Simulation of Power Converter with Repetitive Control System for Higher Harmonics Elimination

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***Abstract*—This article deals with the simulation of the power converter with voltage-source inverter and sine-filter. The repetitive control system was designed. The existing power converter has a control system which makes Fourier transform of the output voltage to inject these harmonics with opposite phase. The new proposed system based on repetitive controller which is much simpler and with smaller CPU load. The higher harmonics elimination works perfect and the power converter produces output voltage with less than 5% THD under linear or non-linear load. This paper describes the improved control system structure and its implementation in MATLAB Simulink environment. The advantages of the repetitive algorithm facing Fourier transform harmonic compensation are shown. The performance of the new control method is shown in simulation results. The algorithm is carried out in C language using MATLAB S-Function block so it is suitable for implementation in the real-time control systems.**

Keywords—AC-AC converters, Adaptive control, Digital control, Harmonic distortion, Power filters, Pulse width modulation, Total harmonic distortion

I. Introduction

High level of modern power electronics and microcontrollers enables the development of new power conversion and distribution devices with previously unreachable parameters and their implementation in the areas that were previously considered untypical for semiconductor power converters. Aircraft AC power generation systems can be an example of such areas. Electric power supply systems of most modern aircrafts (such as Airbus A310, A330, A340, Boeing 747-100, Il-96-300, Tu-204 and etc.) contains a synchronous generator driven by a constant speed drive (CSD). CSD in this system acts as the regulator for generator speed and as a result for the onboard network voltage frequency. CSD has some fundamental disadvantages, so VSCF system ("Variable Speed — Constant Frequency") is one of the most promising solutions of aircraft electrical systems evolution. In addition, power quality improvement, achievable in VSCF system will allow us in perspective to improve the weight and size and power consumption of onboard equipment [1].

The earlier paper [2] is dedicated to the simulation of a special frequency converter for VSCF systems. It also shows the necessity of the output voltage harmonic content correction. The control system proposed there uses a discrete Fourier transform for compensation of harmonic distortion. Measurements are made for the period of the output voltage. Magnitudes of fundamental and sine and cosine components of the most significant higher harmonics (from 3^{rd} to 9^{th}) are calculated at the end of the period using measurement results. Each magnitude is a feedback for its own integral controller. The reference for the fundamental harmonic regulator is the rated peak phase to neutral voltage, while the higher harmonics references are zero. Outputs of the controllers, multiplied by the referenced harmonics curves, are summed to form the inverter voltage reference. Thus, maintaining of the rated value of the fundamental and zero values of higher harmonics is carried out by means of their separate regulation by the vector of integral controllers. The circuitry of a single-phase converter channel is shown in Fig. 1, and the control system structure is shown in Fig. 2.

Method, which is described in [2], gives a positive result, but requires quite high computing performance from the microcontroller. Using one of the most advanced MCU of Motor Control family from Texas Instruments it made possible to implement that method only after deep software optimization up to the use of assembly language programming.

An analysis of the papers in the field of repetitive control shown that it is possible implement a repetitive control system with much lower requirements for the computation power of the target microcontroller [3][6][7][8].

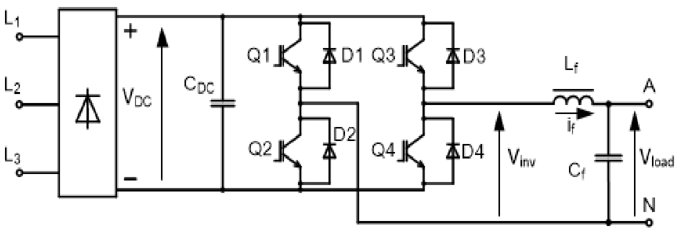

Fig. 1. Power converter configuration (single-phase)

