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An Improved Repetitive Action Corrector for Reduction of Steady-State Error and Nonlinear Distortion in Power Amplifiers

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Abstract. The paper presents a control method suitable for reducing effects of nonlinear periodic disturbances on voltage and current. Its focus is on the theory of a modified repetitive control method based on a recurrent integral action procedure distributing the controlled signal in a certain number of intervals and subsequently correcting each interval separately and independently of the remaining intervals. The method was implemented in an experimental three-phase electronic phantom power source with special requirements, designed for calibrating mostly electronic energy meters. Two different power amplifiers, i.e. a voltage and a transconductance amplifier, and other individual components of the power calibrator are introduced and explained. Measurement results acquired with the help of the implemented experimental source are presented.

Key words: periodic disturbances, repetitive control methods, regulated power sources

Izboljšan repetitivni korektor za zmanjšanje statičnega pogreška in nelinearnega popačenja v močnostnih ojačevalnikih

Povzetek. V članku predstavljamo eksperimentalni trifazni močnostni kalibracijski vir za umerjanje (predvsem elektronskih) števcev električne energije, ki mora biti sposoben napajati do pet števcev v fantomski vezavi. Vir mora izpolnjevati poostrene zahteve po stabilnosti, nastavljivi vsebnosti želenih višjeharmonskih komponent in visoki natančnosti generiranih izhodnih veličin toka in napetosti. Opisana sta napetostni in transkonduktančni močnostni ojačevalnik, ki sta uporabljena za samostojno napajanje posameznih napetostnih in tokovnih vej števcev. Podani so razlogi za nastanek popačenj, ki jih števci (in nelinearna bremena na splošno) povzročajo napajalnemu oz. merjenemu signalu. Poudarek članka je predvsem na izbiri korekcijske metode, ki mora biti sposobna učinkovito odpravljati tako povzročena popačenja (oz. popačenja, katerih perioda sovpada s periodo osnovnega merjenega signala ali pa je njen mnogokratnik). Podana je teorija splošnega periodičnega integralnega korektorja, ki temelji na metodi s ponavljajočim se delovanjem. Predstavljene so nekatere modifikacije takšnega korektorja, njegova praktična izvedba ter uporaba v močnostnem kalibracijskem viru. V končnem delu članka so podani merilni rezultati, ki so pridobljeni z omenjenim eksperimentalnim virom. Prikazana so popačenja merjenih signalov pri različnih obremenitvah ter izboljšave, ki jih prinese uporaba regulatorja z opisano korekcijsko metodo. Podani so frekvenčni spektri izmerjenih signalov in pripadajoče celotno harmonsko popačenje za posamezen primer. Pridobljeni eksperimentalni rezultati potrjujejo pravilnost izbire omenjene korekcijske metode in dokazujejo njeno učinkovito zmanjševanje popačenj izhodnih veličin toka in napetosti kalibracijskega vira.

Ključne besede: odpravljanje periodičnih motenj, periodični korektor, napetostni in tokovni viri z veliko natančnostjo

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1 Introduction

Electronic energy meters have to measure energy flows even in case of a distorted, i.e. non-sinusoidal, voltage and current. As a result, the rapid developments of new electronic meters as well as the applicable legislation are strongly followed in the R&D efforts taken to make fast and reliable calibration equipment - sources capable of generating voltages and currents of known, accurate and stable amplitude and phase. Besides these general requirements, power calibrators must fulfill also the following ones:

- the frequency of the fundamental harmonic must be adjustable between 40 Hz and 70 Hz in steps of 0.01 Hz,
- tolerances of the fundamental component of output waveforms should not be above 0.1 %,
- the phase of the three voltage and three current sources must be independent and must be adjustable

between 0° and 359.9° with the minimum resolution of 0.1°,
- they must be able to generate output waveforms composed of higher harmonic components up to the 30^{th},
- they must generate the output voltage and current of the fundamental frequency with the Total Harmonic Distortion (*THD*) below 0.1 %.

The majority of these requirements can be fulfilled with precise reference generators that provide input signals to both (voltage and transconductance) power amplifiers. The exceptions are stable operation as well as low *THD* which are primarily subject of power amplifiers features.

2 Power amplifiers and distortion

The introduced amplifiers were developed for a portable calibrator with a nominal power of 60 VA per output. To minimize their weight and dimensions, they both rely on switch mode operation.

