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Reconfiguring Grid-interfacing Converters for Power Quality Improvement

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***Abstract*—In this paper reconfiguration of grid-interfacing converters is proposed for power quality improvement. In addition to the traditional function of delivering energy between distributed sources and the utility grid, more flexible ancillary functions can be integrated into the control of grid-interfacing converters to both improve the power quality at the user side and the utility side. The potential for solving or improving various problems on different system levels is described in detail. Two three-phase four-leg inverters, together with DC micro-sources and loads, are employed to construct a general grid-interfacing system module. Through the redefinition of system functions, it is possible to achieve voltage unbalance correction, harmonic current compensation at the point of connection with the utility grid, protection of distributed generation systems from grid disturbances, and high quality voltage for sensitive loads under various utility grid situations. While the effect on helping the utility grid is small for a single module, a number of the modules put together could be pronounced. The Control scheme and validation results are presented in the paper.**

I. INTRODUCTION

Concern for power quality problems is growing at the moment. High power quality service from the utility grid is demanded by sensitive loads. More strict standards are required for end-user equipment, especially the booming power electronic devices. Many solutions have been proposed for power quality improvement either from the utility side or the customer side [1][2].

Facing the emerging application of distributed generation (DG), that is the generation of power dispersed throughout the power system, power electronic-based grid-interfacing converters are playing an important role between the DG and the utility grid. As a consequence, a number of important power quality issues are induced. Usually a grid-interfacing converter manages to deliver electrical energy to the utility grid and controls the power flow. Furthermore, techniques are integrated into the DG system to serve some ancillary functions such as active filtering [3]. It has been implicated that power electronics-based converters for DGs not only can service as interfaces with the utility grid, but also have the potential for handling power quality problems [4].

This paper is intended to facilitate alternative energy application and extend it for power quality improvement, from a future application point of view. The possibilities of a proposed grid-interfacing system are investigated. By using the general series-parallel structure to construct grid-interfacing converters for the DG, and reconfiguring the control functions, a versatile power electronics-based interface can be derived. In addition to the function of delivering energy between DGs and the utility grid, more flexible ancillary functions can be integrated into the proposed distributed grid-interfacing system modules in order to both improve the power quality at the user side and the utility side. These functions could be voltage unbalance correction, harmonic current compensation at the point of connection with the utility grid, protection of DG systems from grid disturbances, and high quality voltage for sensitive loads.

This paper is organized as follows. First, a general series-parallel structure is presented. Secondly, the proposed grid-interfacing system module and the functionalities of the module are described. Thirdly, a overall control scheme and related simulation results are presented. Finally, a conclusion and some research possibilities are given.

II. SERIES-PARALLEL STRUCTURE

A general structure consisting of two converters, one in series and the other in parallel with the grid, is considered here for different application situations. Fig. 1 shows the single line diagram of the basic series-parallel structure. The capacitor between the series and parallel converters serves as a common DC-link. The internal components of the two PWM converters can be optimized based on the practical conditions. Three-phase three-wire or four-wire inverters with output filters and isolating transformers are usually applied for the basic converters, but the series-parallel construction also has been used in single-phase systems. This paper will focus on three-phase systems.

Based on the controller design, the system in Fig. 1 offers different functions. One example is the well-known unified power quality conditioner (UPQC) that regulates the bus

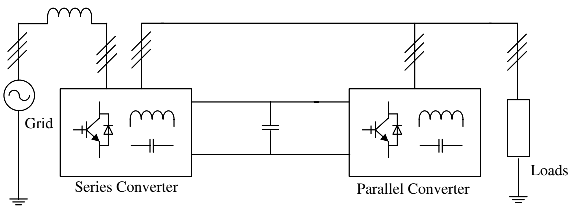

Fig. 1. Single line diagram of a conventional series-parallel structure.

voltage of critical loads against unbalance, harmonics, voltage sag/swell and other disturbances occurring in a distribution network [5][6]. It is still being developed for better performance, such as an universal power quality conditioning system in [7], which is extended by adding a shunt active filter at the load side. As an online conditioner, the UPQC offers comprehensive methods to improve power quality problems. However, when the voltage of the utility grid collapses to a low value, it fails to draw the required amount of power to maintain the DC-link. To deal with larger sags or even interruptions, the dc capacitor can be replaced by a larger energy storage device or a distributed source. A functionally similar line-interactive UPS system [8], or a combined operation of UPQC with rectified dc link [9] were studied. It seems that the general concept of an UPQC plus the uninterruptable service could be achieved if there is a primary energy source in the DC-link.

