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Pole-Restraining Control of three-phase Active Front End – a comparison to state-of-the art controls and its performance under fault-ride-through conditions

Abstract. *State-of-the-art control systems often neglect the time-variant characteristics of power-electronic systems in favour of a time-averaged approach. In consequence, the resulting system is partly instable, thus not optimally controlled. The novel pole-restraining control (PRC) concept removes the inherent instability considerably improving dynamic behaviour.*
This enhancement is demonstrated at hand of a three-phase Active Front End (AFE). The essentials of the pole-restraining control approach are explained, the advanced transient behaviour is illustrated by comparison to other state-of-the-art control schemes.

Streszczenie. *Analizując sterowanie przekształtników energo-elektronicznych ich czasowa zmienność jest często pomijana na rzecz podejścia uśredniającego. Powoduje to częściową niestabilność otrzymanego systemu, nie jest on więc sterowany optymalnie. Nowa metoda sterowania (PRC), ograniczająca bieguny systemu, usuwa wewnętrzną niestabilnośc, poprawiając dynamikę systemu. Poprawa ta jest pokazana w artykule na przykładzie sterowania przekształtnika trójfazowego (Active Front End – AFE). W artykule wyjaśniono istotę sterowania poprzez ograniczenie biegunów systemu, a procesy przejściowe zilustrowano porównaniem ich z wynikami otrzymanymi przy użyciu innych współczesnych metod sterowania.* ***(Sterowanie prostownika aktywnego metodą ograniczania biegunów systemu – porównanie z najnowszymi sposobami sterowania oraz jego zachowanie w warunkach zwarciowych)***

Keywords: pole-restraining control, PRC, Active Front End, AFE, control, fault ride through
Słowa kluczowe: sterowanie metodą ograniczania biegunów systemu, PRC, prostownik aktywny, sterowanie, pokonywanie zakłóceń zwarciowych

Introduction

Renewable energies and small-scale combined-heat-and-power generation (CHP) require advanced power-electronic systems and control for grid connection. They already play an important role, but their impact on the electrical power is growing enormously. In all cases, the demand for converter-control dynamics increases because grid stability relies more and more also on this new kind of power generation. Upcoming grid codes for Active Front Ends (AFE) pose increasing challenges. Strong limitations concerning undesirable line-current harmonics and non-active power exist. Fault-ride-through capability becomes a must.

State-of-the-art control structures often neglect the time-variant characteristics of power-electronic systems in favour of a time-averaged approach [1–9]. In consequence, the system is partly instable, thus not optimally controlled [10].

The novel pole-restraining control (PRC) for power-electronic systems explicitly includes the time-variant characteristics into the control strategy. Consequently, system stability and dynamics are enhanced considerably [10] allowing optimal adaption to grid-related requirements. Additionally, potential is at hand for improving robustness. 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.

This paper analyses the impact of feed-back control on system stability and gives the essentials of PRC. 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 in comparison to PRC.

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 averaged over the modulation period T_p) [10]. However, almost every power-electronic device is feed-back controlled. Thus, the impact of feed-back to the system stability is analysed for a multivariable control, designed as a state feed-back [11]. In case of state-feedback control, the placement of the eigenvalues of the closed loop is of major concern. Therefore, the system analysis is often performed using the resulting system matrix of the closed loop representing the autonomous system. In consequence, from this point onward, only the state-space representation of the system is analysed, including the system matrix **A** and the control matrix **B**. The control is represented by the feed-back matrix **K**. The time-variant set of differential equations can be given in the canonical state-space representation using the continuous averaged conversion ratio $\rho_{Tp}(t)$.