2.1 Voltage Power Amplifiers

Voltage power amplifiers should supply voltage branches of energy meters under test with an accurate voltage waveform in the range between 20 V and 320 V rms. Due to their relatively low output power, a straightforward topology comprised of a half-bridge PWM-controlled inverter with a passive output filter and an output transformer with three taps on its secondary is used [1]. To sufficiently reduce the high-frequency output voltage ripple, caused by transistor switching, and to flatten the frequency response, a second-order filter with an additional notch filter is implemented. The use of a passive output filter inherently causes stability problems of the superior control loop supervising the output voltage. This becomes particularly evident when supplying the load with a capacitive character. In order to maintain stability, a low open-loop gain is mandatory. On the other hand, the low open-loop gain leads to a considerable steady-state error between the reference and output waveform. Deviations in amplitude and phase are load-dependent as well. From the load point of view, their impact on the output voltage can be modeled through the use of equivalent output impedance of the amplifier. Likewise, but with more extensive effects, voltage deviations occur due to the pulsed load current drawn by a nonlinear load, which happen to be nearly all power supply units of modern electronic energy meters drawing power from voltage branches.

2.2 Transconductance Power Amplifier

Due to the extremely wide range of the output current (from 1 mA to 60 A rms) forced into current branches of devices under test, a novel hybrid power amplifier (HPA) was constructed [2]. It consists of a master three-stage class AB linear power amplifier (LPA) and a slave switch mode inverter connected in parallel through a coupling inductor.

Contrary to the voltage branches of the energy meter, the current branches introduce almost negligible load nonlinearity. In spite of that, a stability problem of the superior control loop supervising the output current occurs. Its cause is the inability to maintain the stability criterion in a wide range of output currents especially due to the extreme variations of the load impedance. Consequently, the open-loop gain must be reduced, causing the appearance of amplitude and phase deviations. However, they can be reduced by the superior control loop.

Similarly to the voltage amplifier, the current deviation in the amplitude and phase is load dependent. In both cases, the maximum amplitude error does not exceed 5 % while the phase shift between the reference signal u_{ref} and the output waveform stays within 2°. This imposes moderate demands upon the digital control loops that should be employed to control output quantities of amplifiers in order to comply with requirements specified for the high-quality output voltage and current.

3 Correction principle

In the past, repetitive control methods have seen extensive applications in instances where correction of a periodic waveform is required [3, 4]. In our case, we chose an integral repetitive control method since the output waveforms of both amplifiers as well as their disturbances are always periodic, even in the case of a nonlinear load supplied by the voltage amplifier [5, 6].

A simplified representation of the voltage or transconductance amplifier is shown in Fig. 1. The above mentioned periodic disturbances causing output voltage distortions are summarized in disturbance signal *d*. This representation is especially appropriate when analyzing the impact of periodic disturbances caused by structural nonlinearities inherent to almost all switched-mode power supplies. Thus the nonlinear distortion of the output voltage can be initiated with a nonlinear load as well as with structural nonlinearities, e.g. with dead time imposed …

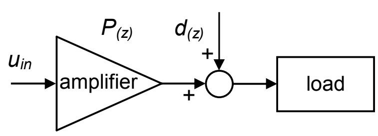

Figure 1: Voltage / transconductance amplifier

Regardless of different types of repetitive control mechanisms, they all rely on operation of a discrete number of period-based integrators. Fig. 2 shows a

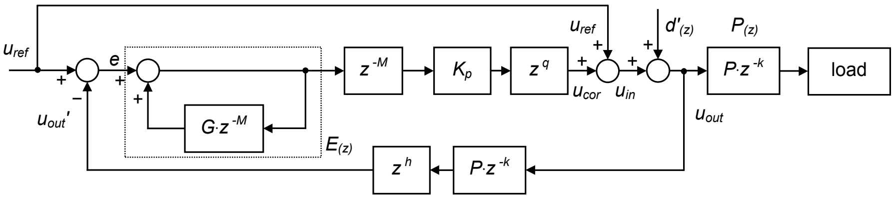

Figure 2: Block diagram of the repetitive controller system

variant of a plug-in repetitive controller [7]. It processes the tracking error e, which is (at least in the first correction period) the difference between the input reference waveform u_{ref} and the actual output waveform u_{out}. The controller periodic output waveform u_{cor} is added to the original reference waveform u_{ref} in a way that compensates the disturbance d.