Thanks to the increasing interest in sustainable energy applications, many techniques to convert alternative energy sources to electrical energy are studied nowadays [10]. Furthermore, these may try to maintain a stable DC-link with a regulated DC bus and a good dynamic performance for load variation. Therefore, by connecting pre-regulated DC distributed sources to the DC-link, the general structure in Fig. 1 can be employed to construct a grid-interfacing system module, as presented in the next section.

III. PROPOSED SYSTEM MODULE

In this paper, the proposal of combining the distributed grid-interfacing converter with a power quality compensator is associated with the series-parallel structure. However, this is quite different in functionality and control strategy from the conventional UPQC etc. By configuring the grid-interfacing part, a modular system is presented in this section.

A. Modular System

Fig. 2 shows the proposed modular system structure. The modules are divided into two levels. The fundamental unit of the first level, consisting of series-parallel grid-interfacing converters, distributed sources, and so-called sensitive loads, is connected to the utility grid at the POC. The reason to point out sensitive loads within the unit is to emphasize the demand for a continuous and balanced sinusoidal voltage. Above this first level, other loads are present at the same POC. These are not sensitive to power quality problems but possibly induce current harmonics. To help understanding, the configuration of the system module 1 could for example be a DG-backed office building, where computers are regarded as the sensitive loads. Other regular loads, possibly nonlinear, are put on the second level.

B. PWM Converter

To configure the system module, a four-legged power converter is selected as the basic PWM converter unit for three-phase four-wire systems. Because of the extra degree of freedom brought by the fourth leg of the structure, the outputs of the three phases become independent. As a result, a balanced output voltage can be achieved for unbalanced loads, and the neutral current in an unbalanced or distorted utility situation can be handled.

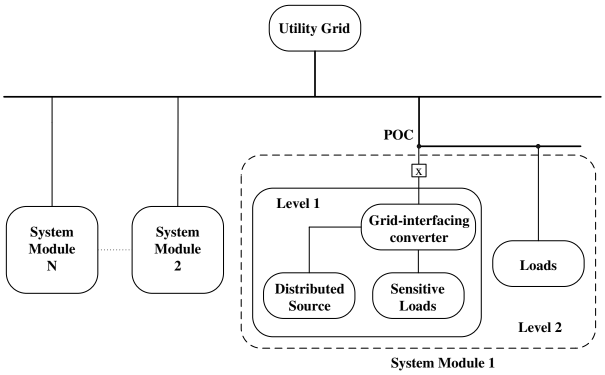

Fig. 2. Proposed modular system structure.

C. Module Configuration

Taking the four-legged converter as the basic unit, the whole module circuit is constructed as shown in Fig. 3. Two levels of the system module are correspondingly identified according to Fig. 2.

IV. FUNCTION RECONFIGURATION

It was suggested that the future direction of power quality performance standards should include at least [2]:

1) interruptions (including momentary);
2) voltage sags;
3) steady-state voltage regulation;
4) voltage unbalance (negative sequence);
5) harmonic distortion in the voltage;
6) transient voltages.

Taking these problems into account, we want to find an optimum approach maintaining good power quality for the sensitive loads, and improving the power quality for the utility grid, based on the above system structure. Starting from the bottom level, through the second level, and then the modular system level, different control objectives are necessary.

A. Level 1

The aim of the first level in Fig. 3 mainly deal with maintaining good power quality for the sensitive loads within the system module, and delivering energy. A parallel converter working as a voltage source is used to enhance the voltage quality for the sensitive loads. It maintains a balanced sinusoidal voltage when the grid voltage varies and supplies the uninterruptable service when the grid voltage drops away. Besides, it tracks the phase of the fundamental positive sequence component of the grid voltage in order to decrease the reactive power flow when the grid voltage is not balanced or sinusoidal.

Power flow control is achieved by the series converter. When the grid voltage distorts or varies within a certain range, the module delivers energy to the grid or absorbs energy from the grid by controlling the current flow. Note that the

