Pole-Restraining Control of Active Front End for Shore-Side Power Supply of Ships

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***Abstract*—Shore-side power supply by power-electronics systems for merchant ships as well as for cruise ships is a new issue in electric-ship technologies. Fault scenarios on-ship and within the harbour grid and the variability of the parameters of on-ship distribution require fast and robust control.**

Pole-restraining control is a novel control approach, taking the time-variant characteristics of power electronics fully into account. In consequence, the full physically available control capability can be used.

This paper gives a short introduction of the pole-restraining control approach. A comparison to other state-of-the-art control schemes illustrates the improvements.

I. Introduction

During their lay days, merchant ships and cruise ships need a considerable amount of electrical energy. Conventionally, this energy is produced by diesel-powered generators – causing emission of particulate matter, nitrogen oxides and carbon dioxide. A direct connection of the ship to the harbour energy distribution grid is not possible because voltage and/or frequency may not match. Rotating converters are also hard to use due to the various configurations and requirements of the on-board ship grid grids.

Since some years, static converters – based on power electronics – provide shore-side power [1]. With decreasing cost and increasing ecological constraints, this option becomes more and more interesting from an economical perspective – for the harbour operator as well as for the ship owner. An additional advantage is given by the bidirectional energy-flow capability of modern power-electronic converters: Final tests of the on-ship power systems, including full-load tests of the on-board generators, can be realized by feeding energy from the ship into the harbour grid doing away with bulky ballast resistor loads. Under quasi-steady-state conditions, the technology for all this is readily available – under dynamic conditions, improvements are possible by applying improved control schemes.

Shore-side power supply systems have to meet several challenges:

- fault scenarios on-ship
- fault scenarios within the harbour grid
- power quality on ship and harbour side
- sudden load changes
- high variability of the parameters of on-ship distribution
- resonances including ship-side and harbour-side filters

Meeting these challenges optimally requires fast and robust control schemes.

State-of-the-art control approaches [2]–[10] often neglect the time-variant characteristics of power-electronic systems in favour of a time-averaged approach. In consequence, the system is partly instable, thus not optimally controlled [11].

Pole-restraining control (PRC) eliminates instabilities inherent to power-electronic systems [11], improving the dynamic behaviour and robustness. Also, mitigation of undesirable harmonics is simplified, giving excellent power quality on ship and harbour side.

This paper analyses the impact of feed-back control on system stability and gives the essentials of PRC. Subsequently, PRC is applied to a three-phase AFE. Simulation results illustrate the differences in the dynamic performance of state-of-the-art control schemes as state feed-back and virtual-flux approach [4], [6]–[10], [12] in comparison to PRC.

II. Power electronics systems: Stability issues

Eigenvalues can be used to assess the stability of power-electronic systems. In feed-forward controlled operation, the eigenvalues show that a power-electronic system is critically stable, with stability not depending upon the actual conversion ratio $\rho_{Tp}(t)$ (in this case, the ratio of converter-output voltage and DC-link capacitor voltage). However, almost every power-electronic device is feed-back controlled. Thus, the impact of feed-back to the system stability is analysed for a state feed-back [13].

The multivariable control is designed as a state feed-back. From this point onward, only the system matrix $\mathbf{A}$ and the control matrix $\mathbf{B}$ as well as the feed-back matrix $\mathbf{K}$ are relevant. Thus, the new system matrix $\mathbf{A}_r$ of the closed-loop system can be calculated.

The conversion ratio resulting in the converter voltage is the only input signal which can be influenced by the controller. The places of the eigenvalues depend – beside upon the parameters of the plant – upon the actual conversion ratio. In order to visualize this effect, a LQ-optimised multivariable-

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control design [14] has been applied leading to a suitable control vector **K** [11].

The eigenvalues $\lambda_i(\rho_{Tp})$ plotted for $\rho_{Tp}(t) \in [-1, 1]$ are partly instable (cp. Fig. 1). This is not due to wrongly chosen feed-back parameters, but inherent in the system using common control approaches which require all system matrix elements to be constant.

