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Single phase active rectifier with low harmonic content in input current

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***Abstract*—In this paper, an advanced control algorithm in single-phase active rectifier for reduction of grid current harmonics is presented. In addition to PI current controller, three advanced types of controllers are investigated: resonant, discrete cosine transforms (DCT) and repetitive controller. These controllers are able to effectively reduce harmonics, caused by periodic disturbances. A simulation model has been built to test the proposed algorithms. Simulation results confirm significant improvement in grid current harmonic content, achieved by these advanced current controllers. Analysis of memory usage and computing power requirements is also provided.**

***Keywords*—active rectifier; control algorithm; resonant controller; DCT controller; repetitive controller; THD**

I. Introduction

Nowadays, vast majority of electrical devices is supplied from public power grid, which is guaranteed to have very stable frequency and also amplitude of sinusoidal voltage waveform. This would hold true, if the input current of every single load connected to grid had sinusoidal waveform. However, most electrical devices draw non-sinusoidal currents. Consequently, the grid voltage waveform becomes distorted, resulting in questionable quality of provided electrical power.

To limit the higher harmonics in the grid, standard IEC 61000-3-2 has been introduced [1]. It prescribes input current spectrum of electrical devices connected to electrical power grid. Amplitudes of every higher harmonic up to 40^{th} are restricted and these limitations are very tight.

Power converters without some kind of power factor correction (PFC) cause distortion in the grid. Rectifiers, which are the most common front-end converters of the power supplies and especially diode rectifier, directly inject higher harmonics into the grid. Consequently, diode rectifiers with some active PFC are frequently used. In [2]–[5] only disadvantages of diode rectifier are alleviated with some kind of simple active topology, implemented near rectifier. Better approach is to remove the cause of the problem. In [6]–[8] a single phase bidirectional active rectifier is presented instead of diode rectifier. As it uses pulse width modulation (PWM), it is also called PWM rectifier. In this paper, active rectifier is also used. With an appropriate control algorithm it ensures low total harmonic distortion (THD) of the input current and it can provide a bidirectional power flow. In addition to PI controller, three advanced types of controllers are investigated in this paper: resonant controller (RES), discrete cosine transforms controller (DCT) and repetitive controller (REP). Their task is to reduce higher harmonics in the steady state frequency spectrum of the input current (this is a drawback of the PI controller), and simultaneously not deteriorating the transient response. To achieve appropriate transient response of controlled signals, two compensation loops are implemented. Simulations of the proposed control algorithms were performed to validate the need for additional controllers.

II. Review Of Active Rectifier Topology And Basics

The topology of a single-phase bidirectional active rectifier is shown in Fig. 1. In this case bipolar PWM is employed [6].

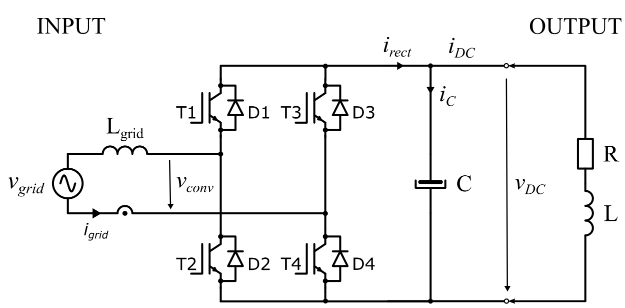

Fig. 1. Topology of single-phase bidirectional active (PWM) rectifier.

In Fig. 2 the control algorithm with cascaded structure is shown. The inner loop controls the grid current through choke L_{grid}, while the outer loop controls the DC (output) voltage. PI controllers are usually used.

To obtain zero reactive power flow from grid, sinusoidal grid current reference and synchronization to the grid voltage must be realized. This is accomplished through discrete Fourier transform (DFT), which provides the fundamental harmonic of the grid voltage.

Outer control loop is meant to provide constant DC voltage. However, the ripple in the DC voltage affects the output of the voltage PI controller, which should ensure constant amplitude of sinusoidal current reference in steady state. To reduce this voltage ripple influence, the moving average filter [9] is implemented in the feedback of the outer, voltage control loop.

