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High quality repetitive control system for a grid-tied converter under distorted grid voltage conditions – design and implementation

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Abstract. The paper features a grid-tied converter with a repetitive current controller. Our goal here is to demonstrate the complete design workflow for a repetitive controller, including phase lead, filtering and conditional learning. All key parameters, i.e., controller gain, filter and fractional phase lead, are designed in a single optimization procedure, which is a novel approach. The description of the design and optimization process, as well as experimental verification of the entire control system, are the most important contributions of the paper. Additionally, one more novelty in the context of power converters is verified in the physical system – a conditional learning algorithm to improve transient states to abrupt reference and disturbance changes. The resulting control system is tested experimentally in a 10 kW converter.

Key words: AC/DC power converters; current control; particle swarm optimization; power quality; repetitive control (RC).

1. Introduction

One of the challenges of the control system for grid-tied converters is to provide symmetrical sinusoidal phase currents under distorted and asymmetrical grid voltage conditions. The growing number of electric loads with passive front-end converters within the power system worsens the quality of grid voltage, which in turn affects phase currents of other connected converters. Therefore, methods aimed at reducing harmonic content of current drawn by the devices from the power system are currently gaining importance as a research subject. This is important from two perspectives: newly installed devices should draw sinusoidal currents from the non-distorted grid to keep it this way and at the same time they should be able to draw sinusoidal currents from grids already distorted by other devices. The latter is needed to prevent the compounding effect.

Operation of grid-tied converters in today's power systems with often distorted grid voltages requires implementation of repetitive schemes for effective grid current control. Model predictive control techniques offer here excellent performance under no or moderate parameter identification errors [1, 2]. Another set of techniques exploit the repetitiveness of the process at hand to improve tracking and disturbance rejection abilities of a control system. There are two main approaches to such systems: multiresonant (also known as multioscillatory) controllers and repetitive controllers. The two most common techniques draw upon the internal model principle, which is discussed in detail in [3]. Lack of consistency in naming for these methods may lead to some confusion. Our take on this is presented in [3], where we propose a more distinct categorization. In our opinion, the term repetitive controller should refer to any controller that takes into account the repetitiveness of the process at hand. And the two distinct subcategories should be multiresonant (AKA multioscillatory) controllers and iterative learning controllers. However, this is not the case historically [4] and the naming problem prevails. Most authors, especially those active in the field of power electronics, prefer labelling the two distinct techniques multiresonant controllers and repetitive controllers. Historically, repetitive controllers were meant for continuous repetitive processes and iterative learning controllers – for batch repetitive controllers. Both of them have exactly the same control law and the only difference lies in the fact that for the batch process initial conditions are reset every pass, whereas for the continuous one, initial conditions come from the final state of the previous pass and are not resettable. To avoid any further confusion, this paper deals with the repetitive control law based on the universal periodic signal generator

$$G(s) = \frac{1}{e^{sT} - 1}\,, \tag{1}$$

where T is the period of the process. Its discretized form under the assumption that the pass is spanned over an integer number of samples is as follows

$$G(z) = \frac{z^{-n_s}}{1 - z^{-n_s}}\,, \tag{2}$$

where n_s represents the number of samples per period.

There is a vast body of papers describing the practicalities regarding multiresonant controllers, including adaptive damping, and other anti-windup algorithms such as e.g., in [5], as well as tuning procedures. The reported solutions provide a potential designer with a set of comprehensive procedures with almost no parameters to be guessed, except for, e.g., one penalty fac-

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tor in a cost functional [6]. As a result, those controllers are usually first hand choices for practitioners. On the other hand, the repetitive control (RC) technique, which could also be employed to draw sinusoidal currents under distorted grid voltage conditions, is less explored and then less often successfully exploited. The reported solutions with these controllers for three-phase grid-tied converters are quite incomplete – they often focus on one aspect of the synthesis, whereas other parameters are not discussed or are tuned using the trial and error method. In recent years, the RC technique has gained noticeable traction in the field of power electronics. Several variants of this approach are applied to enhance performance of grid-tied converters. The most relevant ones include adaptation to variable frequency conditions [7, 8], RC for particular harmonics [9] and Discrete Fourier Transform (DFT)-based RC, which allows to enhance dynamic response of the system [10]. Nevertheless, in the authors' opinion, the aforementioned publications do not fully cover the issues related to this kind of a control system. For example, publications about repetitive control often analyse stability, but no information is provided how to clearly choose, for example, controller gain. Moreover, RC systems suffer in the presence of sharp changes of the reference signal. This problem is gaining importance for the system with relatively high gain of the RC part. Herein, the solution is provided by introducing a concept of conditional learning of the RC part.

The next section discusses a set of modifications to the signal generator (2) in order to make it practical. All the modifications are inspired by the ones already proposed in the topical literature for multioscillatory controllers, although these two techniques are unrightfully treated by some practitioners as totally unrelated. Conditional learning is incorporated to complete the picture of all similarities – to mimic the concept of variable damping coefficients in multiresonant controllers [3]. Different concepts of conditional learning were proposed previously [11] but to the best of the authors' knowledge they have never been adopted and reported for power electronic converters. However, the most significant contribution in this paper is experimental verification of the particle swarm optimized (PSO) repetitive controller. The PSO-based tuning has already been verified experimentally and reported for multioscillatory controllers [12]. In [13], RC designed according to PSO which cooperates with a dead-beat controller is shown. Dead-beat provides a very high dynamic response of the system, nonetheless in several applications it does not provide satisfactory robustness of the system. Therefore, this kind of design for RC which cooperates with the PI controller is shown. The paper demonstrates that such tuning is also effective for the repetitive controller in grid-tied converters such as the one shown in Fig. 1 as a viable approach to simultaneous tuning of three parameters of the repetitive controller. For experimental validation a 3-level neutral point clamped converter is used. Additionally, a DC/DC converter is employed to control DC-link load current. The detailed topology of the power converter used in this study is shown in Fig. 2.