Accordingly, the system is only partly instable, and it can be operated as it is typical for state-of-the-art industrial applications [2], [15]. Yet it goes without saying that a control-design method which eliminates this instability will achieve notable improvements in system stability and dynamics compared to traditional approaches.

III. Novel pole-restraining control

The novel control approach directly includes the variable conversion ratio, solving the problem stated above: The restraining of the eigenvalue movement is the maxim of the pole-restraining approach. Different concepts have been derived for observer [Patent pending PRO] and control [Patent pending PRC] design. The major aim of the control design is the stabilization of eigenvalue variations by counteracting time-variant and non-linear system characteristics [11].

The novel approach can be illustrated using pole-zero maps. With regard to common control design for the averaged system matrix, large eigenvalue variations result, even leading to instable eigenvalues, though the design promises a stable control. Applying the PRC approach guarantees solely stable eigenvalues in the left complex half-plane. In this way stability for each conversion ratio $\rho_{Tp}(t)$ is achieved (cp. Fig. 2).

IV. Simulation results

All simulations are performed using a control cyle time of $125\,\mu$s and a converter switching frequency of $1000\,$Hz. The converter feeds a DC-link capacitor ($C = 4\,$mF) with a parasitic parallel resistance ($R_p = 10\,$kΩ) from an ideal three-phase grid with line-to-line rms voltage of $U_g = 400\,$V via a leakage inductance of $L = 1\,$mH and a serial resistance of $R_s = 1\,$mΩ.

First, the AFE controlled by a basic state feed-back (voltage control-approach) leading to unsatisfactory dynamic behaviour (cp. Fig. 3). Besides very low stability being weakly damped, leading to a significant DC-link voltage ripple, a huge voltage dip of the DC-link voltage can be observed in case of the load step at $t = 310\,$ms. A minimal voltage value of 380 V is reached. The transient response takes more than $250\,$ms.

Secondly, the pole-restraining approach is applied without changing any control parameters leading to a stabilized behaviour (cp. Fig. 4). Here, the DC-link voltage shows a much smoother behaviour. The grid currents reach steady-state within $80\,$ms, the DC-link voltage still takes much longer to reach steady-state.

The performance can be improved by the virtual-flux concept (cp. Fig. 5), but the pole-restraining approach with optimised feed-back parameters offers the best dynamic performance (cp. Fig. 6). It is obvious that the DC-link voltage

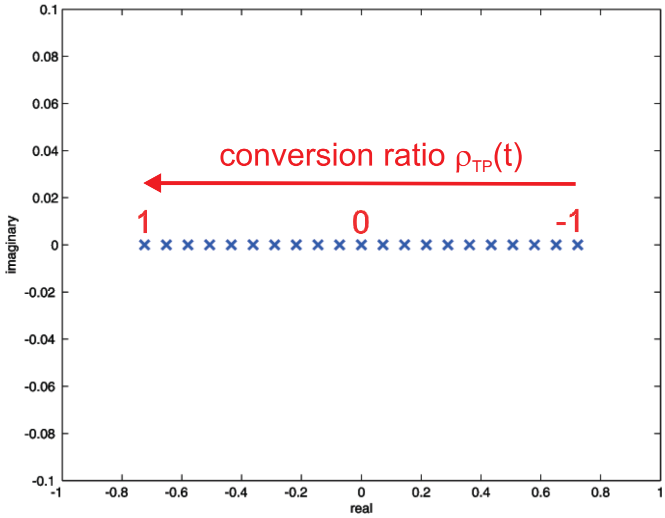

Fig. 1. State feed-back control by constant time-averaging without PRC: pole-zero map