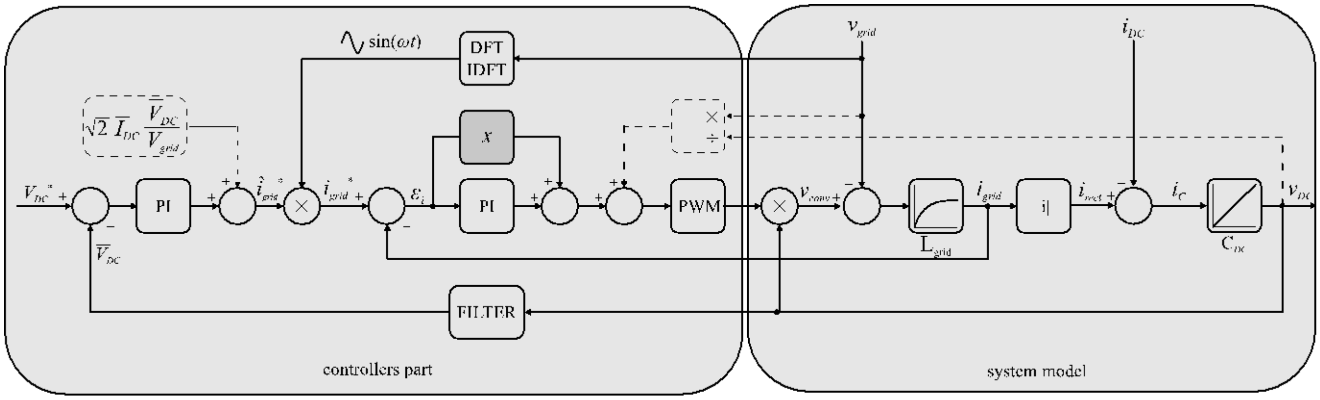

Fig. 2. Proposed control algorithm.

Two compensation loops are implemented to improve performance. First is added to the output of the current controller to reduce the steady state error, which is caused by grid voltage. As can be seen, the difference between voltages v_{grid} and v_{conv} dictates the current through the choke L_{grid} (Fig. 1 and Fig. 2). The control algorithm affects only the waveform of v_{conv} to provide sinusoidal grid current; thus v_{grid} is considered as a disturbance for the current controller.

The second compensation loop is added to the output of the voltage controller to improve the voltage loop transient response. By neglecting the power losses, the instantaneous active power of AC and DC side should be equal. Through this condition the compensation loop is designed to improve transient response of voltage controller.

Similar control algorithm, but for three phase topology without compensation loops, was implemented in [10].

III. Proposed Control Algorithm

The basic control algorithm from Fig. 2, without the block marked "x", unfortunately cannot achieve sinusoidal input current. The main reasons are: dead time in the PWM and higher harmonics present in the grid voltage. Both of them act as a disturbance in the current control loop and ordinary PI controller has difficulties rejecting this disturbances. This is reflected in higher harmonic content of the grid current. To solve the problem various solutions were presented. Most common ones introduce additional controller in parallel, with current PI controller as shown with block "x" (Fig. 2), which implements one of the three advanced controllers: multiple resonant controllers, discrete cosine transforms (DCT) controller or repetitive controller. Such an upgrade of the control algorithm provides a significant improvement in tracking the grid current reference.

1) Resonant controller

Resonant controller is an upgrade of the classical I controller, which has a difficulties tracking sinusoidal reference [11]. For a selected frequency (ω_{res} in Fig. 3), the resonant controller eliminates the steady state error.

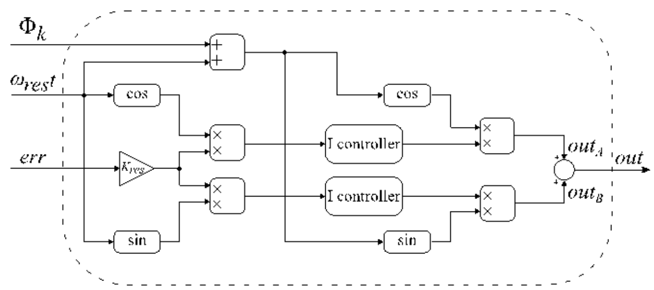

Fig. 3. Schematic of resonant controller.

However, only at selected frequency the steady state error is zero. If zero steady state error at more frequencies is required, multiple resonant controllers must operate in parallel. Fig. 4 presents the idea of multiple resonant controllers, where each of them reduces control error of one frequency. Selected frequencies are usually multiples of fundamental frequency, which means that first harmonic and higher harmonics can be affected. For every resonant controller the selected frequency ω_{res}, gain K_{res} and phase lag compensation ϕ_k can be set, independently. Multiple resonant controllers are the first option to improve the performance of the current control loop.

This principle is used in many power electronics applications i.e. [7], [11]–[15].