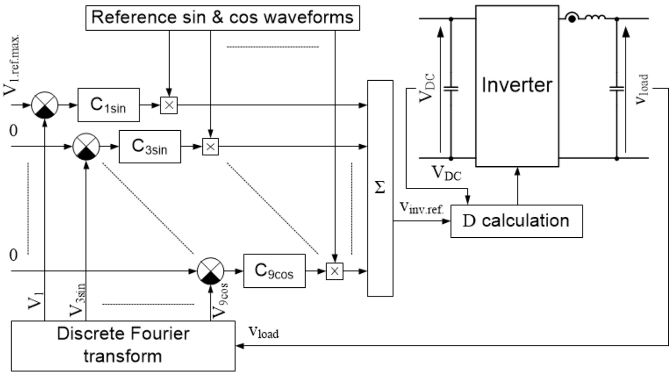

Fig. 2. Control system with the output voltage waveform correction using discrete Fourier transform

II. THE NEW CONTROL SYSTEM ALGORITHM

The idea of the repetitive control method is similar to the proposed previously [2]: reference voltage for the next cycle (k+1) is corrected by measurements in the previous cycle (k). The difference is in the method of the collected in the previous cycle data analysis and usage. In the new control system the measurements are compared with the reference directly for each "point" (for each of i=64 PWM cycles) on the fundamental frequency cycle of the output voltage. If the desirable output voltage value at the i^{th} point of the current cycle is greater than the actual one, it is necessary to raise the reference for the inverter at this (i^{th}) point of the next period and vice versa. Such a regulator is called a periodic integrator in [3]. There only problem happens due to the transport delay between the application of the control and the response in the controlled variable. In this particular case this transport delay depends on PWM frequency and time constant of the sine-filter. Thus, the reference applied to the inverter in the i^{th} point will affect the output voltage only in the i+n^{th} point, where n depends on the inverter PWM cycle duration, sine filter inductance and capacitance.

This problem is solved by phase-lead correction [4]: if the desired output voltage value at the i^{th} point of the current period was greater than the actual voltage, then it is necessary to increase the reference for the inverter in $(i–n)^{th}$ point for the next cycle of the fundamental frequency. System operation with phase-lead correction (n=2) is shown in Fig. 2. A control system diagram is shown in Fig. 5.

The principle of operation of the control system is quite simple. The output voltage at the i^{th} point of the current k^{th} cycle is subtracted from a reference of the i^{th} point and is fed to the input of the $i–n^{th}$ periodic integrator (n – anticipation given in PWM cycles). The output of the periodic integrator becomes the inverter voltage reference in the next k^{th} cycle at the point $i–n$. If i is less than n, i.e. it is the beginning of the current period, the reference will be applied at the end of the current k^{th} period at the point 64+$i–n$.

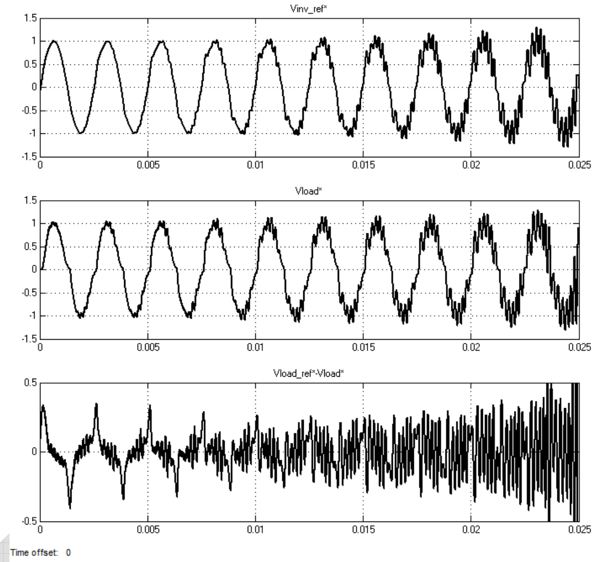

Fig. 3. Unstable operation of the repetitive control system. Inverter voltage reference, p.u.; measured output voltage, p.u.; output voltage error, p.u.