The basic idea of the repetitive controller is that a period T of the reference (and sampled output) voltage is divided in N discrete intervals of duration τ (where $T = N\cdot\tau$). In each interval n, the acquired sample of the amplifier output voltage $u_{out(n,T)}$ is subtracted from the reference value $u_{ref(n)}$. The calculated error $e_{(n,T)}$ at the present discrete interval n in a particular period T is then stored in a table of correction values (which has N different positions) at the position corresponding to the discrete interval n [8]. The same procedure is applied to all intervals in a given period of the generated waveform. In the next period ($T+1$), the stored value of the error in a particular interval n is used to correct the original value of the reference waveform. The two values are summed up and the result is a new reference waveform $u_{in(n,T+1)} = u_{ref(n)} + u_{cor(n,T+1)}$. The stored values of the error $e_{(n,T)}$ are used to form a periodical correction voltage $u_{cor(n,T+1)}$, which is added to the reference one $u_{ref(n)}$, thus effectively reducing the error of the output waveform of the amplifier.

The output voltage $u_{out(n,T+1)}$ of the amplifier is again sampled and the new error $e_{(n,T+1)}$ in a specific interval is recalculated. It is then summed up with the error $e_{(n,T)}$ of the n-th interval from the previous period and (again) stored in the corresponding position in the table of correction values for subsequent use in the next period ($T+2$).

Owing to the repeating execution of the correction procedure, the table of correction values contains the sums of all past errors $e_{(n)}$ of a specific interval for each correction interval n independently. Consequently, the correction waveform $u_{cor(n,T)}$ behaves as if it were formed with the help of N correctors, each integrating the value of one correction interval n.

Because of practical limitations of the used analog-to-digital converters (ADCs), the implementation of the repetitive method differs from the described one. While the reference waveform u_{ref} is still formed of N discrete intervals, the output waveform is sampled at a lower rate thus involving only M discrete intervals (where $N = X\cdot M$). Each m-th interval is of equal duration as X n-th intervals (Fig. 2).

Since the calculation of the voltage error (and despite the reduction of sampled intervals) still occurs at every n-th interval, these X results should be averaged in order to recalculate the error e in the m-th interval of the output voltage u_{out}. Consequently, the correction waveform u_{cor} is composed of M different intervals, too. It should be noted that without averaging, the Nyquist theorem could be jeopardized.

The time delay unit z^{-M} delays the computed correction waveform for one entire period T (comprised of M samples) and the internal model K_p controls the amplitude of the correction waveform u_{cor}.

The key element of the repetitive action integral controller is the inner loop with the internal model $G\cdot z^{-M}$. Its closed loop transfer function is:

$$E_{(z)} = \frac{1}{1 - G\cdot z^{-M}}, \qquad (1)$$

where G can be a constant or a function of z, e.g. a low-pass filter [9]. In the time domain, this internal model is an integrator (if $G = 1$) summing up the error e of the m-th correction interval from the first to all successive periods.

4 Repetitive controller implementation

Because of practical reasons, some simplifications and additions were introduced into the block diagram of the proposed controller. Fig. 2 shows a block diagram where the function describing the amplifier $P_{(z)}$ is replaced by a simplified internal model with amplitude gain P and a time delay unit z^{-k} representing the output waveform phase shift of the amplifier. This simplification is valid since the frequency range we are interested in lies below the cutoff frequency of the output filter and as long as the sampling rate of the ADC is low enough. The amplifier gain P is partially neutralized by the K_p internal model in the direct path of the controller, which additionally controls the magnitude of the correction waveform u_{cor}. The time delay z^{-k} in the external feedback path is neutralized by the time advance unit z^{q}.

The controller has a natural tendency to suppress the sustained phase shift between the output waveform and the input waveform of the amplifier. Consequently, the amplitude of the correction signal in the steady-state condition is proportional to this phase shift. In order to prevent the excessive occupation of a correction DAC's voltage span with this kind of correction signal, an additional predictive unit z^{h} is incorporated in the external feedback path to neutralize the effect of the z^{-k} delay unit at the place of its origin.

5 Power calibrator description and controller evaluation

The experimental three-phase power calibrator with independent voltage and current control comprises three voltage amplifiers and three transconductance amplifiers (Fig. 3). Apart from that, it has three slave Digital Signal Processor (DSP) control modules supervised by a master DSP module.