When designing an individual resonant controller, the resonant frequency is chosen as multiple of fundamental frequency and the other two parameters are usually calculated from open loop system response. System phase lag of individual harmonic at resonant frequency can be read from Bode plot and compensation is set to the same value. As long as resonant frequency is well below crossover frequency, where system phase lag is close to -180°, design of the gain K_{res} is same as I controller gain design [11].

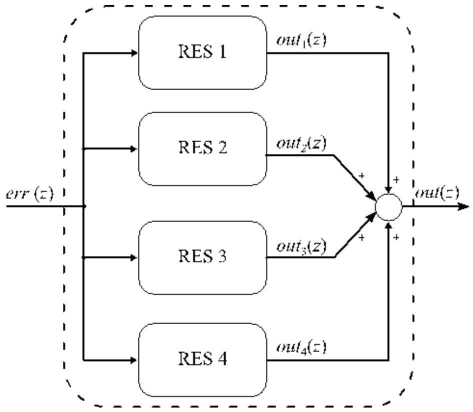

Fig. 4. Multiple resonant controllers configuration for reduction of higher harmonics in control signal.

2) DCT controller

Alternative to multiple resonant controller is the DCT controller [11], shown in Fig. 5. It is discrete integrator with additional DCT filter. The latter is finite impulse response (FIR) type of digital filter, allowing only the first harmonic and selected higher harmonics to pass. All the other frequencies are attenuated. Phase delay compensation k_{DCT}, as a multiplier of sample interval, can also be set. However, in this controller the same delay compensation is used for all selected harmonics.

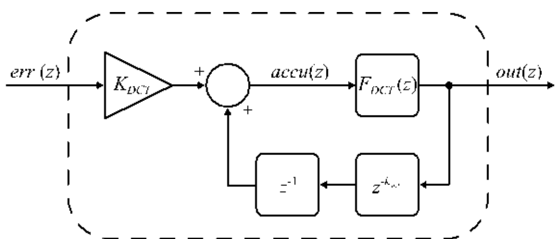

Fig. 5. Schematic of a DCT controller.

Design of DCT controller comprises setting gain, phase lag compensation and all the higher harmonics. The latter is trivial again, since DCT filter is used [11], where all FIR filter coefficients are easily calculated. Gain and compensation are designed from open loop system response, but are the same for all the harmonics. So, the highest harmonic, which passes through DCT filter, is the most relevant for gain design, since it introduces the highest phase lag and threatens stability the most. The phase lag compensation value must not be set too high, otherwise it can cause instability at low harmonics (overcompensation). It must not be undercompensated either, to avoid instability at high harmonics, where phase lag is near 180°.

3) Repetitive controller

Repetitive controller is another solution for reduction of higher harmonics. It reduces periodic error with all harmonics up to the Nyquist frequency. At high frequencies phase lag of the system also causes instability in the control loop, therefore some kind of low-pass filtering is necessary [16]. Among many variants of this filter, the proposed repetitive controller is shown in Fig. 6. White-shaded blocks depict its simplest form (no additional filter used), while shadowed blocks mark the low-pass FIR filter that does not add any additional delay in control loop. Although proposed FIR filter is not an optimal low-pass filter, it suppresses high frequencies well enough to guarantee a stable control loop. Gain K_{REP} and phase lag compensation k_{rep} (as multiple of a sample interval) can be modified, but the same values for all harmonics.

When designing repetitive controller, low-pass FIR filter design causes many problems, because the number of taps is not a high number, thus frequency response cannot have sharp roll-off and very low attenuation at stop band. Consequently, design of gain and phase lag compensation becomes even more complicated as in the case of DCT controller.

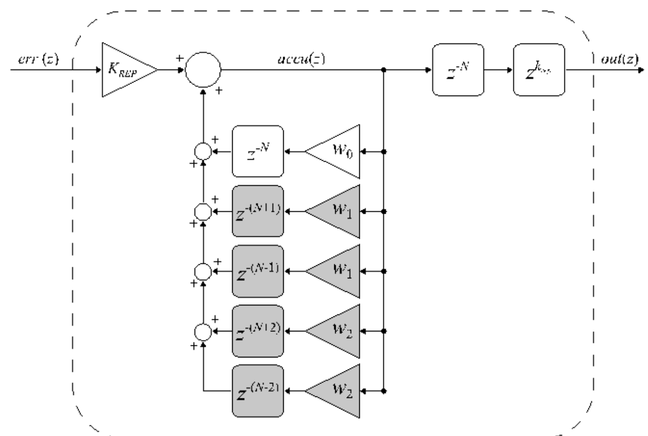

Fig. 6. Schematic of a repetitive controller.