$$\frac{d\mathbf{x}}{dt} = \mathbf{A}\cdot\mathbf{x} + \mathbf{B}\cdot\mathbf{u} \tag{1}$$

$$\mathbf{A} = \begin{pmatrix} 0 & -\frac{\rho_{Tp,\alpha}(t)}{C} & -\frac{\rho_{Tp,\beta}(t)}{C} \\ 0 & -\frac{R}{L} & 0 \\ 0 & 0 & -\frac{R}{L} \end{pmatrix} \tag{2}$$

$$\mathbf{B} = \begin{pmatrix} 0 & 0 \\ -\frac{1}{L} & 0 \\ 0 & -\frac{1}{L} \end{pmatrix} \tag{3}$$

$$\mathbf{x} = \begin{pmatrix} u_{DC} \\ i_{L,\alpha} \\ i_{L,\beta} \end{pmatrix} \tag{4}$$

$$\mathbf{u} = \begin{pmatrix} u_{conv,\alpha} \\ u_{conv,\beta} \end{pmatrix} \tag{5}$$

The new system matrix $\mathbf{A}_r$ of the closed loop can be calculated. The places of the eigenvalues depend – beside upon the parameters of the plant – upon the actual α-β-conversion ratios. In order to visualize this effect, a LQ-optimised multivariable-control design [12] has been applied leading to a suitable control matrix **K** [10].

The eigenvalues for one of the two orthogonal dimensions, namely the α and β dimension, $\lambda_i(\rho_{Tp})$ 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.

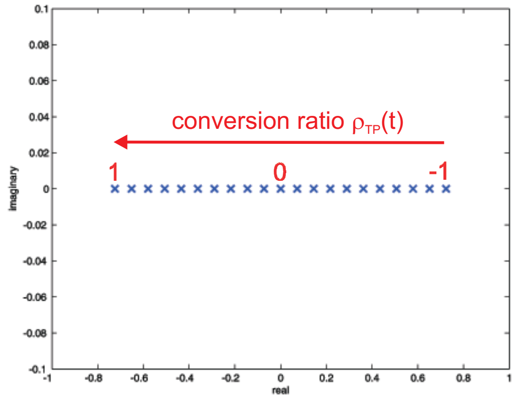

Fig. 1. State feed-back control by constant time-averaging without PRC: pole-zero map

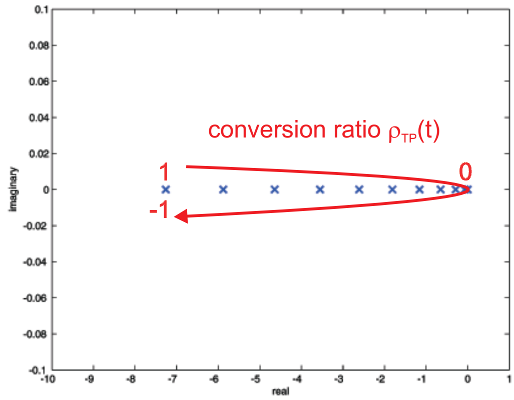

Fig. 2. State feed-back control with PRC: pole-zero map

Accordingly, the system is only partly instable, and it can be operated as it is typical for state-of-the-art industrial applications [1, 13]. Yet it goes without saying that a control-design method which eliminates this instability will achieve notable progress in system stability and dynamics compared to traditional approaches.

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 [10].

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 (cp. Fig. 1). Applying the PRC approach guarantees solely stable eigenvalues in the left half of the complex plane. In this way, stability for each conversion ratio $\rho_{Tp}(t)$ is achieved (cp. Fig. 2).

Additional performance improvements can be achieved using the pole-restraining control. State-of-the-art controls use the available control margin in order to compensate the neglected time-variant characteristics of the power-electronic system. In contrast, in case of PRC, this control margin can be used to fulfil advanced control aims more exactly. Beside the increased robustness, undesired DC-components in the grid currents can be avoided. This is a major advantage because DC currents with high magnitude will saturate transformers [10].

Simulation results

All simulations are performed using a control-cycle time of $125\,\mu\mathrm{s}$ and a converter switching frequency of $1000\,\mathrm{Hz}$.

The electric circuit diagram of the test-configuration is shown in figure 3.