In recent years, there has been a trend towards a shift to renewable energy sources inter alia, to reduce the consumption of

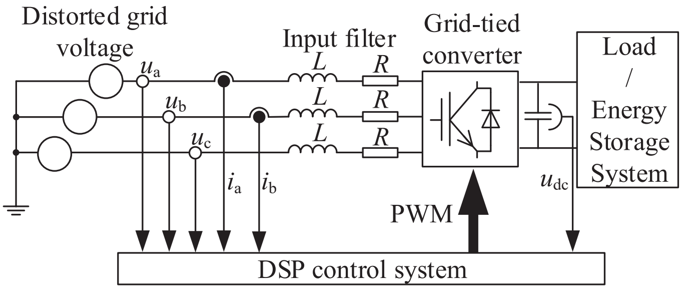

Fig. 1. Scheme of the analyzed three-phase three-wire grid-tied converter

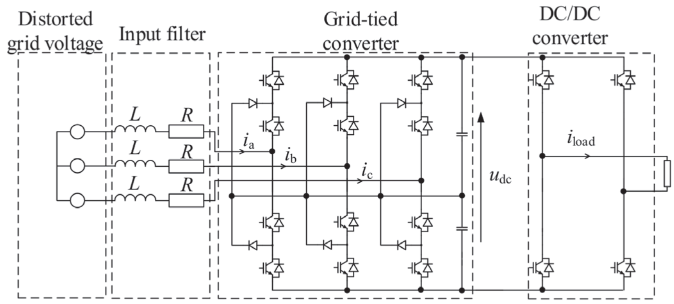

Fig. 2. Topology of the converter used for experimental validation – a three-phase three-level NPC converter on the grid side plus a two level H-bridge converter on the load or energy storage side

fossil fuels [14]. In this field, the grid-tied converter is one of the main parts of the system. The presented control system can be utilised in the grid-tied converter in the areas of wind turbine generating systems, photovoltaics or with superconducting magnetic energy storage (SMES) [15]. Moreover, RC is used in such applications as Permanent Magnet Synchronous Machine-based drives [16], Modular Multilevel Converter circulating current suppression [17], Impedance-Source Converters [18] and therefore PSO-based tuning potentially can be employed there as well.

2. Practical repetitive controller

First and foremost, it is important to acknowledge that the multiresonant controller with a complete set of oscillatory terms up to the Nyquist frequency

$$G_{\mathrm{MOSC}}(s) = \frac{k_0}{s} + \sum_{n=1}^{\infty} \frac{k_n s}{\left(\frac{s}{n\omega_1}\right)^2 + 1} = \frac{N_{\mathrm{MOSC}}(s)}{s\prod_{n=1}^{\infty}\left(\left(\frac{s}{n\omega_1}\right)^2 + 1\right)}, \tag{3}$$

where ω_1 represents fundamental angular frequency and k_n are controller gains, introduces exactly the same generating polynomial as the universal periodic signal generator used in the repetitive controller [19]

$$G_{\mathrm{rc}}(s)=\frac{k_{\mathrm{rc}}}{e^{2\pi s}-1}=\frac{N_{rc}(s)}{s\prod_{n=1}^{\infty}\left(\left(\frac{s}{n\omega_1}\right)^2+1\right)}, \tag{4}$$

where k_{rc} is the controller gain. This has two major consequences: both controller types experience the same problems of lack of robustness, oscillatory transients and sensitivity to frequency variations, but at the same time it is reasonable to infer that all improving modifications frequently reported for practical resonant controllers should have their counterparts in the case of the repetitive controller. However, this fact seems to be overlooked and most control engineers in the field of power electronics tend to implement a set of oscillatory terms instead of one universal periodic signal generator – even if the latter seems to be more straightforward and imposes less computational burden [20].

2.1. Selectiveness and phase lead compensator. As it is very challenging to implement resonant terms for frequencies near the Nyquist frequency (in [21] experiments for oscillatory terms up to 950 Hz for sampling frequency $f_s = 2$ kHz are demonstrated), it is also hardly practical to use unmodified universal periodic signal generator (2) as part of the controller. The unlimited bandwidth of such a controller results in overlearning and makes the control system unstable. In multiresonant controllers we simply limit the bandwidth by implementing only selected oscillatory terms. In a repetitive controller, a similar property is achieved by low pass filtering

$$G_{\mathrm{rc}}(z)=k_{\mathrm{rc}}\frac{z^{-n_s}}{1-Q(z)}, \tag{5}$$

where $Q(z)$ is a zero phase shift low pass filter. The relevant block diagram is shown in Fig. 3.

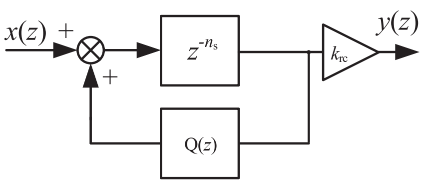

Fig. 3. Repetitive controller with the Q filter

Note that zero phase shift filtering is non-causal. Nevertheless, this does not pose any implementation challenge as all the calculations are performed using samples from the previous pass. A first hand choice for practitioners is a finite impulse response (FIR) filter of the form

$$Q(z)=\left(\frac{1-\alpha}{2}\right)z+\alpha+\left(\frac{1-\alpha}{2}\right)z^{-1}, \tag{6}$$

which introduces one parameter to be tuned. In general, any FIR filter can be turned into a zero phase shift one by reversing the order of once filtered samples and feeding them again to the filter. For more details, see, e.g., Matlab's `filtfilt`. Nevertheless, for the purpose of this study a very basic low pass filter of the form (6) is used. Such a filter is often chosen by practitioners and $\alpha = 0.5$ is often selected without any strong justification. In our case α is assumed to be one of the decision variables for the optimization process.