Each slave DSP control module generates two reference and two correction waveforms, one for each voltage and transconductance amplifier. The module is composed of one DSP, two ADCs and three digital-to-analog converters (DACs). The DA converters generate input waveforms ($u_{u,ref}$, $u_{u,cor}$, $u_{i,ref} + u_{i,cor}$) for each corrector, while the AD converters capture instantaneous values of output currents and voltages from amplifiers. Two different methods for generating the correction input waveform u_{in} were tested. In the first method two DACs are used: one for the reference waveform u_{ref} and one for the correction waveform u_{cor} [6]. Both generated waveforms are externally summed up by an analog summator. The second method requires only one DAC since the reference and correction waveforms are summed up inside the DSP. The first method is more accurate than the second one and has a greater amplitude span.

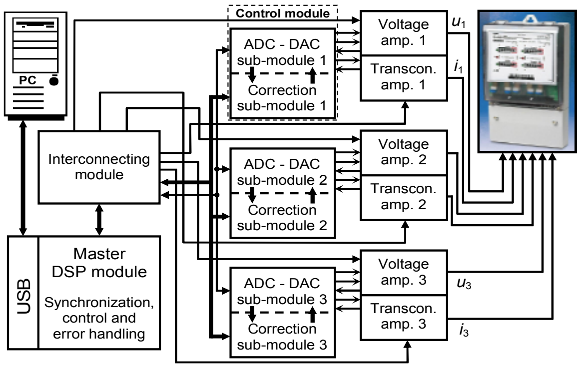

Figure 3: Block diagram of the three-phase power calibrator

The reference waveform u_{ref} of the implemented repetitive corrector is composed of 3600 discrete intervals (N) which simplifies the phase angle setting with a resolution of 0.1°. The output waveform is sampled by a 100 kSPS analog-to-digital converter. ADC with such a low conversion speed was chosen because of its other positive features (amplitude resolution, input voltage, data interface, price…).

One of the requirements for the three-phase calibrator was that it should be able to generate waveforms with superimposed harmonic components up to the 30th harmonic. At the fundamental frequency of 70 Hz, the frequency of the 30th harmonic is 2.1 kHz. To simplify implementation of the control algorithm, the ADC was set to a constant sampling rate of 720 samples per period (SPP).

The number of the acquired samples of the output waveform u_{out}, differs from the number of correction intervals (M) per period. The latter number was chosen empirically on the basis of its influence on the output waveform *THD* and on the overall system stability. The preferred number of these intervals is 144 SPP, which is relatively low compared to the conversion speed of the ADC.

One discrete correction interval m is consequently made up of five ADC samples ($720 / 144 = 5$) or 25 (n) DAC samples ($3600 / 144 = 25$). These five ADC samples are averaged and the computed average value is used instead of their original values in the subsequent calculation of error e in the m-th interval in order to reduce the influence of the sampled noise on the calculated error.

This way of operation allows for an efficient correction of higher harmonic components up to (theoretically) the frequency of 3.6 kHz, both in the voltage as well as in the current amplifier.

6 Experimental results

Our measurements were made on an experimental model of the described three-phase power calibrator. The numerical values of output quantities were measured with an (universal) energy meter etalon TEZ 200.3 ($r = 0.02$) by EMH, while the frequency domain analyses were made by means of a dynamic signal analyzer HP35665A. For the *THD* calculation the harmonic components up to the 64th were observed.

Our initial tests were made on the power calibrator with no load or with only linear loads. Correction of the output waveform was disabled. Under such conditions we observed that *THD* of the generated reference waveform was about 0.01 %. *THD* of output waveform of an unloaded voltage amplifier was about 0.65 %.

In the next stage, measurements with nonlinear loads and with no correction were made. Fig. 4 shows the output voltage waveform deformation for different load currents. The two upper waveforms in Fig. 4 (u_{cor1}, i_{out1}) show output voltage waveform deformation being the result of current flowing into three voltage branches of a single electronic energy meter MT351 (manufactured by Iskra Emeco) while the two lower waveforms (u_{cor2}, i_{out2}) show the same two quantities for four voltage branches of four three-phase energy meters MT300 (with a different power supply topology than the MT351) connected in parallel. For comparison, the *THD* of a public power network voltage waveform is some 4 %.