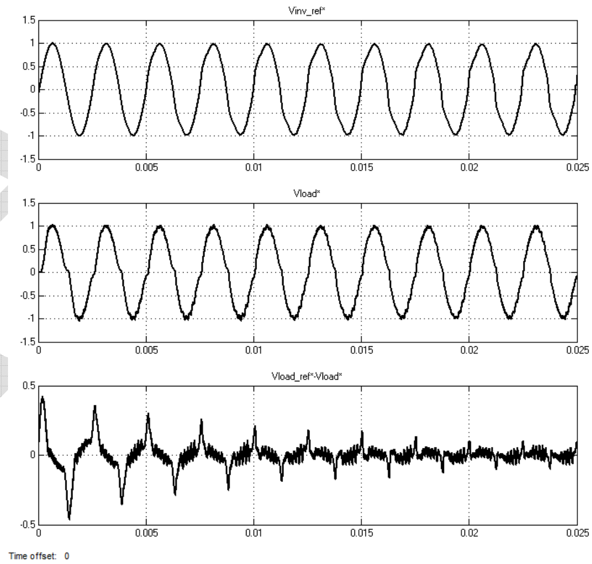

Fig. 4. Stable operation of the repetitive control system with phase-lead correction. Inverter voltage reference, p.u.; measured output voltage, p.u.; output voltage error, p.u.

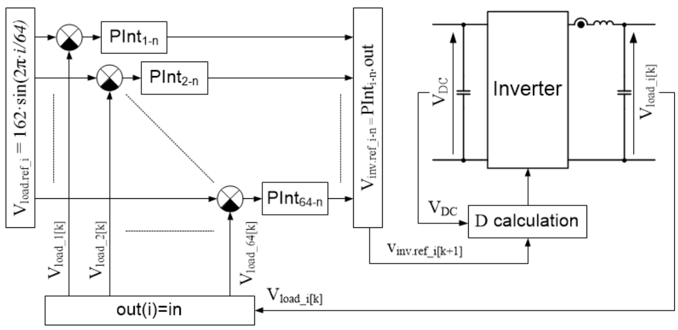

Fig. 5. Repetitive control system diagram

III. Model of Power Converter and Control System

The model of the power converter consists of a three-phase AC voltage source, a three-phase rectifier, DC link, a single-phase full-bridge inverter and a PWM generator (see the Fig. 6). The PWM generator with dead-time module is shown in Fig. 7. The model of the sine filter and load includes the filter itself, current and voltage sensors and diode bridge rectifier with its own LC-filter and a resistive load — Fig. 8.

The control system model consists of a sinusoidal output voltage reference block, a measured voltage block and S-function implementing array of periodic integrators for calculating the inverter voltage reference (see Fig. 9).

The core of control algorithm implemented in the S-function is shown in Listing 1. Regulator multiplier PIntKi and anticipation PIntAdv are configured under the S-function block mask.