A phase lead compensator shifts the root locus to the left, which enhances the responsiveness and stability of the system. It has been already demonstrated that introducing phase lead to the resonant terms in the grid-tied converter control systems is beneficial [21–23]. Similarly, reported practical repetitive controllers are often modified to introduce the relevant phase lead capability [24]. The majority of the proposed solutions assume that the lead is realized like in Fig. 4 by tapping to the previous control signal samples already directly stored in the shift register of the controller. The controller takes the form of

$$G_{rc}=k_{\mathrm{rc}}\frac{Q(z)z^{-n_s+p_c}}{1-Q(z)z^{-n_s}}. \tag{7}$$

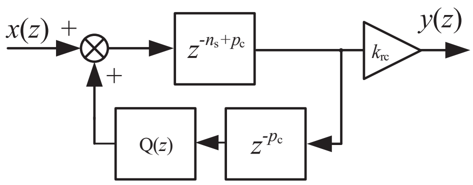

Fig. 4. Repetitive controller with generic phase lead

2.2. Fractional length of the pass. Before moving to the optimization procedure, two more algorithms should be implemented. The first one is to address possible fluctuations of grid frequency. This study assumes that the overall control algorithm is implemented as a fixed step one, i.e., sampling time is constant. This does not have to be always the case – alternatively variable sampling could be used [25, 26]. That approach is significantly more challenging and it is not preferred in commercial grid-tied converters. Therefore, a non-integer length of the pass should be approximated using FIR denoted FD_1 in Fig. 5. More advanced solutions assume that also the phase lead can be of non-integer length with respect to the sampling time [27, 28]. In this case the non-integer delay z^{-p_c} is approximated using an FIR depicted in Fig. 5 as FD_2. The control law of fractional delay repetitive controller (FDRC) is then

$$y(z)=k_{\mathrm{rc}}\frac{z^{-N}G_{\mathrm{FD}_1}(z)}{1-G_{\mathrm{FD}_1}(z)G_{\mathrm{FD}_2}(z)Q(z)z^{-N}}e(z), \tag{8}$$

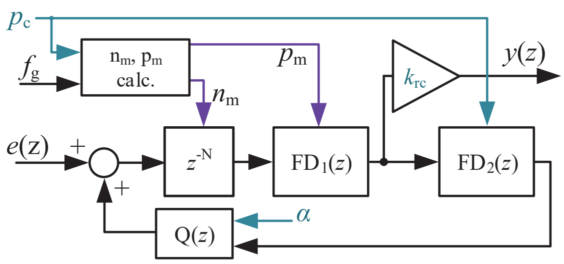

Fig. 5. Scheme of the fractional delay repetitive controller (FDRC)

where z^{-N} represents delay of n_m samples G_{FD_1} of p_m and G_{FD_2} of p_c. Filters FD_1 and FD_2 have exactly the same structure. The relevant fractional delay is realized using Taylor approximation. It has been reported in [29] and rechecked by us that the third order approximation of the form of four sub-filters F_0, F_1, F_2, F_3 with transfer functions $\mathrm{F}_0 = 1; \mathrm{F}_1(z) = -11/6 + 3z^{-1} - 3/2z^{-2} + 1/3z^{-3}; \mathrm{F}_2(z) = 1 - 5/2z^{-1} + 2z^{-2} + 1/2z^{-3}; \mathrm{F}_3(z) = -1/6 + 1/2z^{-1} - 1/2z^{-2} + 1/6z^{-3}$ is sufficient for the task at hand and the resulting fractional delay is shown in Fig. 6, where p_x is the delay that has to be approximated.

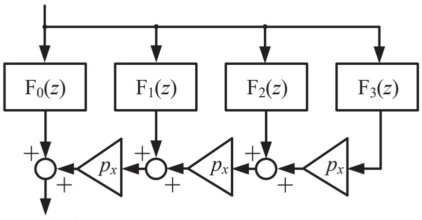

Fig. 6. Scheme of fractional delay approximation using four third order subfilters

The relevant delays to be approximated are calculated based on estimated grid frequency f_g. This frequency is estimated using phase locked loop (PLL) of a type like in [30]. Coefficients of the FD_1 filter are adapted according to the estimated f_g according to:

$$n_s = \frac{f_s}{k_b f_g}, \tag{9}$$

$$n_m = \mathrm{floor}(n_s - p_c), \tag{10}$$

$$p_m = (n_s - p_c) - n_m, \tag{11}$$

where f_g is the fundamental frequency of the grid voltage and k_b is the rank of the main harmonic that is supposed to be affected by FDRC. All parameters of FD_1 can be calculated directly from the identified grid frequency and as such this filter does not introduce any parameters that could be the subject of optimization. It is worth noticing at this point that FD_1 gives the repetitive controller an ability similar to the multiresonant controller with adaptive resonant frequencies. The latter is a well-known technique for multiresonant controllers in the context of grid-tied converters [31, 32].

Some authors propose linear matrix inequalities (LMI) [33] or techniques based on continuous [34] and discrete transfer function [35] to design RC. Many papers propose $\alpha = 0.5$, e.g., [36] or [37]. This value is often described as good trade off between robustness and tracking accuracy, but no analytical proof is given that this value is optimal. In [38] and [39] also performance of the system for the Q filter with higher α is described. The aforementioned tuning methods allow to achieve a stable control system but they are far from optimal as the influence of these parameters on the dynamic response of the system is by no means decoupled. For example, lower bandwidth of $Q(z)$ allows us to set higher k_{rc}, whereas appropriate phase lead allows us to use $Q(z)$ of a higher bandwidth. The idea is then to tune them simultaneously in one optimization procedure.

Harmonics that can be affected are determined by the base frequency (inversely proportional to the pass length) of the repetitive controller. For example, distortion caused by a 6-pulse rectifier consists of $6n$ order harmonics in the synchronous coordinate system. In that case it is enough to apply a controller with $k_b = 6$. However, in case of anticipated asymmetry in the grid voltage, the 2nd harmonic appears in the dq system. This case is described herein, thus to achieve symmetrical currents, the base frequency of FDRC is chosen to be 100 Hz ($k_b = 2$). Another approach is $k_b = 1$, which allows zero steady-state error for the system with repetitive controllers applied in the stationary reference frame.