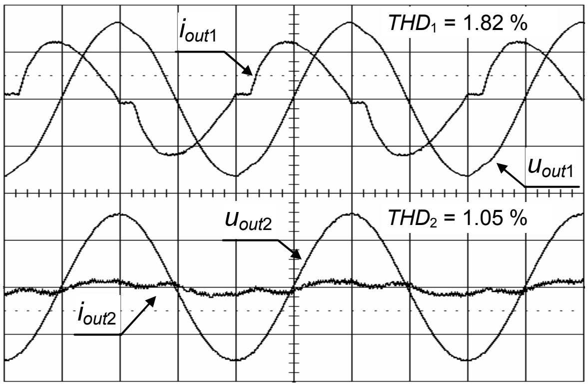

Figure 4: Output voltage and current of an uncorrected voltage amplifier in case of nonlinear loads (k_t = 2 ms/div, k_u = 200 V/div, k_i = 0.2 mA/div)

Fig. 5 shows conditions after the corrector was activated. The loads were the same as in Fig. 4. Besides the previous waveforms, the figure shows also the correction waveforms u_{cor} needed to achieve the low-distorted output voltage waveform.

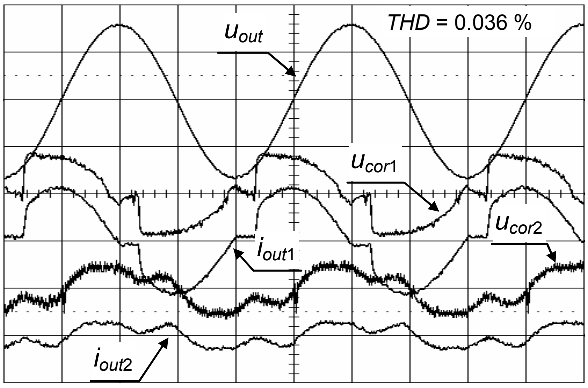

Figure 5: Output voltage and current of a corrected voltage amplifier in case of nonlinear loads (kt = 2 ms/div, kuout = 200 V/div, kucor = 0.5 V/div, ki = 0.2 mA/div)

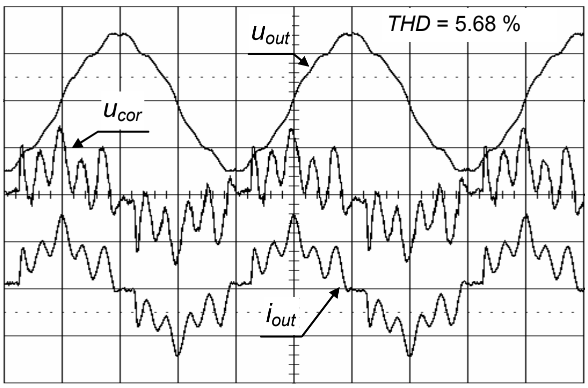

Figure 6: Output voltage, correction waveform and current of a corrected voltage amplifier with nonlinear load and superimposed higher harmonics (5 % of the 5th and 3 % of the 11th harmonic) (kt = 2 ms/div, kuout = 200 V/div, kucor = 0.5 V/div, ki = 0.2 mA/div)

Further experiments were carried out on output voltages of non-sinusoidal waveforms. Fig. 6 shows the output voltage with the superimposed 5th harmonic (5 %) and the 11th harmonic (3 % of the fundamental harmonic component). The second waveform is the correction waveform and the third is the current drawn by the nonlinear load, i.e. parallel voltage branches of four energy meters (MT351).

All the output voltage waveforms were analyzed in the frequency domain and their relative frequency spectra are shown in Figs. 7 and 8. The majority of the undesired higher harmonic components are approximately 80 dB below the fundamental component and in overall they do not contribute much to the *THD*.

As clearly seen from both frequency spectra (Figs. 7 and 8), the corrector response declines after the frequency of 3.2 kHz.

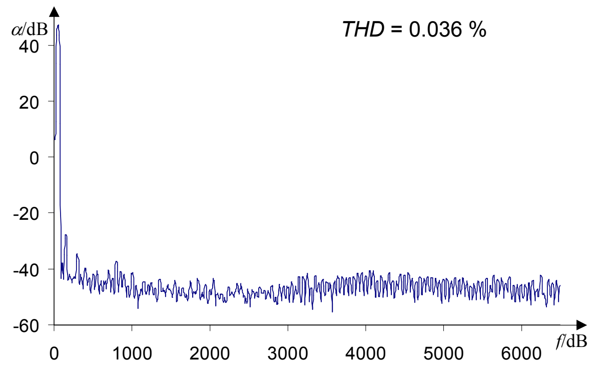

Figure 7: Frequency spectrum and calculated *THD* of the sinusoidal output voltage shown in Fig. 5