The converter feeds a DC-link capacitor ($C = 4\,\mathrm{mF}$) with a parasitic parallel resistance ($R_p = 10\,\mathrm{k\Omega}$) from an ideal three-phase grid with line-to-line rms voltage of $U_g = 400\,\mathrm{V}$ via a leakage inductance of $L = 3\,\mathrm{mH}$ and a serial resistance of $R_s = 1\,\mathrm{m\Omega}$. A current source with a constant current of $75\,\mathrm{A}$ is turned on at $t = 310\,\mathrm{ms}$ to load the DC link. The DC-link voltage set-point is set to $600\,\mathrm{V}$.

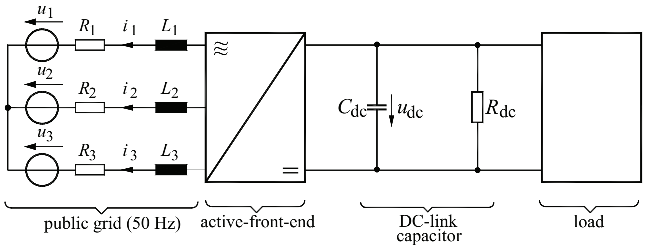

Fig. 3. Electric circuit diagram of the test-configuration

Comparison of the control schemes

First, the AFE controlled by a basic state-feed-back voltage-control approach leads to an unsatisfying dynamic behaviour (cp. Fig. 6). Beside the unstability – leading to a significant DC-link voltage ripple –, a huge voltage dip of the DC-link voltage can be observed, caused by the load step at $t = 310\,\mathrm{ms}$; a maximal DC-link voltage dip of $220\,\mathrm{V}$ is to be seen. The settling time is bigger than $250\,\mathrm{ms}$. This long transient response can also be observed in the grid currents – which are actually used to adapt the DC-link voltage to its desired value. In idle mode, the grid currents show a low-frequency oscillation. During the first $250\,\mathrm{ms}$ after the load step, the grid currents do not attain the desired sinusoidal shape. In total, the voltage control-approach shows a very unfavourable behaviour.

Secondly, the pole-restraining approach is applied – without changing any control parameters – leading to a stabilized behaviour (cp. Fig. 7). Here, the DC-link voltage shows a much smoother transient behaviour. The grid currents reach steady-state within $80\,\mathrm{ms}$, the DC-link voltage takes much longer to reach steady-state. In idle mode, the grid currents roughly equal zero. It is obvious that the control parameters have to be optimized to gain an improved transient response.

Replacing the first voltage control approach without PRC by the virtual-flux concept [14], the performance can be improved (cp. Fig. 8). Here, steady-state operation is obtained $60\,\mathrm{ms}$ after the load-step. Grid currents and DC-link voltage do not differ much from the desired values. A small ripple in the DC-link voltage during the transient response shows that the control parameters are optimized regarding transient operation. In case of the load step, the DC-link voltage drop is reduced significantly to a value below $50\,\mathrm{V}$.

The pole-restraining approach with adapted feed-back parameters still offers the best dynamic performance (cp. Fig. 9). Having roughly the same voltage drop in case of the load step, steady-state operation is reached already within $30\,\mathrm{ms}$.

The differences between the two control concepts can be observed more clearly in a zoom perspective (cp. Fig. 4 and 5). In the first milliseconds after the load step, the amplitude of the grid currents is adjusted to compensate the power drawn from the DC link.