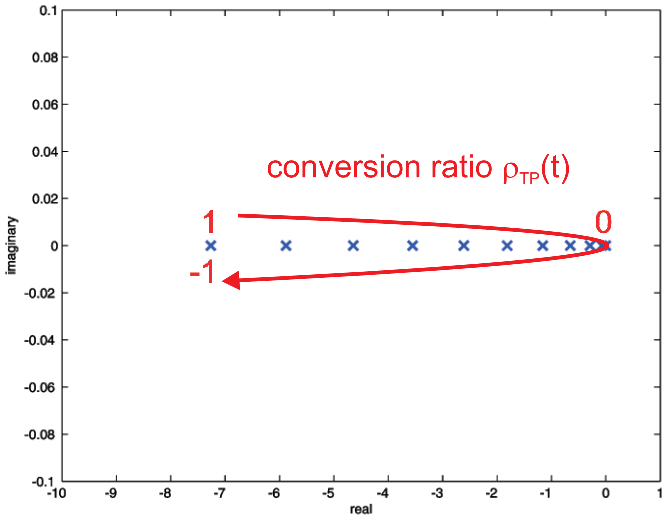

Fig. 2. State feed-back control with PRC: pole-zero map

sag in case of the loadstep is reduced significantly. In both cases values below $50\,$V are reached.

The differences can be observed more clearly in a zoom perspective (cp. Fig. 7 and 8). Here, it can be observed that the PRC control is able to halve the transient response time.

V. Conclusion

An advanced control scheme for the power electronics converters of a shore-side power supply system for merchant or cruise ships is presented – the pole-restraining control approach. The maxim of the pole-restraining control (PRC) is the restraining of the eigenvalue movement, avoiding inherent system instability and leading to outstanding improvements. This is a major difference compared to state-of-the-art control schemes. Thus, more potential is at hand for enhancing robustness. Furthermore, the transient behaviour of basic state feed-back, virtual-flux approach and pole-restraining control are compared, proving significant advantages resulting from PRC. The realized improvement is illustrated using simulation scenarios.

With the presented control excellent reaction to dynamics, for examples fault conditions on-ship or in the harbor grid or sudden load changes, are reached. Undesirable harmonics can explicitly be mitigated, ensuring power quality on-ship and to the harbour grid. This is important for AFE control because grid parameters depend on the actual grid configuration and vary considerably during normal operation and even more under fault conditions.

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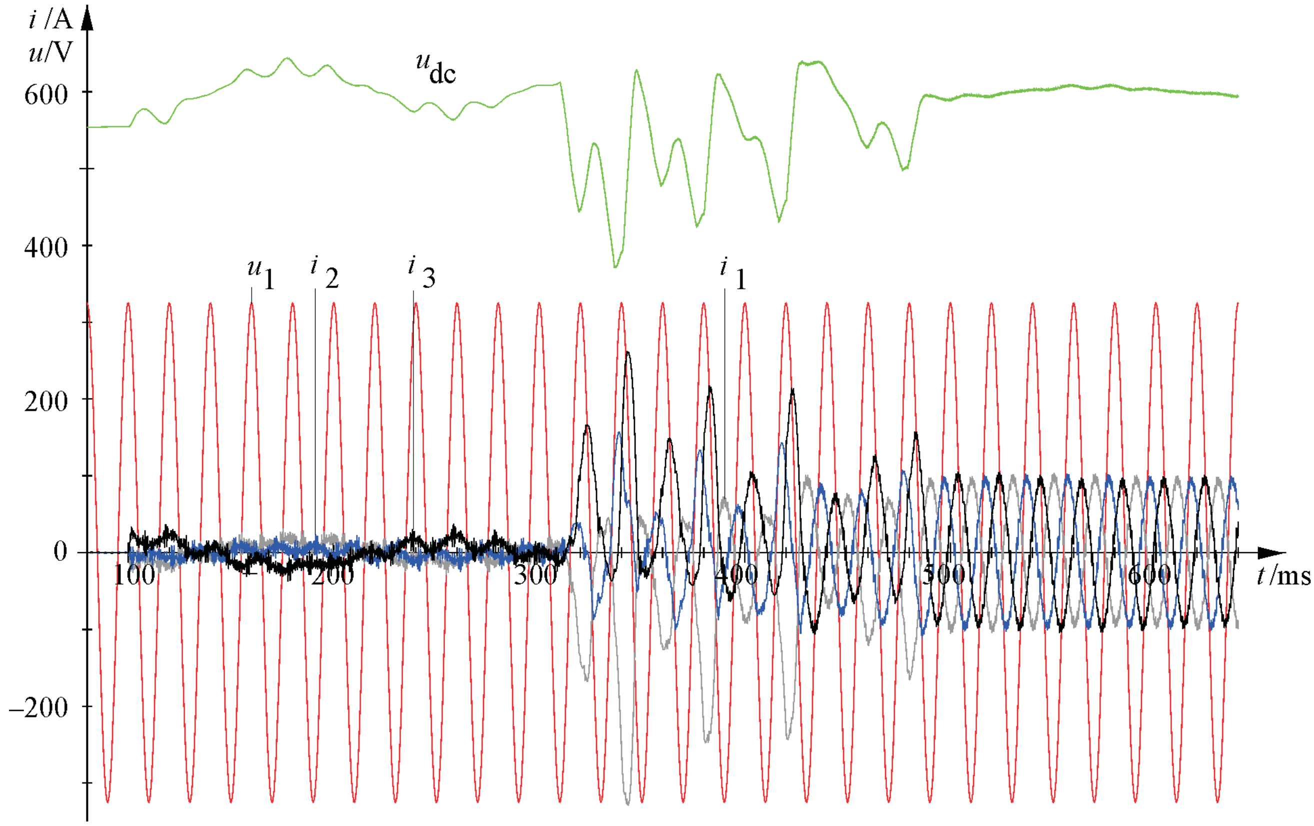