It should be noted that there are also other techniques to tackle grid frequency fluctuations in a fixed sampling time controllers. In [40], Virtual Variable Sampling Repetitive Control is proposed. The method is based on a virtual delay unit which approximates each variable sampling delay. For this reason, it gives flexible variable sampling frequency without disturbing overall system frequency and stability. [41] presents the concept of Parallel Structure Fractional Repetitive Control (PSFRC). The major difference between PSFRC and FDRC is that PSFRC does not approximate the fractional part of the delay but it locates poles accurately for particular harmonics. A drawback of this technique is the need of complex correction factor implementation, which is CPU-intensive for most digital signal processors [8]. The implementation of this method in High-Performance Grid Simulator is shown in [42].

2.3. Conditional learning.

The second algorithm we would like to discuss before moving to the optimization stage is inspired by adaptive damping sometimes implemented in multiresonant controllers. The idea of adaptive damping in resonant terms arises from the need to limit oscillatory state variables in transient states to get smoother responses to abrupt reference or disturbance variations. Also, control signal limiting can be realized thanks to this mechanism. Several different adaptation schemes have been reported for oscillatory terms, e.g., [43, 44]. Similarly, various conditions for suppressing learning in repetitive controllers could possibly be proposed to meet different objectives. The general concept of conditional learning is illustrated in Fig. 7. The main motivation behind this is to

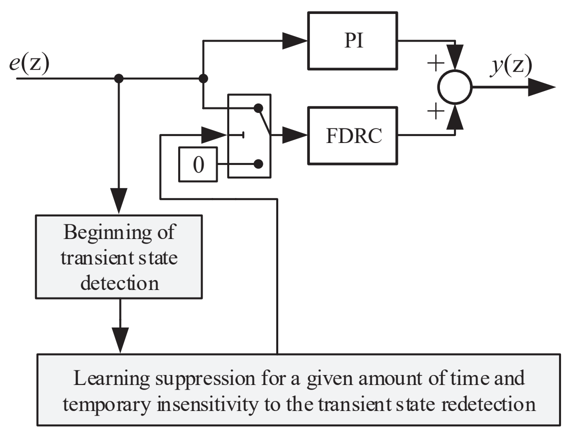

Fig. 7. General concept of conditional learning of the repetitive controller with conditional learning

neglect in the repetitive part of the controller most of the transient component of the control error. That part of the control error should be taken care of in the non-repetitive part of the controller. It should be noted that both paths, the non-repetitive one and the repetitive one, do not operate independently in a standard non-RC (e.g., PI) plus RC controller setup shown in Fig. 7. In an ideal case we would like to have two paths: one active in the over the pass direction and the second one active in the pass to pass direction only for the repetitive part of the control error. Feeding the repetitive part with the non-repetitive errors deteriorates the response of the system. One of the possible conditions is then to suppress learning for errors higher than a given threshold and wait till these errors are drawn below the threshold by the non-repetitive part, and then restart the learning to draw them even closer to zero. Such a mechanism introduces at least one parameter to be tuned, i.e., the threshold. However, our observation is that this mechanism only marginally improves the response of the grid-tied converter when reference current is calculated by a DC-link voltage PI controller, which will be demonstrated in Section III. However, visible improvement occurs if the reference grid current i_d^* is changed very abruptly, i.e., in a near step-wise fashion when i_d^* is shaped by feed-forward of the DC-link load current.

To the best of the authors' knowledge, the algorithm proposed in [11] or any other conditional learning algorithm inspired by it has not been incorporated into the grid-tied converter. Therefore, we have included this algorithm to have a complete picture with all modifications inspired by multiresonant controllers. The threshold is selected to be 25% of the maximal error and in this study it is not the subject of optimization.

3. Optimization

A simulational model of the system presented in Fig. 8 has been built in Simulink with PLECS blockset to facilitate a population based gradient-free optimization. A particle swarm optimizer [45] is used, but any other stochastic search algorithm of the designer's choice could also be employed here. The algorithm is implemented in Matlab. The mathematical model serving the role of the critic for the swarm should mimic the physical system as closely as possible. It is then necessary to identify R and L, as well as the overall delay introduced by the pulse width modulator, the digital control system and the optional EMI filters as well as optional measurement signal conditioning [46, 47]. The delay introduced by PWM equals that of a sample & hold element, that is of $0.5T_s$, where T_s is the sampling period. The current controller is implemented in an interrupt service routine and the processing time introduces delay T_s. During optimization and experiments no additional EMI filters are applied. All parameters of the physical system needed for the mathematical model are collated in Table 1. The PI part is tuned according to the modulus optimum method. The dominant time constant is $\tau_{LR} = \frac{L}{R}$, the plant gain is $K_s = \frac{1}{R}$ and the sum of all small time constants is $\tau_\Sigma = 1.5T_s$. Controller gains for the parallel configuration are then equal to

$$k_P = \frac{\tau_{LR}}{2K_s\tau_\Sigma} \tag{12}$$

and

$$k_I = \frac{1}{2K_s\tau_\Sigma}\,. \tag{13}$$

In case of outputs saturation standard clamping is employed as the anti-windup mechanism [48].