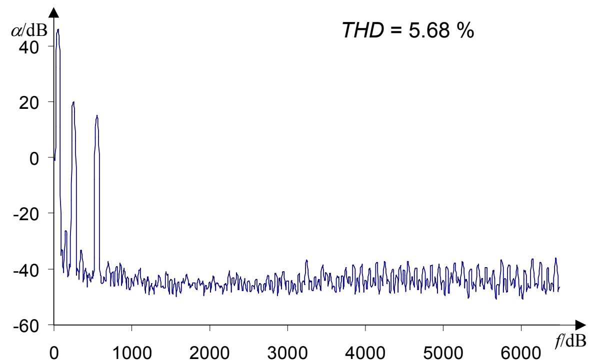

Figure 8: Frequency spectrum and calculated *THD* of the output voltage shown in Fig. 6

7 Conclusion

In this paper we described a three-phase power calibration source that uses a modified repetitive action control method. The calibrator is designed to supply up to five energy meters in a phantom load test arrangement. It generates independent sinusoidal and non-sinusoidal voltage waveforms with amplitudes between 20 V and 320 V rms (split into three sub-ranges) and current waveforms from 1 mA to 60 A rms (split into five sub-ranges).

The corrector which is based on the repetitive action correction principle performs well up to 3.2 kHz or until the 72nd higher harmonic component, whereupon the frequency response declines, as expected. The same conclusion can also be drawn from the figures showing the spectrum components of output waveforms (Figs. 7 and 8). In all our experiments, *THD* of the corrected output waveform is very low (*THD* = 0.036 %), stable and meets the given requirements for energy meter calibration, with the use of 12-bit DACs and only 144 correction intervals per period. The amplitude stability of the output waveform is also good and mainly depends on temperature variations of ADCs and voltage reference sources.

The measured results show that all the design parameters are being met with. The repetitive action control method with integral action is fast enough, easy to implement in a DSP microprocessor and reliable for the use in the presented task. It actually proved to be a very suitable solution for this kind of applications.

8 References

[1] P. Zajec, J. Nastran, Elektronski vir za umerjanje števcev električne energije, Elektrotehniški vestnik, Vol. 68, No. 1, pp. 45 – 50, 2001.

[2] H. Lavric, D. Voncina, P. Zajec, F. Pavlovcic, J. Nastran, A precision hybrid amplifier for voltage calibration systems, *Informacije MIDEM*, Vol. 34, No. 1, pp. 37 – 42, 2004.

[3] T. Yokoyama, A. Kawamura, Disturbance Observer Based Fully Digital Controlled PWM Inverter for CVCF Operation, *IEEE Transactions on Power Electronics*, Vol. 9, No. 5, pp. 473 – 480, Sep. 1994.

[4] C. G. Anwar, M. Tomizuka, Plug in Repetitive Control for Industrial Robotic Manipulators, *Proceedings of the IEEE International Conference on Robotics and Automation*, Vol. 3, pp. 1970 – 1975, May 1990.

[5] A. Gubisch, P. L. Lualdi Jr., P. N. Miljanic, J. L. West, Power Calibrator Using Sampled Feedback for Current and Voltage, *IEEE Transactions on Instrumentation and Measurement*, Vol. 46, No. 2, pp. 403 – 407, Apr. 1997.

[6] C. Rech, H. Pinheiro, H. A. Gründling, H. L. Hey, J. R. Pinheiro, Comparison of Digital Control Techniques With Repetitive Integral Action for Low Cost PWM Inverters, *IEEE Transactions on Power Electronics*, Vol. 18, No. 1, pp. 401 – 410, Jan. 2003.

[7] N. M. Oldham, O. B. Laug, B. C. Waltrip, Digitally Synthesized Power Calibration Source, *IEEE Transactions on Instrumentation and Measurement*, Vol. IM-36, No. 1, pp. 341 – 346, June 1987.

[8] K. Zhang, Y. Kang, J. Chen, Direct Repetitive Control of SPWM Inverter for UPS Purpose, *IEEE Transactions on Power Electronics*, Vol. 18, No. 3, pp. 784 – 792, May 2003.

[9] Y. Ito, S. Kawauchi, Microprocessor Based Robust Digital Control for UPS with Three-Phase PWM Inverter, *IEEE Transactions on Power Electronics*, Vol. 10, No. 2, pp. 196 – 204, Mar. 1995.

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