IV. Simulation Results

Simulations of the control algorithm with only PI current control and the proposed solutions have been performed in Matlab/Simulink. Topology and control parameters are presented in table I.

TABLE I. PARAMETERS OF SIMULATED ACTIVE RECTIFER

Description	*Symbol*	*Value*
grid choke inductance	L_{grid} (μH)	700
grid choke resistance	R_{grid} (mΩ)	100
grid (input) RMS voltage	V_{grid} (V)	24
grid frequency of 1st harmonic	f_{grid} (Hz)	50
sampling and PWM frequency	f_s (kHz)	20
dead time	t_{dead} (μs)	1
MOSFET forward resistance	R_{mosfet} (mΩ)	10
voltage drop of intrinsic diode	V_{diode} (V)	1
DC link capacity	C (μF)	5 · 2200
load resistance	R (Ω)	10
load inductance	L (H)	0

Description	***Symbol***	***Value***
DC (output) voltage reference	V_{DC}^{*} (V)	44
rated (maximal) power	P_{max} (W)	500
maximal amplitude of grid (input) current	$I_{grid,max}$ (A)	20
maximal DC (output) current	$I_{DC,max}$ (A)	20
maximal DC (output) voltage	$V_{DC,max}$ (V)	50

Multiple resonant controllers and DCT controller are set to remove first 20 odd harmonics. Repetitive controller bandwidth is set indirectly through 5-tap FIR filter, with cutoff frequency of 1.8 kHz. The DC load is constant during simulations and represents around 50 % of rated power.

Fig. 7 shows grid current at steady state, controlled by algorithm from Fig. 2, when only PI current controller is used. Reference and feedback waveforms differ, thus this control algorithm is not performing well enough. Additionally, phase lag between reference and feedback appears. If only first harmonic of grid current is observed, both active and reactive powers are drawn.

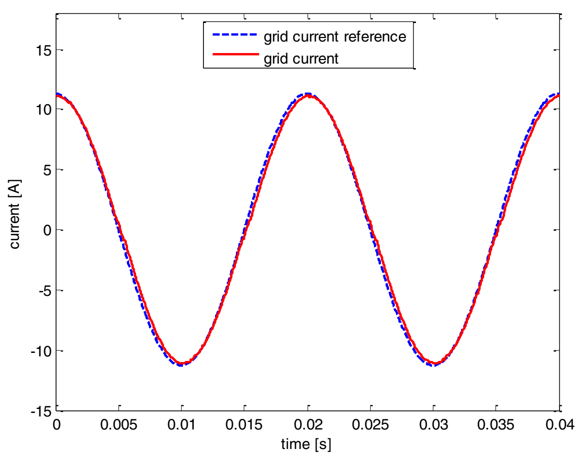

Fig. 7. Steady state grid current waveforms (reference and actual current), with control algorithm with only PI current controller

Far better results are obtained with control algorithm, where advanced controller is added in parallel with PI controller. Four different cases of current controller are realized. In the first case only current PI controller is active, in the second case the PI and the resonant controller are operating in parallel, the PI and the DCT controller operating in parallel is the third case, and in the last case the PI and the repetitive controller operate in parallel. Grid current errors between reference and feedback for all four cases are shown in Fig. 8. The maximum error in the first case reaches almost 8 %, with respect to grid current amplitude of the first harmonic. An improvement in other three cases is obvious. If any of the three additional controllers is added, the maximal error is drastically reduced (almost by factor of 10).

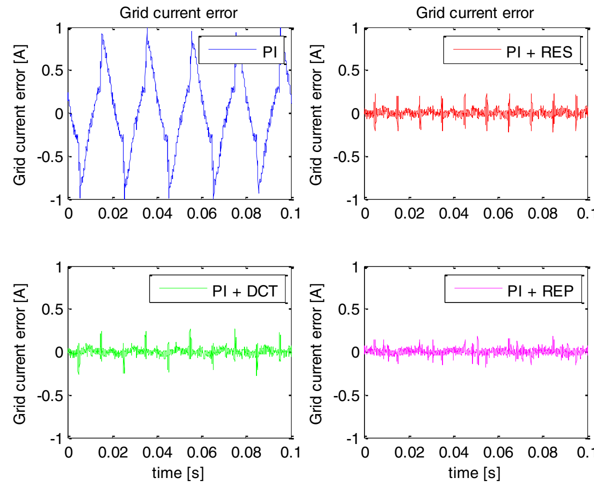

Fig. 8. Grid current errors with control algorithm from Fig. 2 (current PI controller is operating in parallel with one of the three advanced controllers).