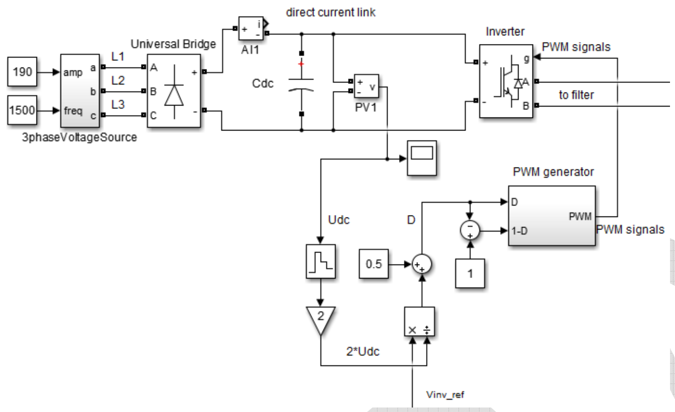

Fig. 6. Inverter model

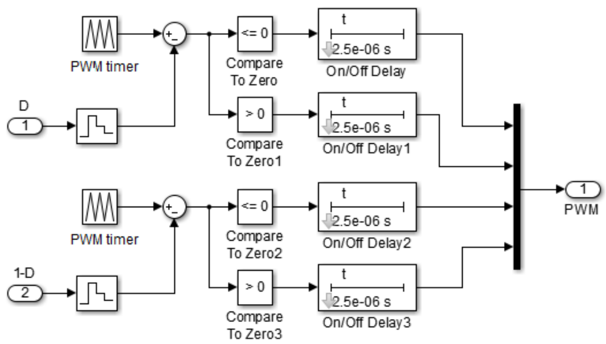

Fig. 7. PWM generator

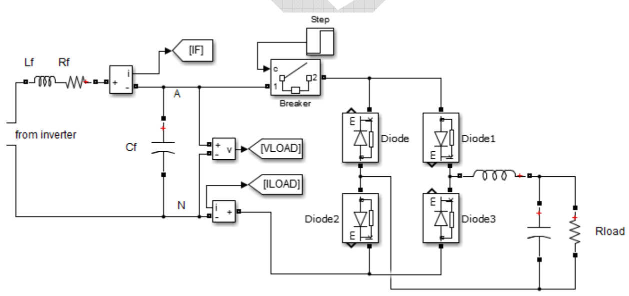

Fig. 8. Sine filter and non-linear load model

LISTING 1. CONTROL SYSTEM CORE

```
CurrDelta = *RealInpPtr[0]; // get Delta =
                            // = Vload_ref - Vload
CurrPoint++;      //proceed to the next point
CurrPoint &= 63; //if i==64, then i=0
//calculate point for inverter voltage reference:
PrevPoint = CurrPoint-PIntAdv; //point for
// control with advance (PIntAdv = 2 Tpwm)
PrevPoint &= 63;
PInt[PrevPoint] = PInt[PrevPoint] +
CurrDelta*PIntKi;//P-Integrator calculation
```

The calculation of the control system core is performed each PWM cycle. Maximum of 5859 CPU cycles for the calculation of the control strategy is given for a microcontroller with a clocking frequency of 150 MHz and a PWM frequency of 25.6 kHz (64×400 Hz). Calculation of periodic integrators contains no slow mathematical operations and does not exceed several tens of CPU cycles. This is much less than the various service functions such as analog channels processing, fault protection and other functions. Furthermore, this algorithm, unlike the previous one, does not require any calculations at an ADC sampling frequency which is 4 times higher than PWM frequency and, therefore, there is four times less CPU cycles available (1464 cycles).

IV. Testing of Control System Performance

The quality of the control system is rated under load, and its performance is compare with the previous solution. To do this, experiments of throwing on a linear (RL) and a nonlinear (rectifier) load are carried out. Two parameters are the most interesting for us: THD and the magnitude of the first harmonic of the output voltage. The output voltage and the load current are displayed to illustrate it.

As can be seen from Fig. 10 – Fig. 13, the quality of the new simplified control system is not inferior to the system with a discrete Fourier transform. The harmonic content correction accuracy of the new system is even higher, because it compensates all possible sources of distortion, not limited to a specific number of higher harmonics. All achieved parameters meet the standards requirements [5].

Fig. 14 and Fig. 15 allows us to estimate visually the output voltage waveform under non-linear load.

It is noticeable that the small high-frequency distortions not compensated by the old system are successfully suppressed by the new one.