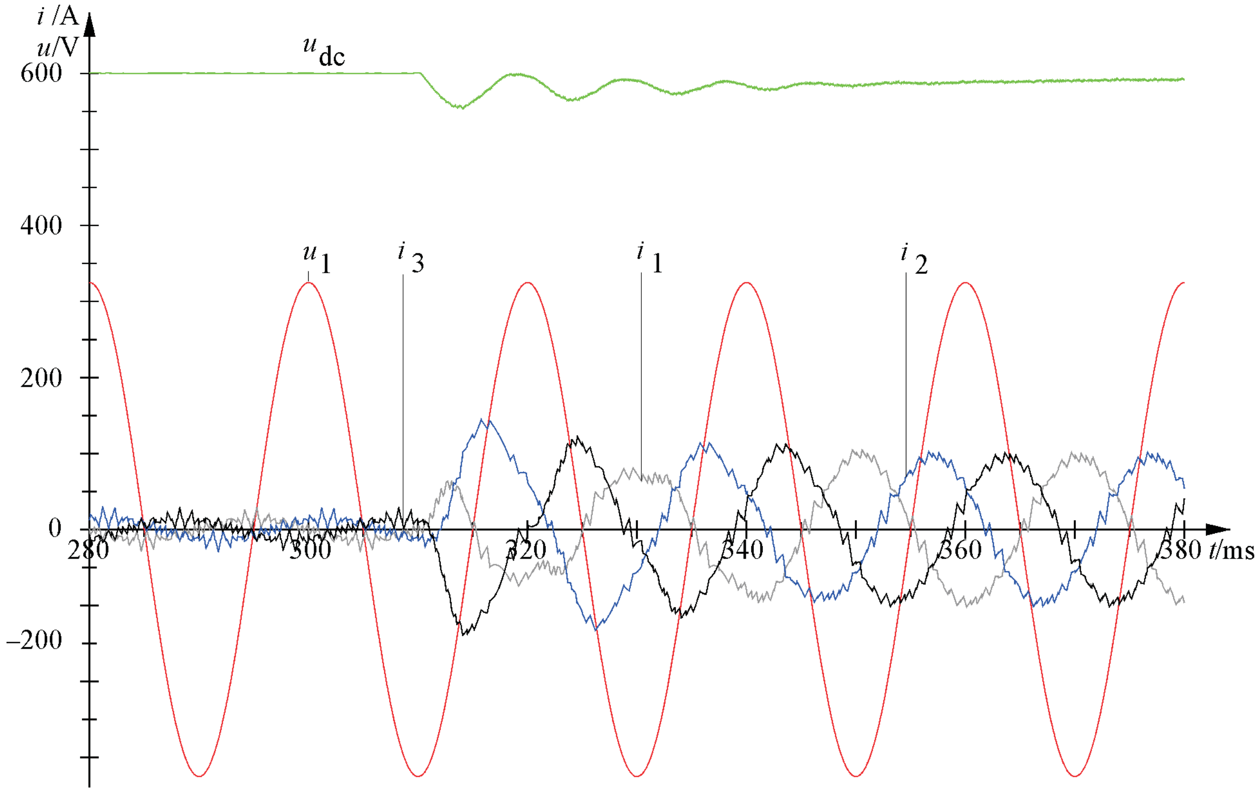

Fig. 4. Virtual-flux approach – zoom

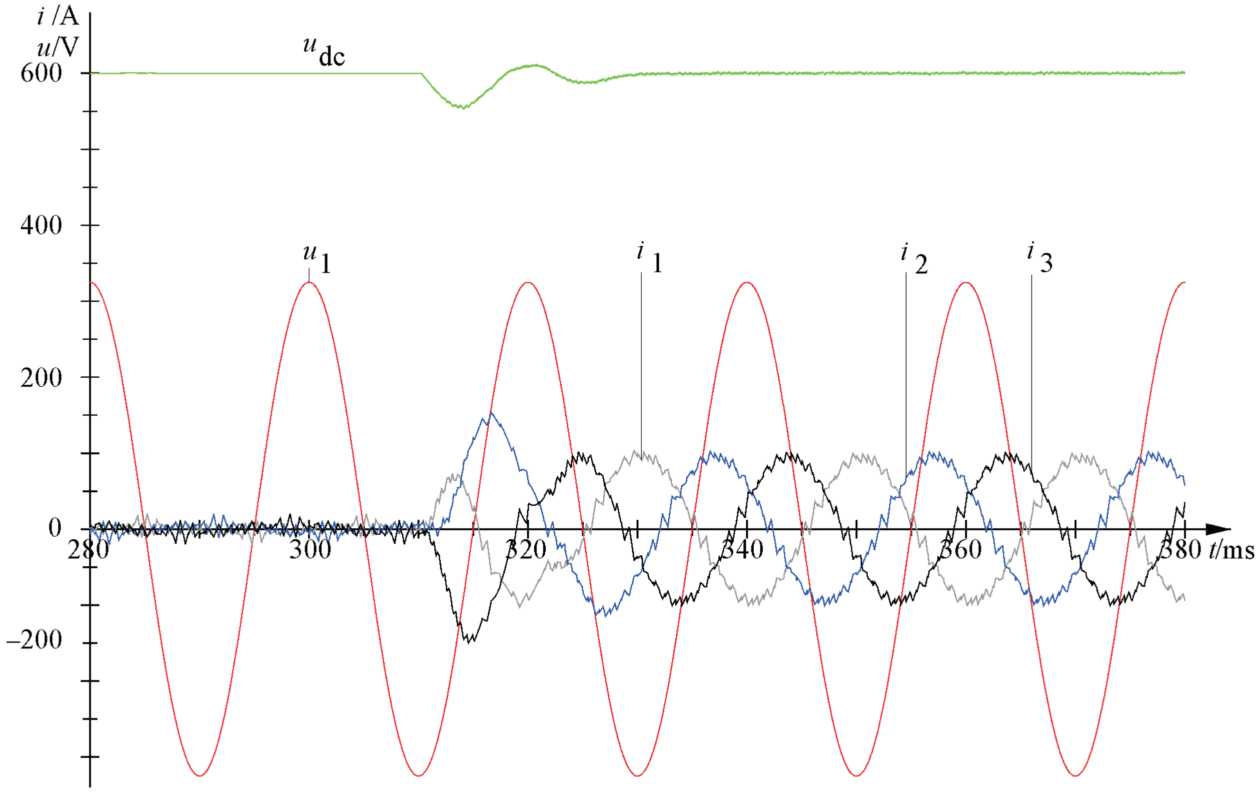

Fig. 5. Voltage-approach state feed-back control with PRC – optimised parameters, zoom

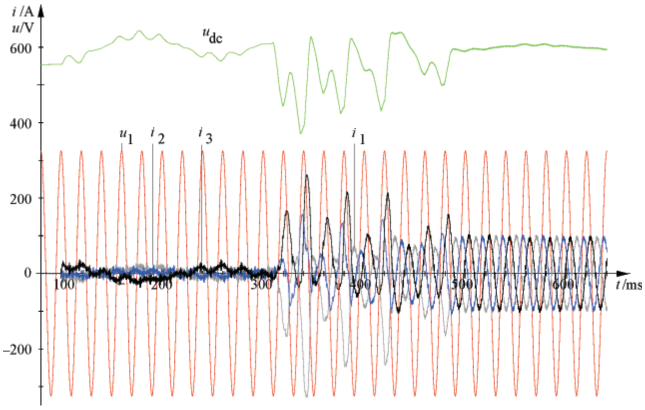

Fig. 6. Voltage-approach state feed-back control without PRC

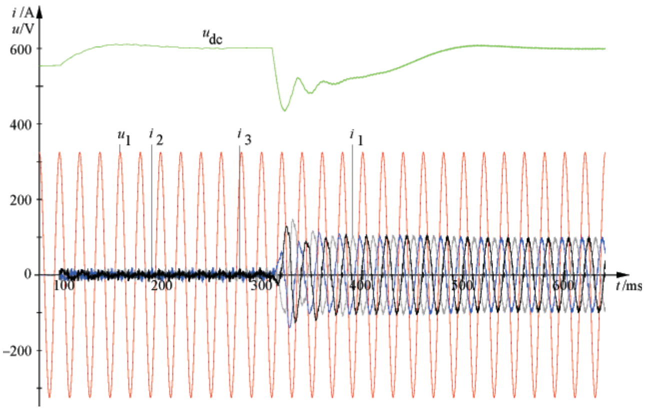

Fig. 7. Voltage-approach state feed-back control with PRC, feed-back parameters are the same as in the simulation without PRC