Table 1
Main parameters of the physical model used for the optimization process

Symbol	Value	Description
L	1.6 mH	input filter inductance
R	26 mΩ	input filter resistance
T_s	100 µs	sampling period

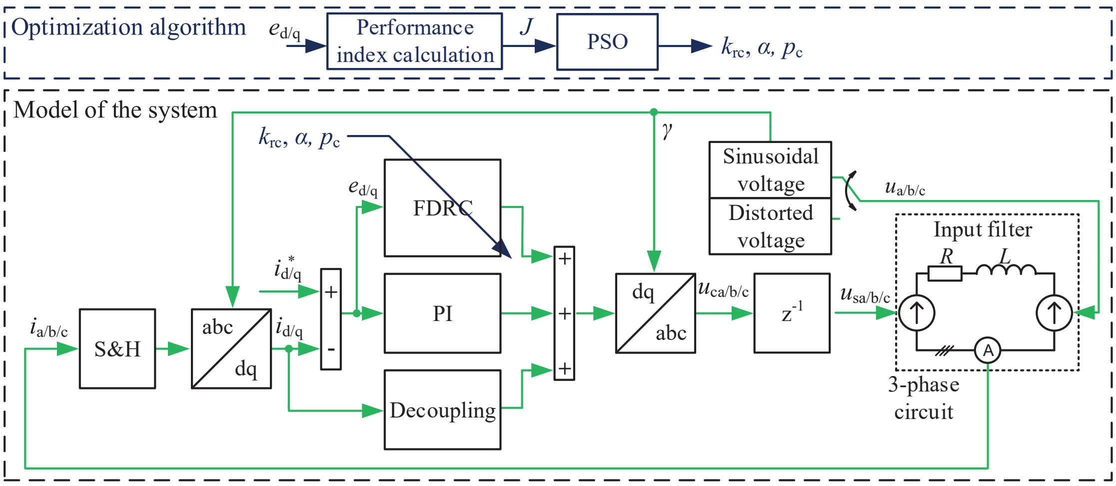

Fig. 8. Simulation model for the optimization process – the converter is modelled as three controlled voltage sources

There is a triplet of decision variables (k_{rc}, α, p_{rc}) and the goal is to minimize the cost functional

$$J = \frac{1}{N}\sum_{n=1}^{N}\left(e_{\mathrm{d}}^{2}(n) + e_{\mathrm{q}}^{2}(n)\right) \tag{14}$$

under the user-defined test scenario. The scaling factor $\frac{1}{N}$ does not influence the optimization method. Its aim is to make the value of J easier to interpret as the average value per sample.

The objective is to assess the performance of the system under load variations, i.e., the reference tracking ability, and under grid voltage distortion variations, i.e., the disturbance rejection capability. The following test scenario (used during the optimization process) is then chosen:

- step change of reference current in the d axis at $t = 0.2$ s from 0 to 100% of the nominal value, and at $t = 0.5$ s back to 0;
- change from sinusoidal to distorted voltage with asymmetry of the fundamental harmonic at $t = 0.1$ s and back to sinusoidal at $t = 0.5$ s.

The desired performance of the system includes high performance behaviour in a steady state as well as during transient states. Herein this is obtained using simple cost functional and proper design of the test scenario. Therefore, it is not necessary to involve a complex cost function or Multi-Objective Optimization [14].

Parameters of the optimizer are given in Table 1. Figure 9 shows particles in three selected iterations from an exemplary run. As PSO is a stochastic search algorithm, it is recommended to run it several times to verify if the results, i.e., the triplet (k_{rc}, α, p_c), are consistent across the runs. The mean value and the standard deviation from 4 runs for each decision variable are shown in Table 2. It can be concluded from the standard deviations that the optimization problem is well-conditioned. The result justifies the introduction of FD_2 instead of an integer lead – the optimal solution is far from an integer one. The triplet is then copied, without any modifications, to the physical system photographed in Fig. 10.

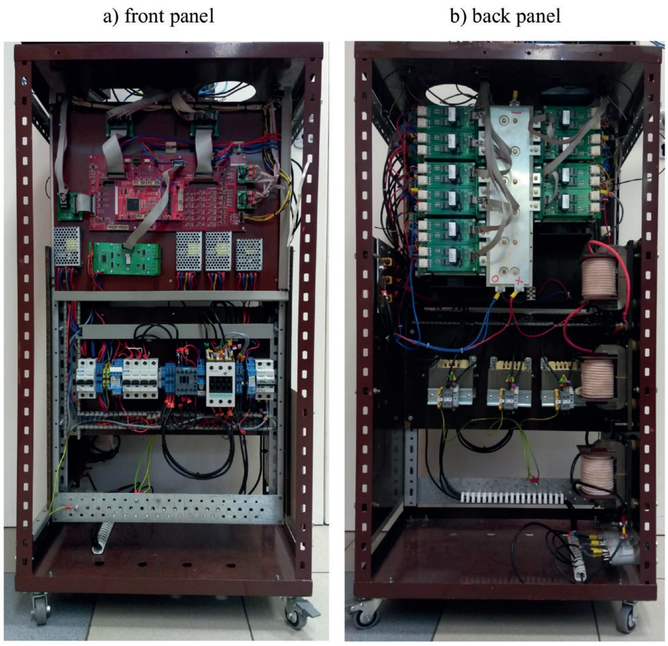

Fig. 10. Laboratory test bench: a front view (a) with visible electronics and electrical apparatus, and a back view (b) with visible gate drivers, DC link and inductors

Table 2
Average values for five optimizations

Parameter	k_{rc}	α	p_c [samples]
Average value	4.48	0.176	3.13
Standard deviation	0	$1.47 \cdot 10^{-3}$	$5.41 \cdot 10^{-5}$

4. Experimental verification

The list of the main components and parameters of the physical system is shown in Tables 1 and 3.