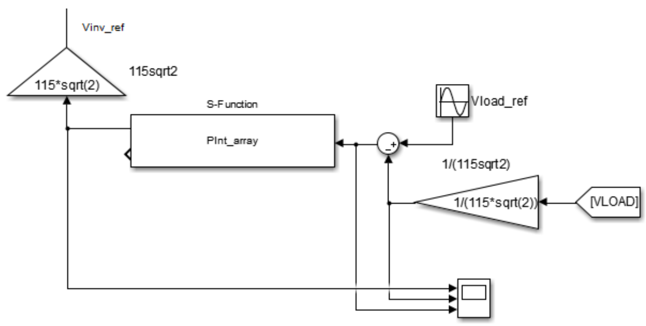

Fig. 9. Control system model

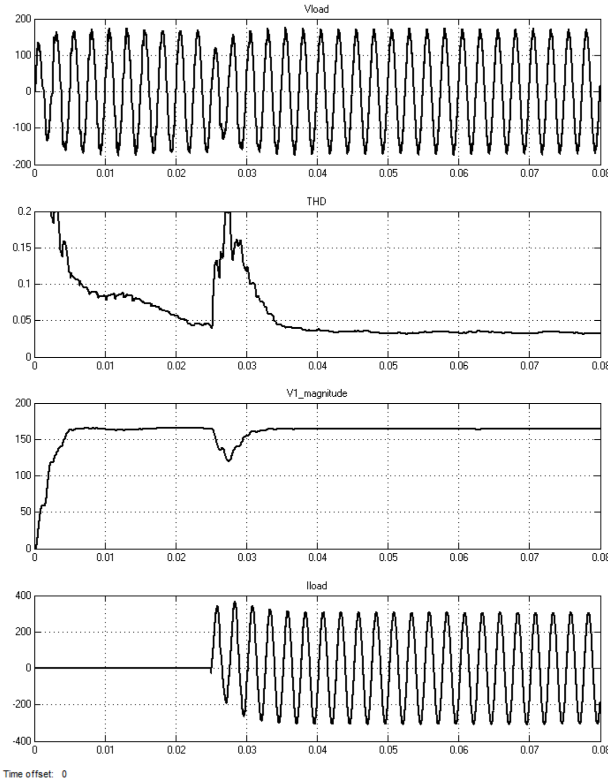

Fig. 10. Step load changing. RL-load. Previous control system

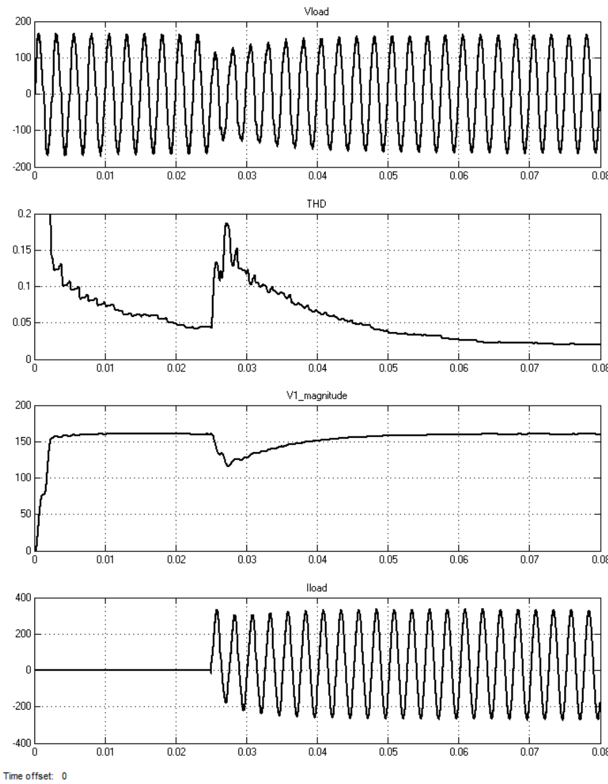

Fig. 11. Step load changing. RL-load. New repetitive control system

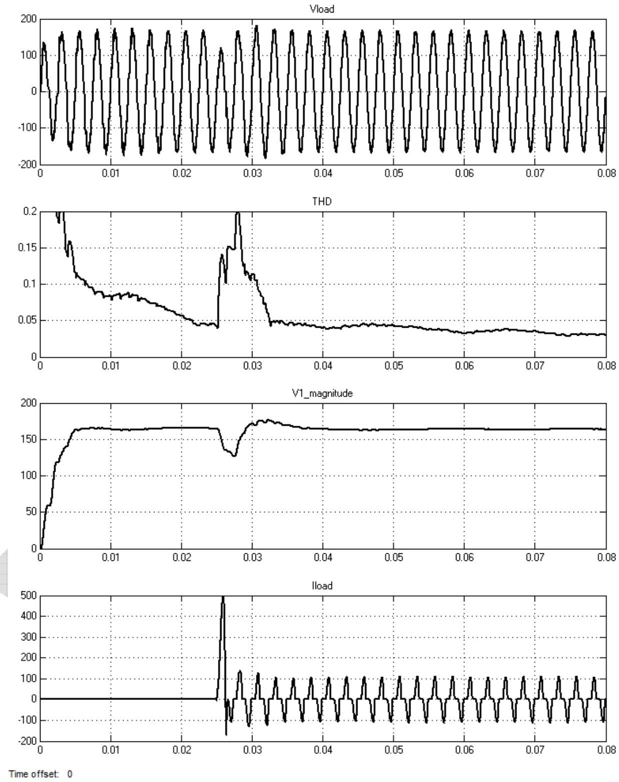

Fig. 12. Step load changing. Rectifier load, 25% of rated power. Previous control system