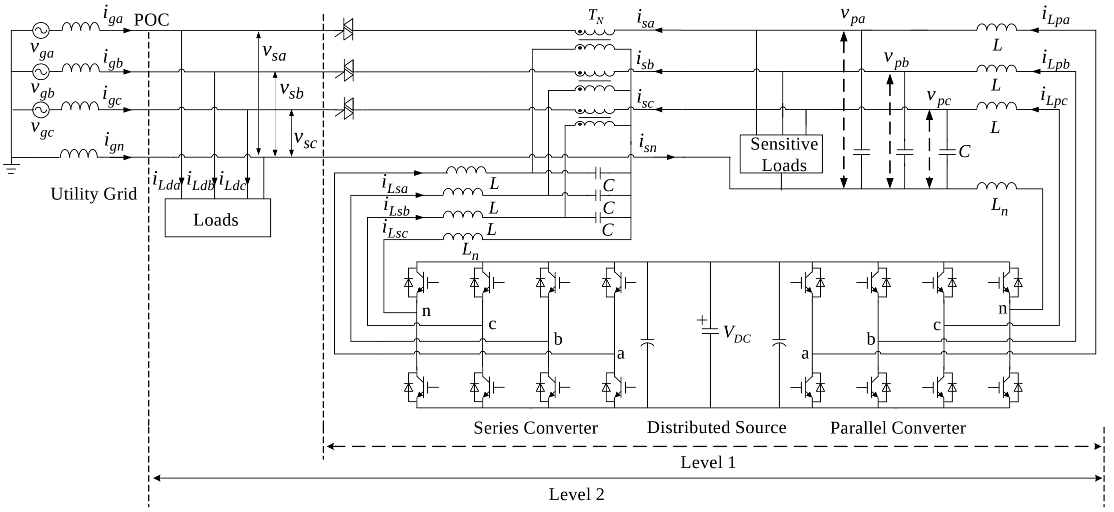

Fig. 3. Employed configuration of the system module.

so-called "certain" range of the voltage variation should be constrained by the system capacity. It can achieve balanced sinusoidal currents when the grid voltage becomes unbalanced or distorted and protect the system from over-current when the grid voltage sags.

B. Level 2

On the second level, loads that produce current harmonics but are not sensitive or critical are connected to the feeder behind the POC, as shown in Fig. 3. The grid-interfacing converter resembles a current source connected in parallel with the loads. The symbol v_{par} denotes the output voltage of the parallel converter. The series converter controls the current flow i_s through the series injected voltage v_{ser}. By detecting the harmonic components of the load current i_{Ld}, it can act as an active filter to compensate the harmonics within the system module. This extra active filter function requires a higher rating for the converters since the harmonic currents increase the rms value of the total current.

C. System Level

Furthermore, it is proposed to integrate voltage unbalance correction on the system level. Each of the system modules in Fig. 2 can help decrease the negative-sequence voltage at the POC by injecting a small amount of negative-sequence current into the grid, based on the voltage unbalance factor (the ratio determined by the magnitudes of the negative-sequence to the positive-sequence voltage). It introduces the idea to correct voltage unbalance by using multiple modules working together in a coordinated manner.

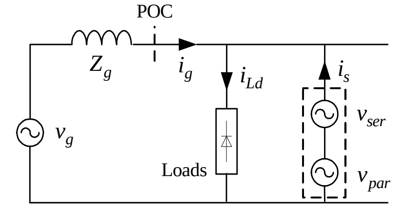

Fig. 4. Per-phase diagram of active filter function.

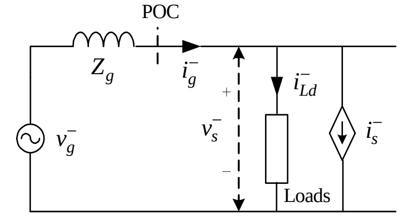

Fig. 5. Equivalent model for the negative-sequence component.

With the theory of symmetric decomposition for three phase systems, unbalanced grid voltages can be divided into three groups of balanced voltages, namely positive-sequence, negative-sequence and zero-sequence. Currents can be separated similarly. Correspondingly, an equivalent circuit model for sequence voltages can be derived. The diagram for negative-sequence components is shown in Fig. 5. Voltage v_g^- and v_s^- are the negative-sequence voltages of the utility grid and POC, respectively. Current i_s^- is the negative-sequence current from the grid-interfacing system. The line impedance is still Z_g, where the line impedance of the three phases is regarded symmetrical.