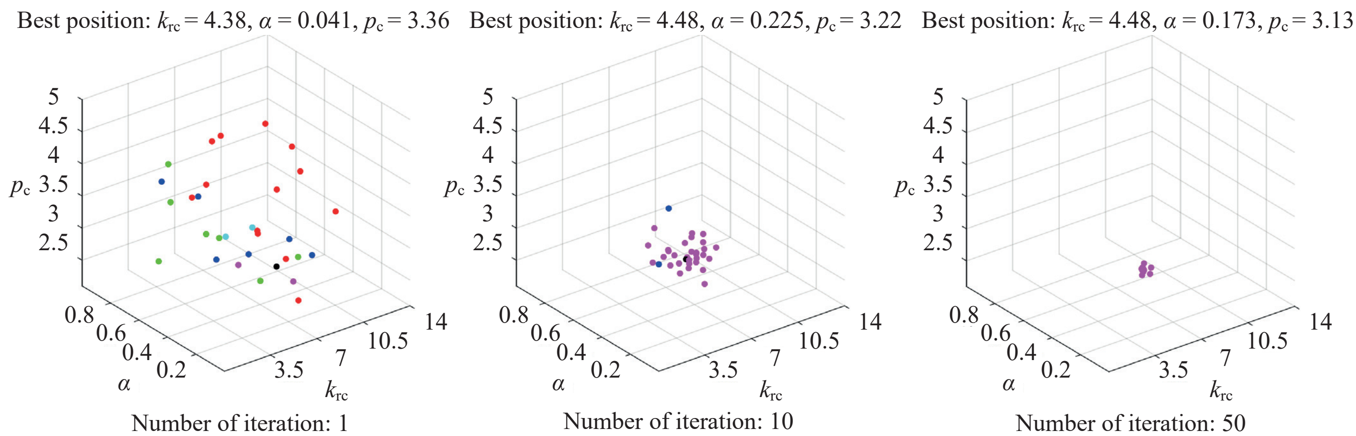

Fig. 9. Position of the particles for different iteration numbers during the optimization process after 1st, 10th and 50th iteration

Table 3
Main components of the physical model

Element	Part/Value
IGBT modules	SK150MLI066T
Gate drivers	CONCEPT 2SC0108T2H0-17
DC-link capacitance	1.5 mF
Digital signal controller	TMS320F28335
Current transducers	LEM LA 55-P
Voltage transducers	LEM LV 25-P

Although optimization with a mathematical model of a plant is prone to identification errors, it is common practice. This stems from the fact that it is often too hazardous to use a physical system as a critic, i.e., to run it with a set of random settings to evaluate a cost function within a stochastic search framework. Nevertheless, it should be acknowledged that this is not always impossible, and there exist iterative learning controllers with on-line PSOs [49]. It is then even possible to employ PSO to directly shape the control signal. PSO performs there fine shaping of the control signal and operates in an intentionally limited range in order not to produce a hazardous solution. On the other hand, in this study, the PSO has virtually unlimited search space thanks to the mathematical model as the critic, and its goal is to perform the parametric optimization of RC.

All model based tuning methods, including all analytic methods, do not guarantee unlimited robustness to identification errors. For systems with many fold variations in parameters, it might be necessary to employ adaptation schemes to get satisfactory results. This is hardly ever the case for the grid-tied converter, as the unknown grid impedance is usually much smaller than the impedance of the filter. However, it is crucial to assess viability of the tuning method by testing the performance in the physical system of the assumed to be parameters, and then for the system with justifiable identification errors. Parameters of the filter have been identified in no load conditions, i.e., for ambient temperature. Impedance of the grid – quite weak grid because of the autotransformer present between the laboratory grid and the converter – has been neglected to demonstrate feasibility of the method even under such uncertainties. All the following results come from the physical converter system. The first one demonstrates that by adding the above optimized RC to an existing PI path the quality of the grid current is improved (Figs. 11 and 12). The relevant frequency spectra are shown in Fig. 13. Next, the disturbance capability is demonstrated in Figs. 14 and 15 – higher harmonics in the grid voltage are effectively rejected. Also asymmetry in these voltages is successfully rejected in the currents (Fig. 16). The tracking response is shown in Fig. 17 for fast increase and decrease in load. Potential benefits of implementing conditional learning are demonstrated for the case of a near step change in i_d^* obtained thanks to a control system with feed-forward of the DC-bus load current. The response for unconditional learning is shown in Fig. 18 and for conditional learning in Fig. 19. Visible improvement in the shape of the current after an abrupt change comes from suppressing integration from pass to pass within the repetitive part of the control system under transients with currents far from repetitive ones.

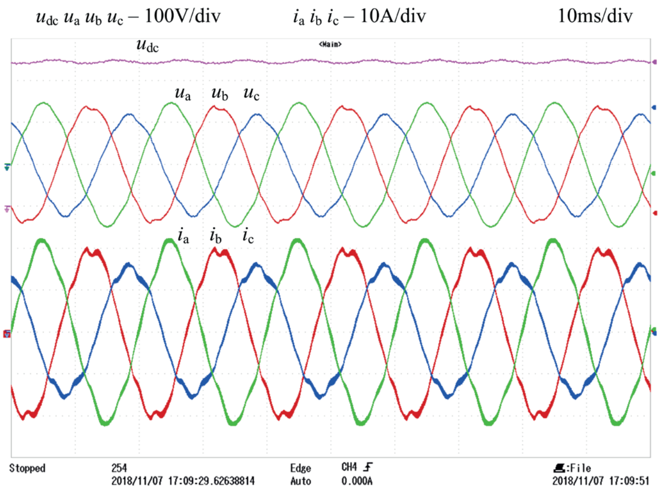

Fig. 11. Experimental results of a steady state for a system without repetitive control

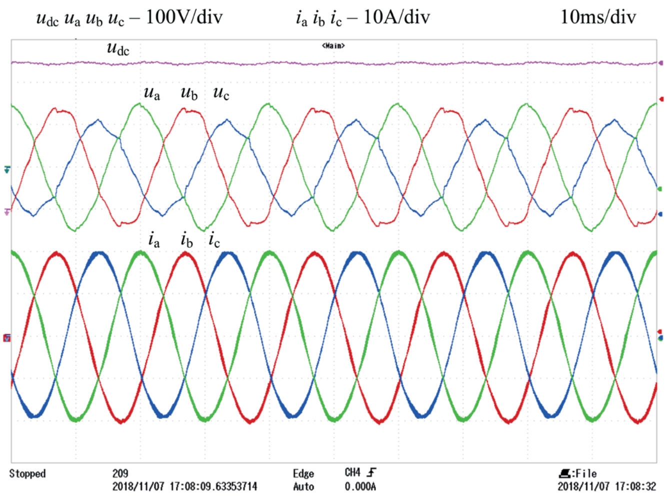

Fig. 12. Experimental results of a steady state for a system with repetitive control

