fig. 4. Two VIs result from this description (I and II as pair, III, IV and V as triplet). The VIs are again controlled as pair, resulting in one root VI.

For the inverters, only inductive filters are used. Between the point of common coupling and the grid, another inductive filter is used to provide different paths for circulating- and output-currents.

Measurement results can be seen in Fig. 7. For clarity reasons, the figure shows only the active current component of each inverter. Two dynamic situations are examined. In the first situation, a dc-link voltage controller reference step is applied, resulting in an active grid current. It can be seen, that the currents are evenly distributed between all five inverters.

In the second situation, a reference step is applied to the controller of the active circulating current between the inverter pair and the inverter triplet. The result is an active current between both virtual inverters. Again the single inverter currents of both VIs are equally distributed.

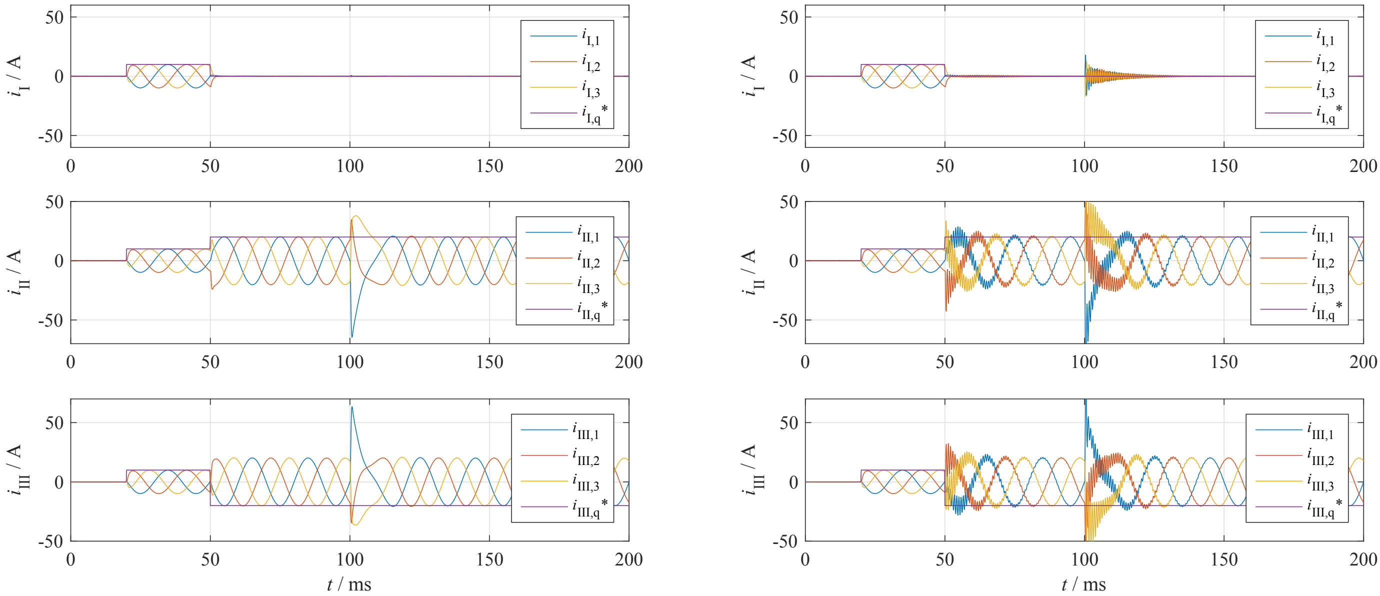


Fig. 6. Comparison of the grid-current and circulating-current control of three parallel inverters. The currents on the left side are controlled with the presented method. On the right side, the currents are controlled independently for each converter, with control parameters optimized for the output-current path.

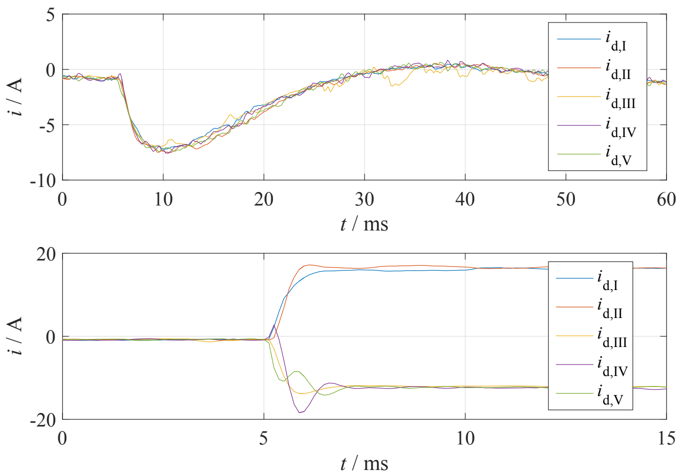


Fig. 7. The figures show the active current components of five parallel, grid-connected inverters with coupled dc-links. On the top image, a reference step is applied to the the dc-link voltage controller. On the bottom image a reference step is applied to the controller of the circulating active current between the inverter pair (I and II) and the inverter triplet (III, IV and V).

## VI. Conclusion

A solution for stability problems, when operating inverters in parallel on a weak grid or with a common filter, has been presented. The performance of the decoupled control for output- and circulating-currents has been shown in a simulation. An implementation with five parallel inverters has been examined and verified. The control parameters of the decoupled current paths can be adjusted independently, which allows an optimal controller design for any filter combination. This is a major advantage over the individual control of every inverter.

This method is presented for three-phase mains-connected voltage-source inverters with inductive filters. It can as well be adapted to different converter topologies and filter setups, load connected inverters or single-phase inverters.

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