Fig. 7 shows a phasor diagram where the negative-sequence current is controlled. By changing the amplitude and phase of the negative-sequence current i_s^-, the negative-sequence voltage v_s^- can be regulated through the voltage drop on the line impedance. For a given amplitude I_s^-, the voltage changes along the dashed circle and reaches a minimum value at the point M when θ^-, that is the phase angle between negative-sequence voltage and current, equals the angle of the line impedance Z_g. Because the negative-sequence current is limited, the reduction contributed by each individual module is very small compared with the total negative-sequence component. Therefore, when there are many system modules, they

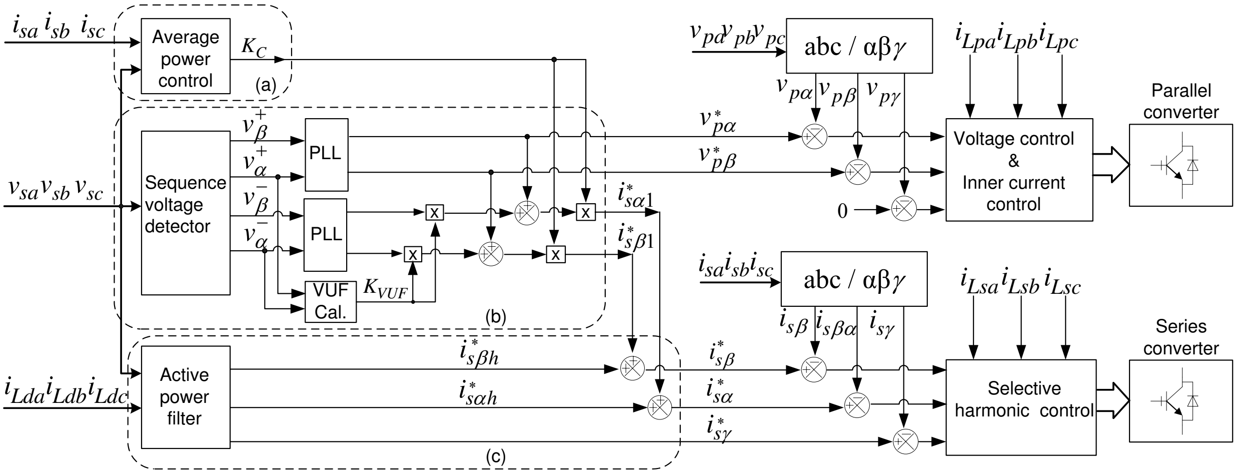

Fig. 6. Overall control structure for both converters, and the generation of reference signals by (a) power control, (b) unbalance calculation, and (c) active power filter.

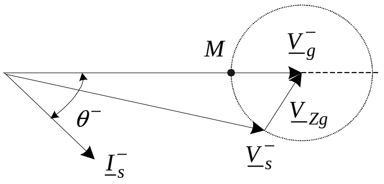

Fig. 7. Phasor diagram of the negative-sequence voltage.

can collectively achieve substantial results in the grid.

V. CONTROLLER DESIGN

To investigate the possibilities of the reconfigured converter module, an overall control scheme for both converters is presented. As shown in Fig. 6, it consists of reference signals generation, i.e. the three parts in the dashed frames, and two individual controllers on right-hand side which are responsible for the voltage and current control. Because this paper mainly intends to introduce the concept of the reconfigured modular system, the controller design will be functionally presented instead of by detailed analysis.

A. Generation of Reference Signals

In the average power control loop of Fig. 6 (a), a combined proportional and integral compensator produces the current coefficient K_C to regulate the amplitudes of the fundamental currents denoted by $i^*_{s\alpha 1}$ and $i^*_{s\beta 1}$. In addition, the amplitudes of the desired currents are constrained by the system capacity.

Fig. 6 (b) shows the generation of the fundamental reference signals for the unbalance voltage correction. This control block incorporates the sequence voltage detector, phase-locked loop (PLL), and voltage unbalance factor calculation (the part named VUF Cal). To detect the fundamental sequence voltages, a multi-variable filter working in the stationary frame, that is the conventional α–β–γ coordinates, is employed [11]. After modification, it is able to directly filter out the fundamental positive and negative-sequence vectors, which are represented as $v_\alpha^+ + jv_\beta^+$ and $v_\alpha^- - jv_\beta^-$.

The voltage unbalance factor, denoted by K_{VUF}, is used to determine the weights between the positive and negative-sequence currents. In this case, the amplitude of the desired negative-sequence current I_s^- is proposed to be designed according to the following constraint equation,

$$I_s^- / I_s^+ = K_{VUF}, \tag{1}$$

where I_s^+ is the amplitude of the positive-sequence current regulated by the average power control loop.

The PLL employs a conventional control method with PI controllers for three-phase systems. Since the input α, β signals for the PLL, output by the filters, are always clean and orthogonal sinusoidal waveforms, the PLLs can have good phase locking even under unbalanced or distorted grid voltages. For the parallel converter, the reference signals $v^*_{p\alpha}$ and $v^*_{p\beta}$ are in phase with the positive-sequence voltage of the grid. For the series converter, a locked phase-shift of the negative-sequence component is set to equal the angle of the line impedance for a maximum correction effect, as described in Section IV.