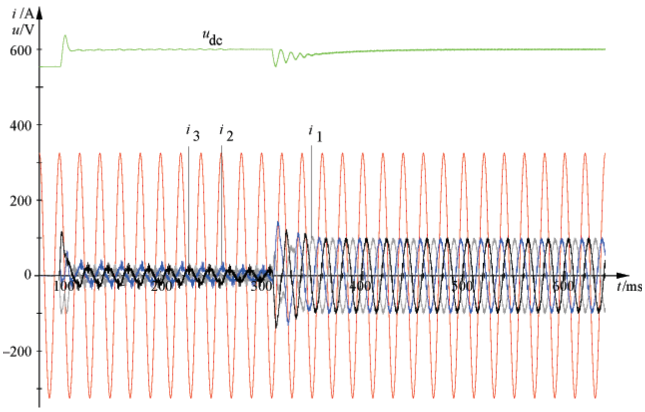

Fig. 8. Virtual-flux approach – overview

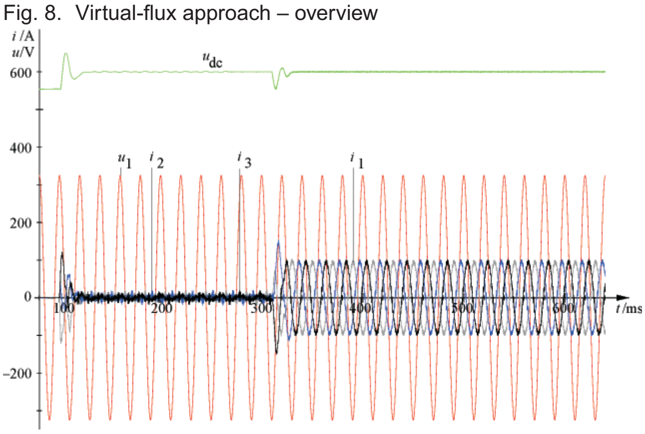

Fig. 9. Voltage-approach state feed-back control with PRC – optimised parameters, overview

Having the flow of active power of AC and DC side of the converter equalled, the DC-link voltage behaviour becomes stable very soon. Here, it can be observed that the PRC control is able to reach this steady-state in half the time of the virtual-flux control, whereas the DC-link voltage dip does not differ.

Fault-ride-through behaviour of the PRC

The following three simulations show the fault-ride-through behaviour of the PRC. Three different grid faults are emulated to demonstrate the robustness of the new control scheme.

Figure 10 presents these quantities at a sudden increase of the grid impedance by $50\,\%$ at $t = 400\,\mathrm{ms}$. The DC-link voltage shows nearly no reaction upon the changed grid impedance. To compensate the increased voltage drop of the grid impedance the PRC raises the desired output voltage of the converter. So grid currents – and with that DC-link voltage – remain in steady-state operation.