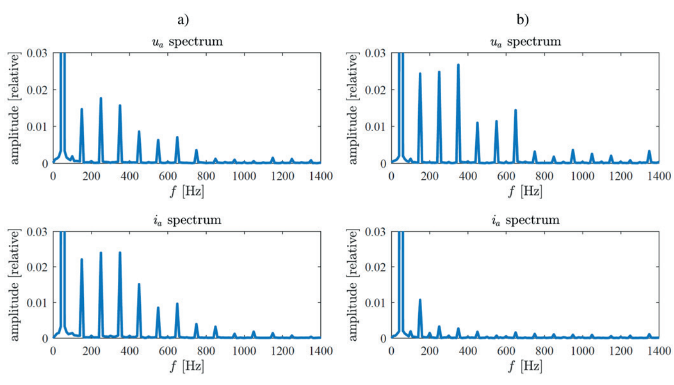

Fig. 13. Spectrum of grid voltage and converter current for control without (a) and with repetitive controller (b) from experimental results

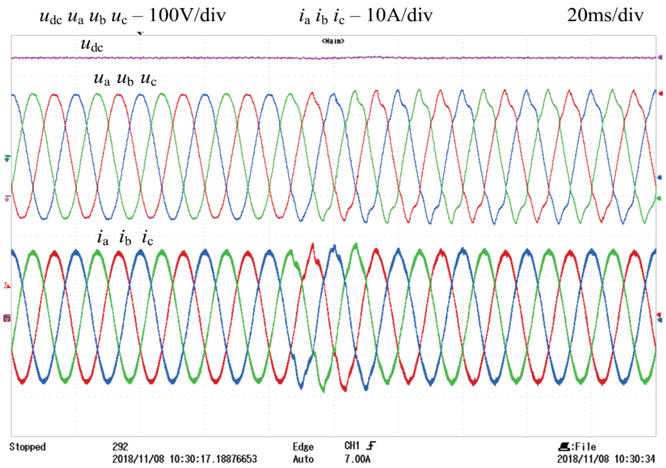

Fig. 14. Experimental results of a transient state after change of the grid voltage from sinusoidal to distorted

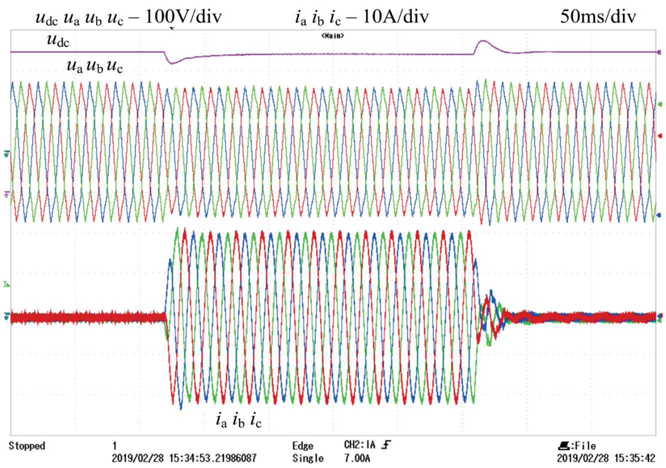

Fig. 17. Experimental results of a transient state after transient states of the load of DC/DC converter

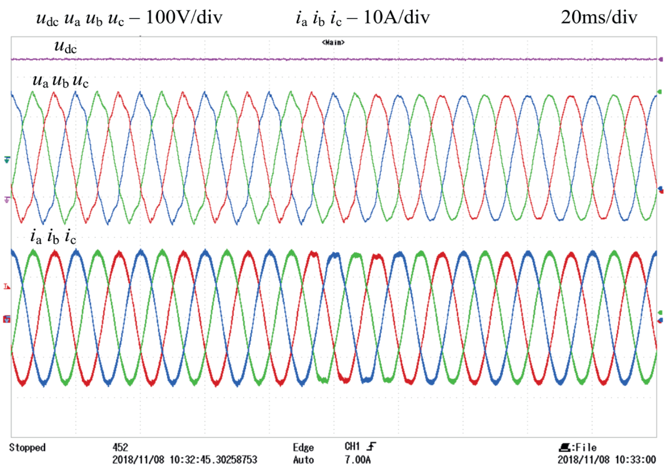

Fig. 15. Experimental results of a transient state after change of the grid voltage from distorted to sinusoidal.

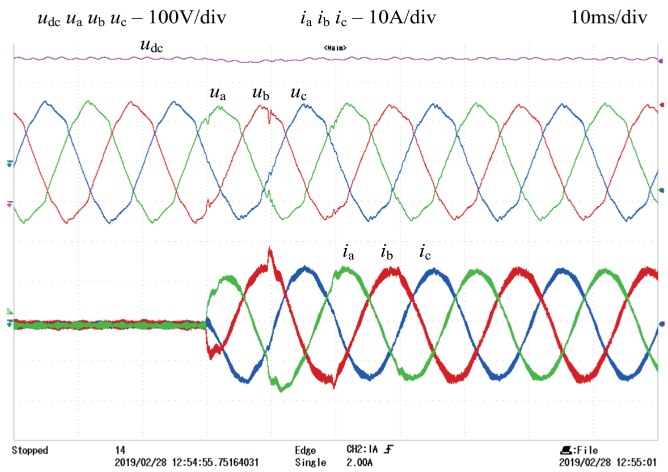

Fig. 18. Experimental results of a transient state after step change of i_d^* without conditional learning