In Fig. 6 (c), an active power filter can be designed to generate the harmonic components of the current reference signals for the series converter with the instantaneous power theory, and can also be optimized to improve the dynamics for the whole system control.

B. Voltage / Current Control

With the derived reference signals $v^*_{p\alpha}$ and $v^*_{p\beta}$, the parallel converter is designed with a double-loop controller, the outer voltage control loop for zero steady-state error and the inner current control loop for dynamic improvement. Note that the reference for the γ channel is zero in order to keep balanced sinusoidal voltages. For the series converter, a fundamental current controller and a selective harmonic controller are combined. Considering the complicated control for both positive- and negative-sequence components, it is preferred to choose the proportional-resonant (PR) controller for the control design [12]. Furthermore, the selective harmonic compensator can also be integrated into the voltage control of the parallel converter to eliminate some harmonic components in the output voltages when there are low-order harmonic currents flowing through the filter inductors, for instance, harmonic currents induced by nonlinear loads or harmonics compensation.

VI. SIMULATION RESULTS

To confirm the feasibility of aforementioned system module, it is simulated with the simulation tool PSIM7.0. The main simulation parameters are shown in TABLE I. The system reaction to several power quality problems is simulated and illustrated in the following simulation waveforms.

TABLE I
SIMULATION PARAMETERS

Description	Symbol	Value
Grid voltage	$v_{ga,b,c}$	230V/50Hz
Line impedance	Z_g	0.003Ω, 100μH
Output filter	L, L_n, C	2mH, 0.67mH, 5μF
DC-Link	V_{DC}	$750V$
Series trans.	T_N	$1:1$
Switching freq.	f_{sw}	16kHz

Fig. 8 shows the simulation results when the grid voltages are unbalanced and distorted. Three-phase grid voltages $V_{ga,b,c}$ are given 350V, 330V, and 330V fundamental amplitudes, respectively, and 10% of 7^{th} harmonic voltage. In this situation, the system can keep delivering balanced sinusoidal currents $I_{sa,b,c}$ to the grid and supplying balanced sinusoidal voltages $V_{pa,b,c}$ for the sensitive loads.

Fig. 9 shows the voltage sag protection within the converter module. With a 10% voltage sag on phase A, and 20% of voltage sag on phase B and C at the time of $0.08s$, the parallel converter maintains stable output voltages. While there are some transient oscillations on the current waveforms at that moment, large current variations are mitigated by the series converter.

Fig. 10 shows the current harmonic compensation. For simplification, current sources with 20A of fundamental current and 6A of 3^{rd} and 7^{th} harmonics are connected to the POC instead of actual loads. As shown in the third group of waveforms, by delivering both fundamental currents and harmonics, the series inverter achieves harmonic compensation and leaves only sinusoidal components in the grid currents $I_{ga,b,c}$. Besides, the output voltages of the parallel inverter are still sinusoidal, although there is slight ripple on the voltage waveforms.

Next, the negative-sequence correction is considered. As already discussed, the compensating amplitude of each individual module is very small. Therefore, for easier observation in this simulation, the line impedance parameters are exaggerated as a $2mH$ inductor combined with an 0.6Ω resistor. Assume

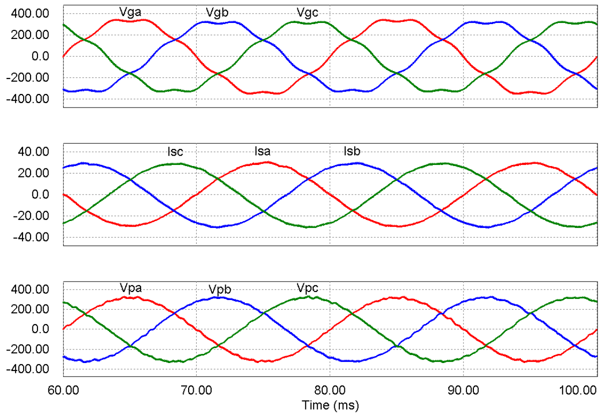

Fig. 8. Unbalanced and distorted grid voltage compensation, showing the balancing of output currents and voltages.