Frequency spectra of the grid current are shown in Fig. 9. Odd higher harmonics up to 20th harmonic are decreased if either multiple resonant or DCT controller are used. Even harmonics are not compensated, yielding non-negligible even harmonics. When repetitive controller is added in parallel to current PI controller, number of reduced harmonics is higher. Frequencies from 1 kHz to 3 kHz are also effectively reduced with repetitive controller.

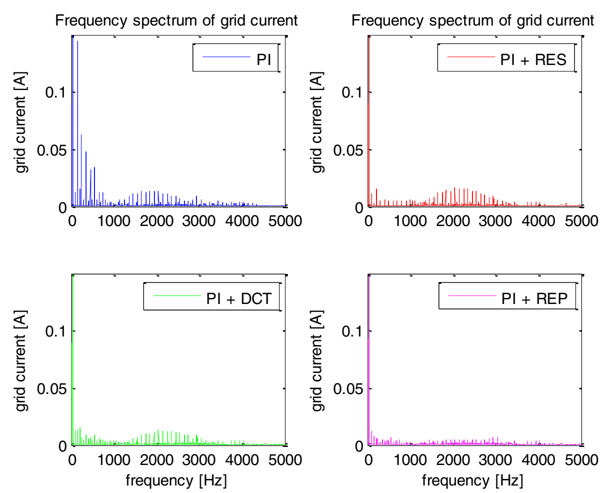

Fig. 9. Frequency spectra of the grid current with control algorithm from Fig. 2 (current PI controller operating in parallel with one of the three advanced controllers).

THD of grid current for resonant, DCT and repetitive controllers can also be compared. THD for all four cases is calculated using eq. (1), where I_1 means root mean square (RMS) value of grid current first harmonic, I_2 RMS value of second harmonic and so on. Results are shown in table II. The lowest THD is obtained when repetitive controller is added in parallel to the current PI controller.

$$THD = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \ldots + I_{200}^2}}{I_1} \quad (1)$$

TABLE II. THD OF GRID CURRENT FOR ALL FOUR CASES

Current controller used	*THD*
PI	1,63 %
PI + resonant	0,53 %
PI + DCT controller	0,48 %
PI + repetitive	0,27 %

As demonstrated, low THD of sinusoidal input current is obtained. However, since the reference of the grid current is sinusoidal, the ripple in output voltage is present in steady state and its amplitude increases with the load. Output voltage transient and load are shown in Fig. 10. In this case, only PI current controller is used. At 0.2 s DC voltage reference changes, while at 0.4 s load is applied, thus ripple in DC voltage can be observed as a consequence of sinusoidal grid current. Predominant DC voltage ripple frequency is 100 Hz.

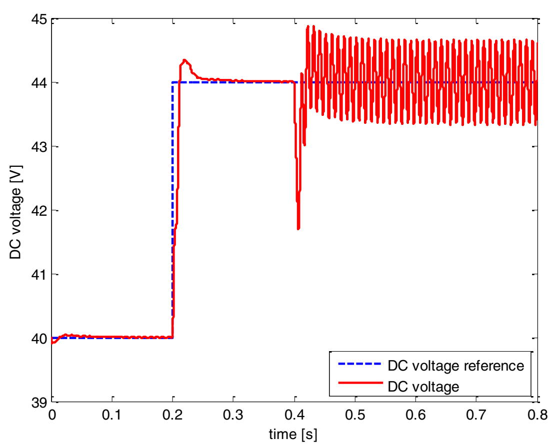

Fig. 10. DC voltage transient response with control algorithm from Fig. 2, without any additional current controller (only current PI controller).

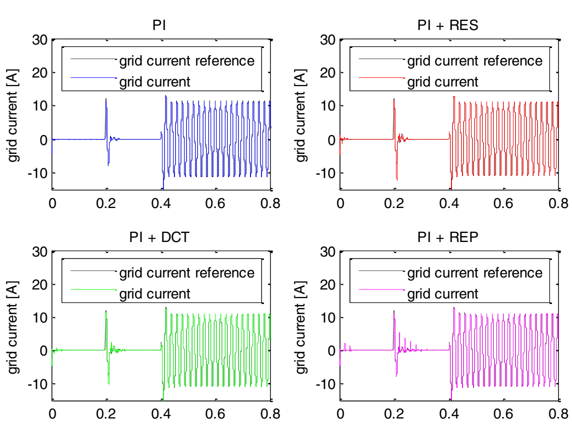

Fig. 11. Grid current transient response.