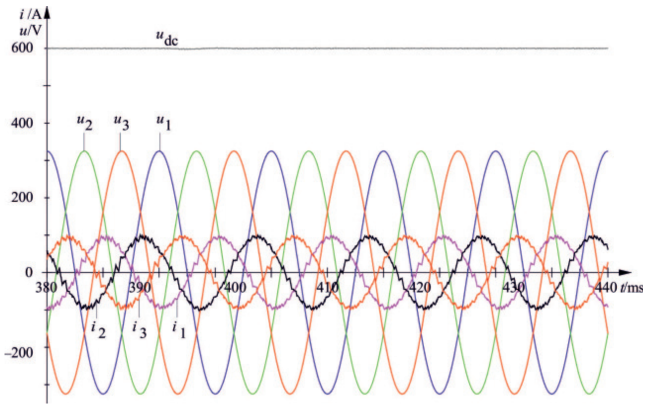

Fig. 10. Symmetric grid fault: grid impedance increased by $50\,\%$ at $400\,\mathrm{ms}$

Figure 11 shows the reaction of the control upon a grid fault leading to a stepwise grid-voltage reduction of $15\,\%$ only in phase 1 at $t = 400\,\mathrm{ms}$. Although the control is able to maintain proper operation a small 100-Hz-oscillation of the DC-link voltage can be observed. This oscillation is due to a common set-point value for α- and β-component of the grid current: In a next step the oscillation might be avoided by setting different grid-current set-points dependent on the actual grid voltage of each phase. Using this calibration a constant active power can be drawn from the unsymmetric grid.

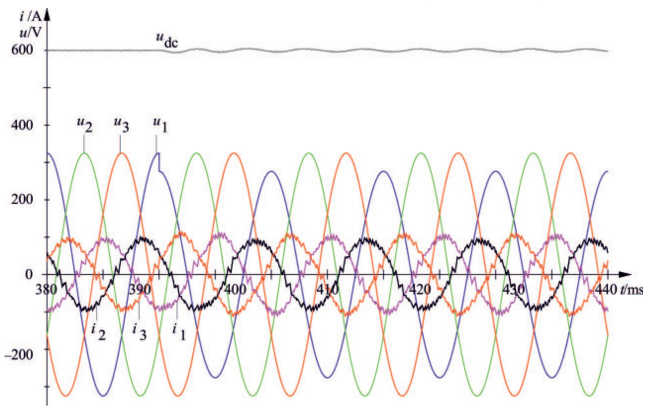

Fig. 11. Unsymmetric grid fault: grid voltage u_1 reduced by $15\,\%$ at $400\,\mathrm{ms}$

Figure 12 presents a sudden symmetrical grid voltage decrease by $15\,\%$ at $t = 400\,\mathrm{ms}$. The control is able to handle this grid fault without any persistent disturbance.

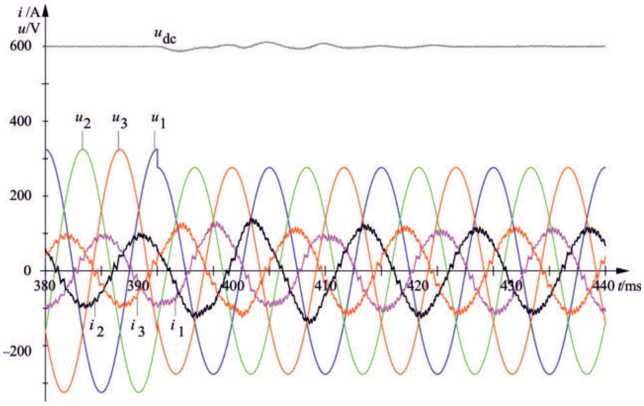

Fig. 12. Symmetric grid fault: all grid voltages $u_1 - u_3$ reduced by $15\,\%$ at $400\,\mathrm{ms}$

The PRC is able to handle all these grid faults with only minor control error.

Conclusion

In this paper, a new control approach for 3-phase Active Front Ends (AFE) is introduced. The maxim of the pole-restraining control (PRC) is the restraining of the eigenvalue movement, avoiding inherent system instability and leading to outstanding improvements. The transient behaviour at load steps of basic state feed-back, virtual-flux approach and pole-restraining control is compared, proving significant advantages resulting from PRC.

Besides better performance, the robustness of the new control against parameter variations is shown. The PR approach emulates the characteristics of hybrid systems with high quality. Thus, more potential is at hand for enhancing robustness. 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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