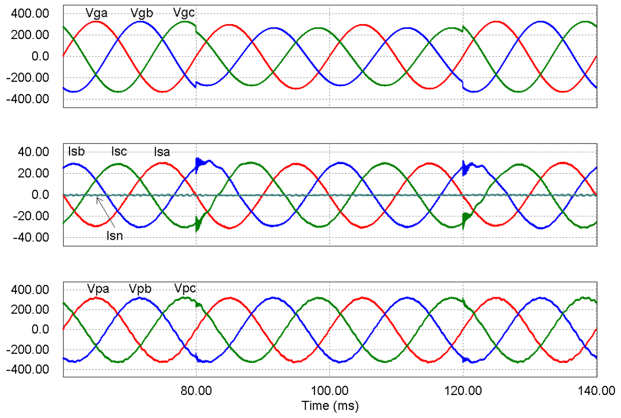

Fig. 9. Voltage sag protection, showing the large current limitation and stabilized output voltage features.

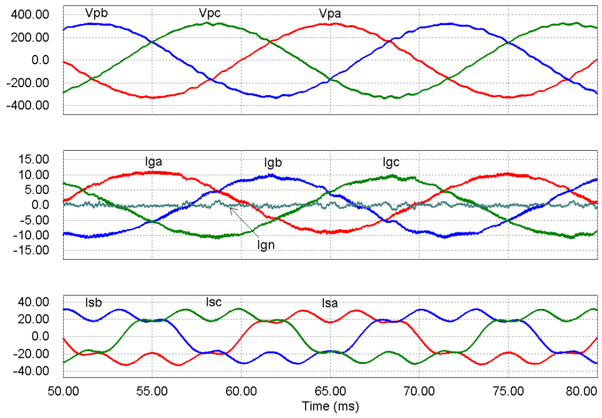

Fig. 10. Current harmonic compensation, showing parallel active filter functionality.

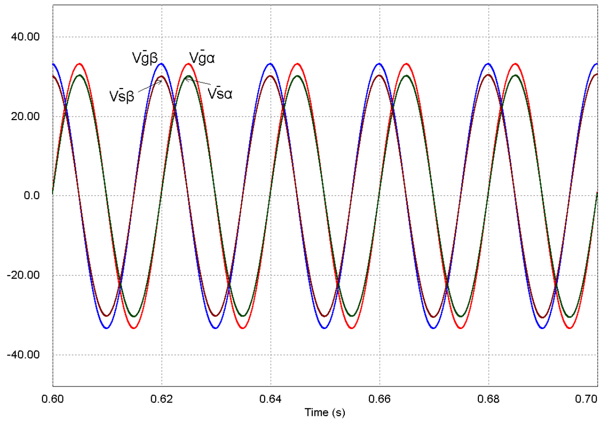

Fig. 11. Negative-sequence voltage correction. The α, β components of the negative-sequence voltage of the POC $V^{-}_{s\alpha,\beta}$ show 9% of amplitude reduction compared to the negative-sequence voltage of the grid $V^{-}_{g\alpha,\beta}$.

that phase B and C have 30% of amplitude reduction, and phase A has a normal amplitude. With the proposed negative-sequence voltage correction, Fig. 11 shows the effect at the POC with a single system module. The effect is illustrated in the $\alpha - \beta$ frame by decomposing from the $a - b - c$ frame. As seen, the amplitude of the negative-sequence voltage is reduced, although the decrease is limited to 9%. Again note that the line impedance parameters have been exaggerated. In a practical utility grid, $200\mu H$ is more realistic, then the decrease is around 1% under the same conditions. However, based on a modular system, the effect of the negative-sequence voltage correction will be more pronounced.

VII. CONCLUSION

Through reconfiguring DG employed grid-interfacing systems, power quality can be improved at the utility side and the user side. The proposed implementation is divided into three parts based on a module structure. A concrete example consisting of two four-leg inverter units is analyzed. The general control scheme was functionally validated by simulation for specific power quality problems.

This paper introduces the feasibility of combining conventional grid-connected inverters and power quality conditioners in a distribution network. However, there are still many topics open for further study. For these extensions, the dynamic features and stability analysis become more complicated. The coordinated operation of multiple modules integrated with the negative-sequence correction has to be considered for more units. With additional reactive power compensation or voltage sag protection, for high quality voltage outputs, the DC-link regulation becomes more important .

From a cost point of view, the presented system module is expensive compared with a conventional single converter system. However, a redesign is possible to choose other types of topologies as the basic converter units. Furthermore, it is possible to reduce cost by optimizing the system modules and increase the utilization of system capacity, since conventional converters used only for the DG interface or active filtering are not always fully loaded.

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