Fig. 3. Voltage-approach state feed-back control without PRC

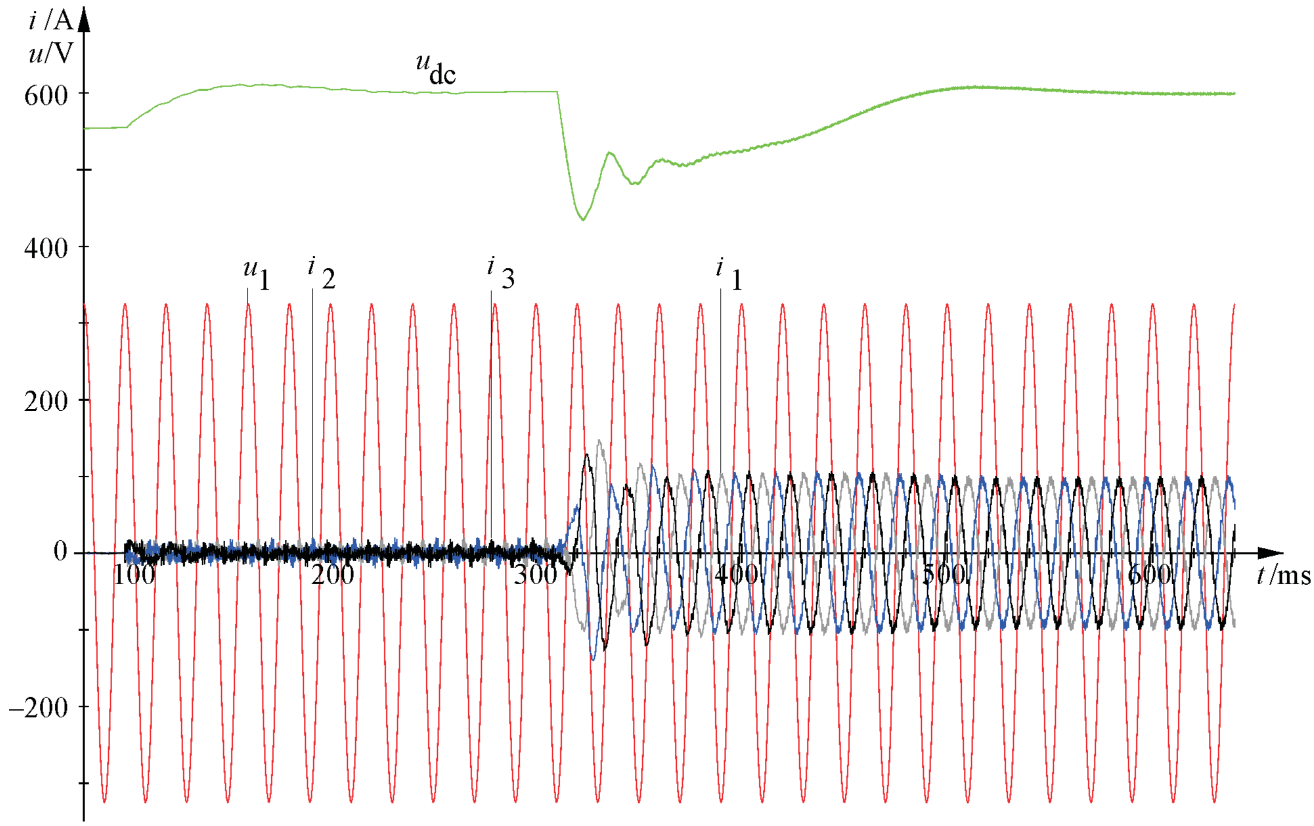

Fig. 4. Voltage-approach state feed-back control with PRC (feed-back parameters the same as in fig. 3)