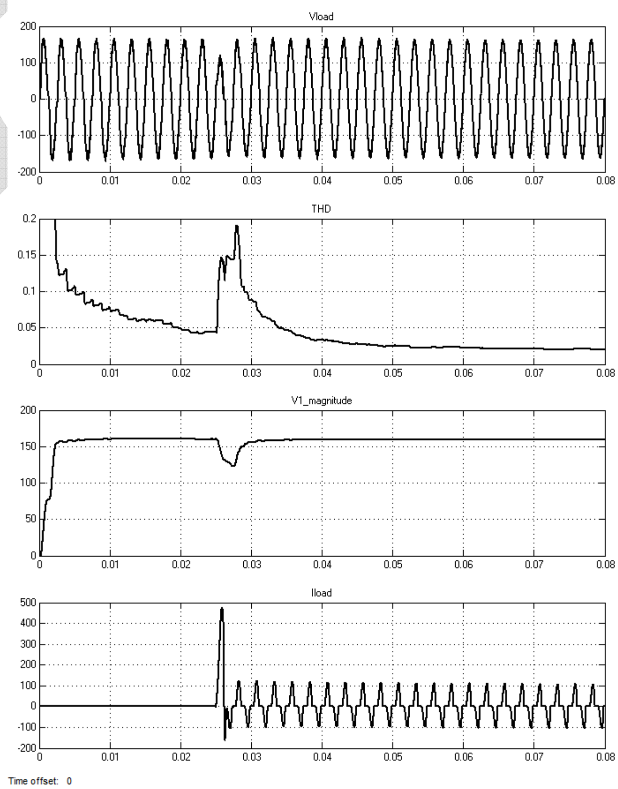

Fig. 13. Step load changing. Rectifier load, 25% of rated power. New repetitive control system

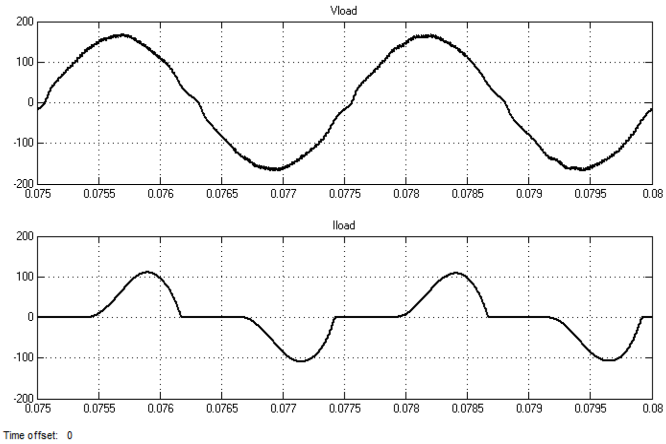

Fig. 14. Output voltage and load current waveform. Rectifier load, 25% of rated power. Previous control system

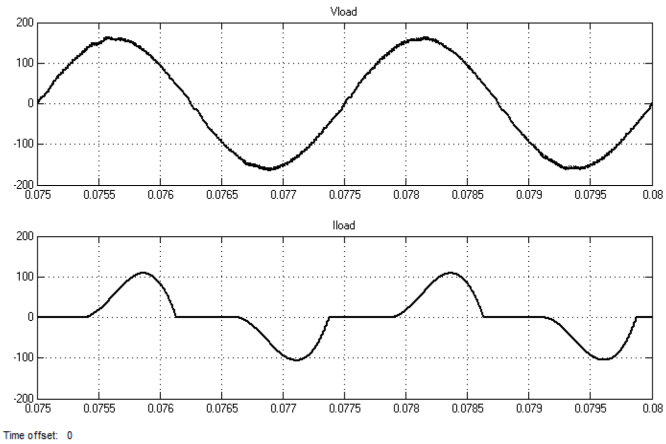

Fig. 15. Output voltage and load current waveform. Rectifier load, 25% of rated power. New repetitive control system

V. CONCLUSIONS

As a conclusion a simple idea can be noticed: sophisticated solution is not always more effective than the simpler one. In this case, a simplified control system performs its functions as good as its more complex precursor, demanding for that much less microcontroller processing resources and programmer labor costs.

New algorithmic solution can be implemented on the same hardware as the previous one, only some software modification is needed.

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