When one of the three additional current controllers is applied, the transient of DC voltage lasts longer with higher overshoot, but the error is small and in most cases tolerable. The same holds true for grid current transient response, shown in Fig. 11. Only in the case of repetitive controller the transient response lasts significantly longer, than in the other cases.

V. COMPARISON OF FUNCTIONALITY AND RESOURCE REQUIREMENTS FOR RES, DCT AND REP CONTROLLERS

To reduce grid current higher harmonics one of the three proposed controllers can be used. Each has its own advantages and drawbacks. Since the control algorithm is running in real-time, two factors are very important. The first is requirement for computing power, i.e. the number of summations, multiplications and sine and cosine calculation (for resonant controller) in real time. The second is memory usage, i.e. the number of variables and buffers.

Multiple resonant controllers are relatively simple to parameterize and each can be tuned independently for a selected harmonic. Gain, phase delay compensation and resonant frequency can be selected. Even a non-integer of fundamental frequency can be chosen to reduce sub harmonics. However, many resonant controllers must be used for reducing more than one harmonic, so computation power and memory usage are increased with each harmonic.

DCT controller special feature is DCT filter. With it, the selection of higher harmonics to be reduced is simple. Consequently, the upper frequency limit can be set precisely, thus the stability of the controller can be easily obtained. Gain and phase delay compensation can be set for all the harmonics. Compared to one resonant controller, DCT controller requires much more resources. However, regardless of how many harmonics must be eliminated, the computing power and memory usage remain the same.

Main advantage of repetitive controller is its low computing power requirement while the biggest problem is the design of controller. In order to achieve stability, setting only gain and phase delay compensation, is usually not enough, as stability is assured with proper design of low-pass filter in the positive feedback. Unfortunately there are no comprehensive resources covering the design of this filter and this makes the design of repetitive controller difficult.

Resources for each controller are shown in table III. Parameter N is a ratio between sampling frequency f_s and fundamental frequency f_{grid}. In our case, N is 400. M is a number of multiple resonant controllers that are working in parallel. In our case M is 10. As we can see, the resonant controller consumes the least computing power and memory. However, if multiple resonant controllers are added, both resource requirements increase proportionally. Computing power depends also on implementation of sine and cosine functions. Execution of repetitive controller is slower than for the single resonant, but still much faster than for DCT controller. The same is valid for memory usage.

TABLE III. RESOURCE REQUIREMENTS OF RES, DCT AND REP CONTROLLERS

Controller	***Number of online calculations***	***Memory usage***
Resonant controller	5 additions, 7 multiplications, 2 calculation of sine and 2 of cosine	5 input/output variables, 2 internal variables
M parallel resonant controllers	5*M* additions, 3*M* multiplications, 2*M* calculations for each sine and cosine	5*M* input/output variables, 2M internal variables
DCT controller	*N* + 1 additions, *N* + 1 multiplications	5 input/output variables, 1 internal variable, 2 buffers of length *N*
Repetitive controller	5 additions, 6 multiplications	8 input/output variables, 5 internal variables, 1 buffer of length *N*

VI. CONCLUSION

With all three additional controllers, higher harmonics in grid current can be significantly reduced, so their implementation is justifiable. Results show that repetitive controller accomplishes the lowest THD, since the other two eliminate only odd harmonics up to 20th, while repetitive controller reduces wider frequency band of higher harmonics. Multiple resonant and DCT controller could be easily improved further to reduce even harmonics. Harmonics above 20th could be also reduced. However, resource requirements for multiple resonant controllers would increase, while for DCT controller would stay the same. At a given number of harmonics compensated, computing power of DCT controller would be lower than that of resonant controller. Each application has its own requirement and demands. Therefore, which controller is the most appropriate (if appropriate at all) for higher harmonics reduction is not completely straightforward decision. In this case, the usage of repetitive controller provides the lowest harmonic distortion in frequency spectrum of grid current in steady-state. But grid current transient response and parameterization is not a positive aspect of repetitive controller. In general, if computing power is not critical, the bank of resonant controllers is also very convenient to use, since parameters are set relatively without difficulties and transients are handled well.

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