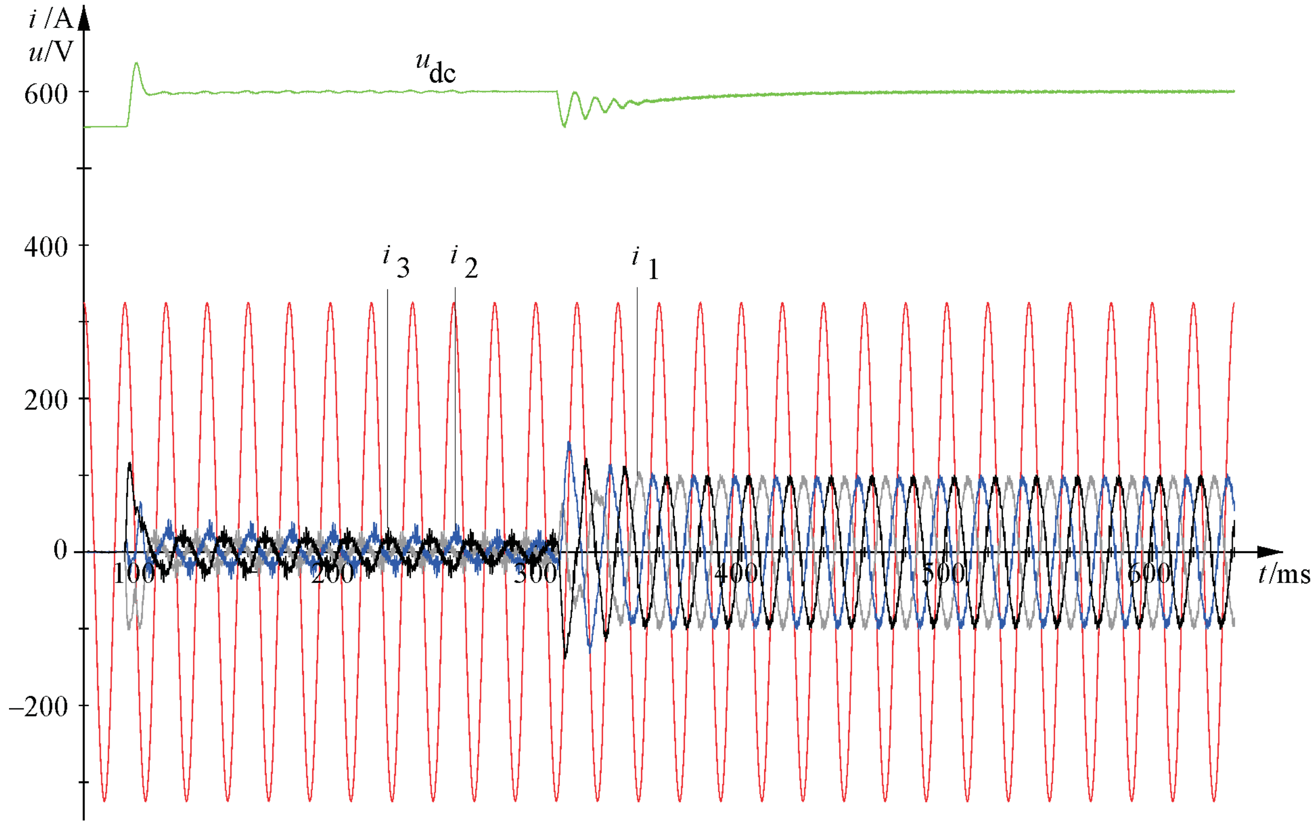

Fig. 5. Virtual-flux approach – overview

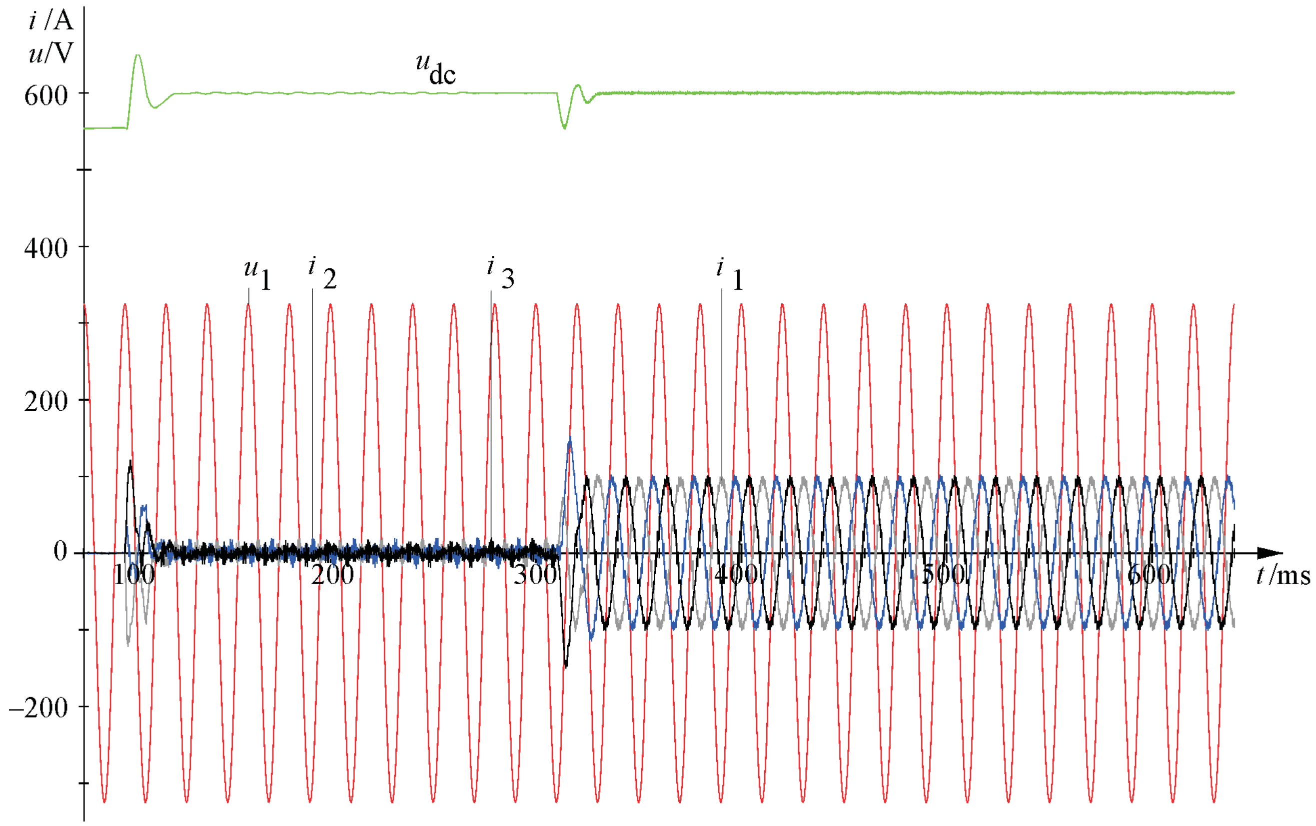

Fig. 6. Voltage-approach state feed-back control with PRC – optimised parameters, overview