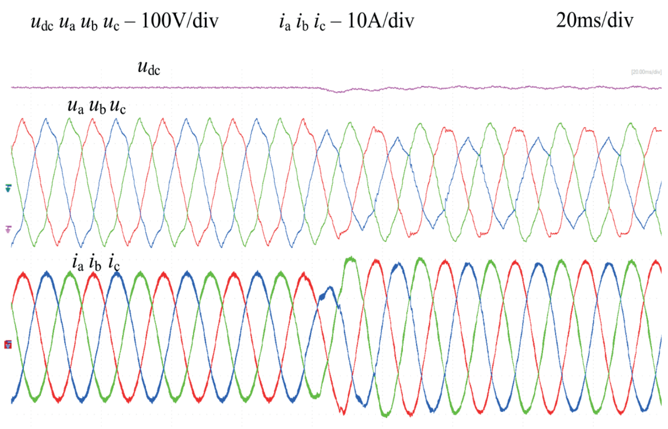

Fig. 16. Experimental results of a transient state between symmetrical and asymmetrical grid voltage

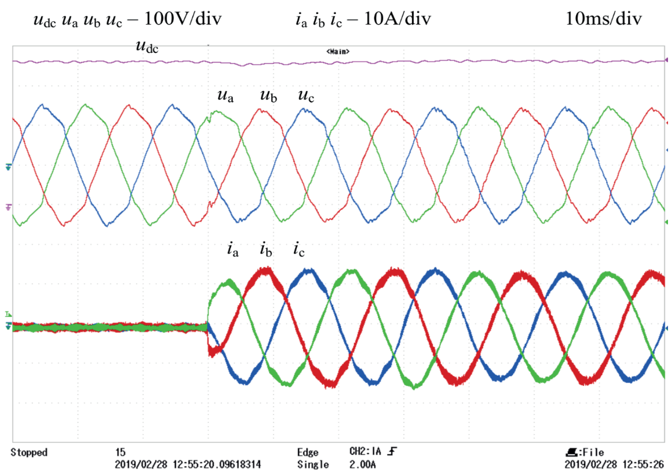

Fig. 19. Experimental results of a transient state after step change of i_d^* with conditional learning

Finally, the sensitivity of the response to 20% identification error in L and R is tested. The physical filter is left unchanged, but the identified parameters are intentionally modified before feeding them to the optimization procedure. Obviously, initial identification errors are unknown to us, but now we are certain that for some of the tests they are no smaller than 20% with respect to the ones assumed for the optimization procedure. Out of four tests (0.8L and 0.8R, 1.2L and 1.2R, 0.8L and 1.2R, 1.2L and 0.8R), the worst case (based on subjective visual inspection) is shown in Figs. 20 and 21. It should be acknowledged that this is by no means a formal sensitivity analysis, which is envisaged further down the way. The goal of these four additional optimization tests is to demonstrate that the technically viable results are not a lucky coincidence and that the design procedure based on offline model-based optimization can be deployed in real-world settings.

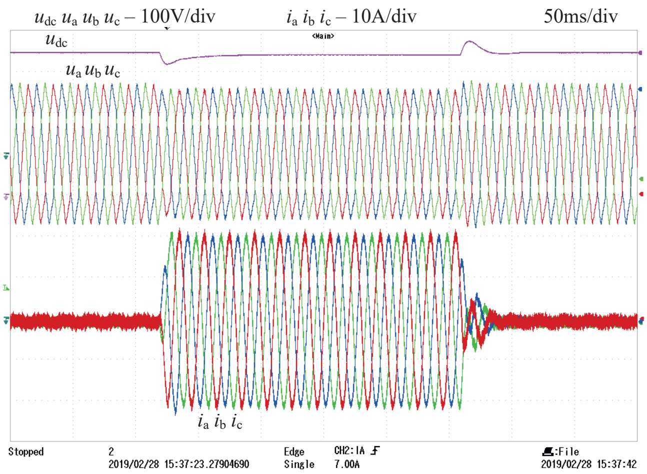

Fig. 20. Experimental results of a transient state after change of the load of the DC/DC converter. During optimization resistance is 20% lower, inductance is 20% higher than the measured values of the test bench

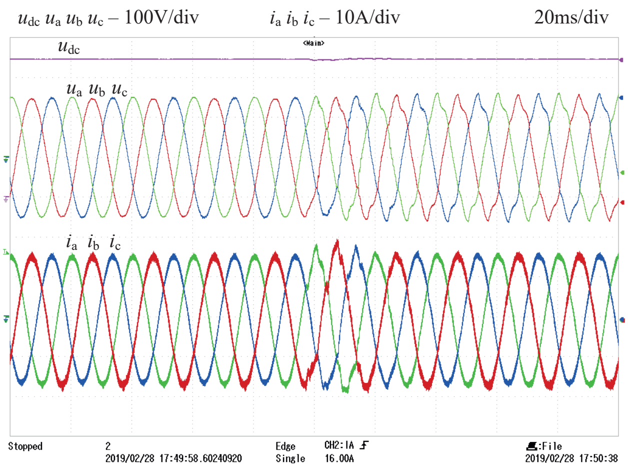

Fig. 21. Experimental results of a transient after change of the grid voltage from sinusoidal to distorted. During optimization resistance is 20% lower, inductance is 20% higher than the measured values of the test bench

5. Conclusions

A complete design procedure for a repetitive current controller in the three-phase grid-tied converter has been proposed and tested experimentally. The three key parameters of the repetitive part of the controller, namely its gain, phase lead and zero phase shift filter, have been tuned using the particle swarm optimization. Additionally, the conditional learning concept has been incorporated to improve transients. Moreover, the controller includes two fractional delay filters not only to robustify the controller against grid frequency fluctuations but also to allow the optimizer decide other phase leads than just the integer ones. The design procedure is regarded as complete because expert knowledge is required only to define the test scenario, i.e., reference and disturbance signals have to be set by the designer. On the other hand, we are convinced that the proposed test signals are sufficient to effectively assess the operation of the converter during its control subsystem optimization, and as such they complete the design procedure to the point of total elimination of any guessing and checking. Viability of the controller along with its tuning method has been demonstrated experimentally and tested against justifiable real-world plant identification errors.

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