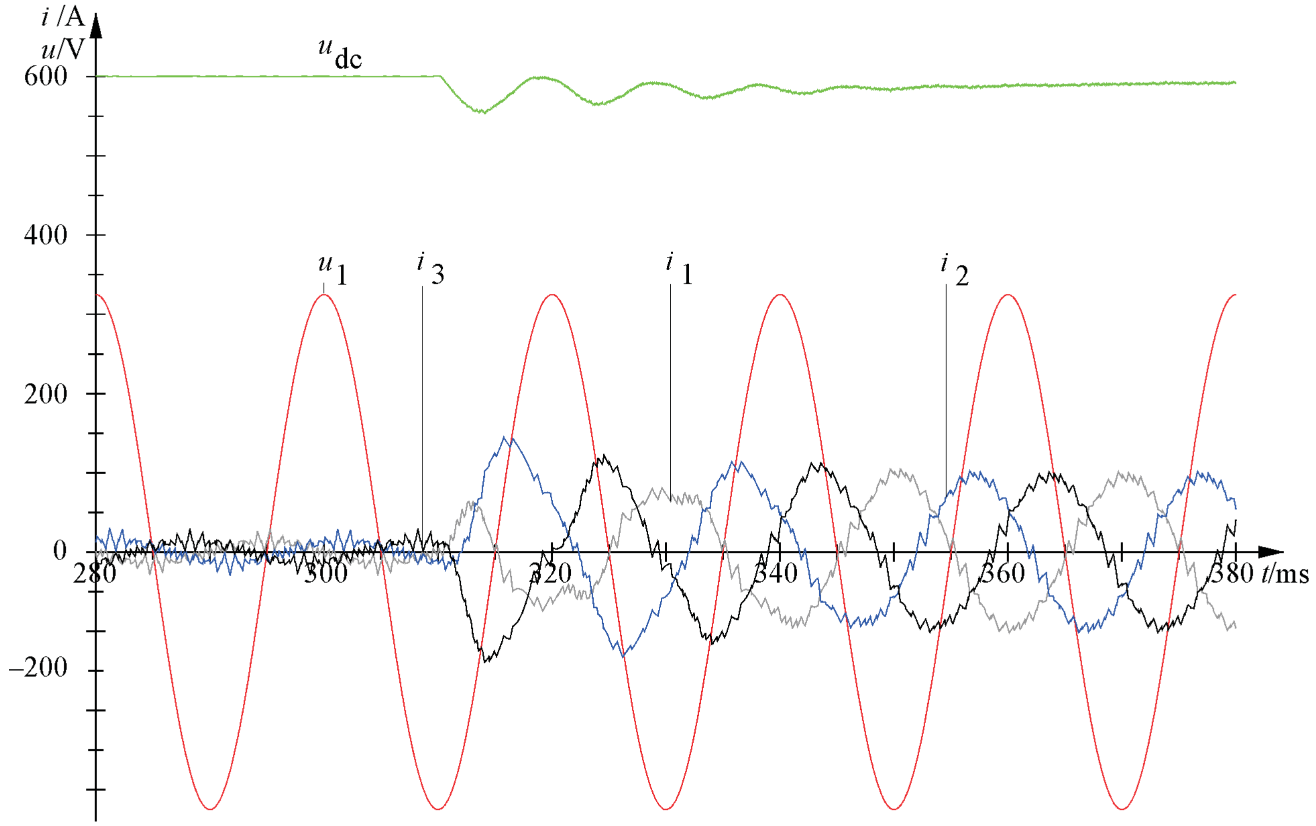

Fig. 7. Virtual-flux approach – zoom

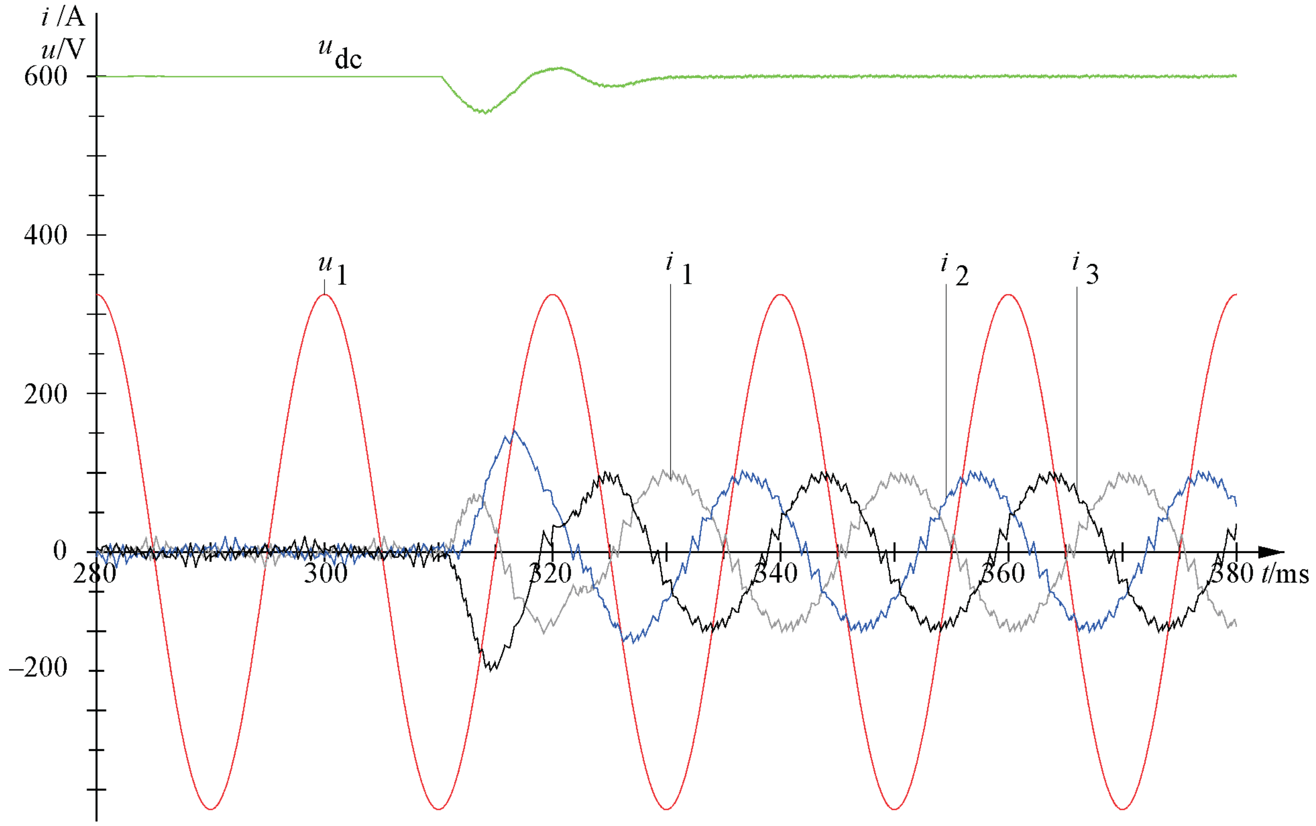

Fig. 8. Voltage-approach state feed-back control with PRC – optimised parameters, zoom