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NONLINEAR CONTROL OF VOLTAGE SOURCE AC-DC AND DC-DC BOOST CONVERTERS

Introduction. Three-phase pulse-width modulated rectifiers establish de facto a standard for the power AC-DC-AC conversion topology of industrial drives, where energy recuperation is required. They provide the bidirectional power flow with unity input power factor, low harmonic distortion of the line current and stabilization of the dc-link voltage. In autonomous systems such as electrical vehicles with battery primary power source the bidirectional DC-DC power converters are widely used to regulate the inverter DC-link voltage [1].

A number of approaches have been considered to solve the control problem of AC-DC power conversion part, which is nonlinear third order control plant. The authors of [2], [3] and others proposed the structure of vector controlled rectifier constructed in line voltage oriented reference frame using an approximate converter model and assuming a time-scale separation between the voltage and current dynamics. A typical structure of control system includes an outer voltage control loop with linear PI-controller that forms the reference for inner active current control loop with P (PI)-controller. The input reactive current component is controlled by PI-controller with the zero reference value. In [4] authors proposed to use the set of switching voltage PI controllers to improve transient performance. Solution, given in [5], exploits a concept of direct power control on the base of virtual flux instead of the line voltage vector orientation. In the most commonly used advanced control schemes [1], the additional decoupling terms are added in order to achieve some sort of linearization of the initial system. A nonlinear control algorithm [6] was designed using Lyapunov's second method, it guarantees asymptotic DC-link voltage regulation as well as zero input reactive power consumption. Passivity-based control technique in [7] uses the Lyapunov's design in order to result in a stable closed-loop system. Adaptive controller [8] is constructed on the base of simplified active power model, it shows satisfactory performance during simulation and experiment. Solution given in [9] exploits the concept of direct converted energy control, it guarantees global asymptotic stability of the DC-link voltage regulation together with the stabilization of the input reactive power on zero level. However, this controller is implementable only if capacitance and inductance of converter are exactly known, since they are used in the controller equations and reference computation.

As it follows from the available results the classical and advanced controllers satisfy the basic requirements for converter control systems, however no well definite solution is still proposed. Some controllers are designed, based on significant simplifying assumptions; no rigorous stability proof and experimental investigation are given.

The important feature of the AC-DC converter control system is that equivalent structure of the voltage subsystem under decoupling vector control is the same as for classical DC-DC converter. Such property allows to construct the voltage subsystems of the three phase AC-DC and DC-DC converters on the base some sort of universal controller.

The aim of this paper is to introduce the universal voltage controller for AC-DC and DC-DC converters based on two time-scale approach and partial system feedback linearization. The experimental results demonstrate the effectiveness of the proposed control algorithm.

Control algorithm design. A schematic diagram of the standard three-phase AC-DC converter in voltage supply mode is shown in the Fig. 1 [1], where standard definitions for all variables are used.

The two phase model of the converter in line voltage vector oriented reference frame (d-q) is given by

$$L\frac{di_d}{dt} = \omega_1 L i_q - R i_d - \frac{1}{2}V_{dc}p_d + E, \qquad (1)$$

$$L\frac{di_q}{dt} = -\omega_1 L i_d - R i_q - \frac{1}{2}V_{dc}p_q, \qquad (2)$$

$$C\frac{dV_{dc}}{dt} = i_0 - i_L = \frac{1}{2}\left(p_d i_d + p_q i_q\right) - i_L, \qquad (3)$$

where ω_1 is network angular frequency, E is mains voltage magnitude, R and L are resistance and inductance, C is DC-link filter capacitance, V_{dc} is DC-link voltage, i_L is the DC-link load current and $(p_d, p_q)^T$ are control inputs in (d-q) reference frame.

Note that equations (1)-(3) are nonlinear and the transformed switching functions p_d and p_q are control inputs. Let $V^* > 0$ is constant reference DC-link voltage, i_L is limited and constant load current. Let us assume that converter parameters are known and constant, currents i_d, i_q and DC-link voltage V_{dc} can be measured. The control problem is to design a control vector $\mathbf{p} = (p_d, p_q)^T$, which guarantees asymptotic DC voltage regulation and stabilization of input reactive power consumption at zero level, i.e: $\lim_{t\to\infty}\tilde{V}_{dc}=0$, $\lim_{t\to\infty}\tilde{i}_q=0$, where $\tilde{V}_{dc}=V_{dc}-V^*$ is voltage regulation error, $\tilde{i}_q=i_q$ is the reactive component of the line current.

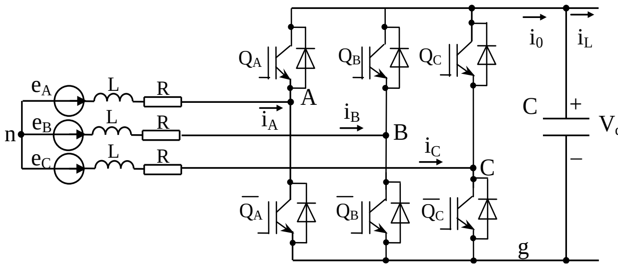


Fig. 1. The three-phase AC-DC converter

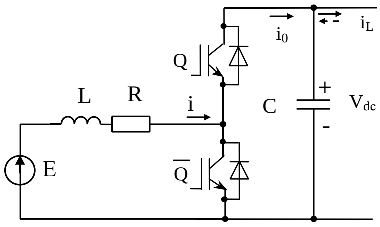


Fig. 2. The DC-DC boost converter

The feedback linearizing control algorithm for reactive component of the converter input current vector is given by

$$\begin{aligned} p_q &= -\left(2L/V_{dc}\right)\left(\omega_1 i_d - k_{iq}\tilde{i}_q - x_q\right),\ V_{dc}\neq 0,\\ \dot{x}_q &= k_{iqi}\tilde{i}_q, \end{aligned} \tag{4}$$

where $k_{iq}>0,\ k_{iqi}>0$ are tuning coefficients of the proportional and integral components of the q-axis current controller.

Substituting (4) into (2), the current error dynamics can be written as follows

$$\begin{aligned} \dot{\tilde{i}}_q &= -\left(R/L+k_{iq}\right)\tilde{i}_q - x_q,\\ \dot{x}_q &= k_{iqi}\tilde{i}_q. \end{aligned} \tag{5}$$

It can be concluded from (5) that error dynamics of the reactive current is independent of the voltage regulation process, it is linear and asymptotically stable for all $k_{iq}>0,\ k_{iqi}>0$.

The dynamic equations of the voltage subsystem, according to equations (1) and (3), can be written as

$$\begin{aligned} \frac{dV_{dc}}{dt} &= \left(\frac{1}{2}p_d i_d\text{-}i_L\right)\Big/C,\\ \frac{di_d}{dt} &= \left(-Ri_d-\frac{1}{2}V_{dc}p_d+E\right)\Big/L, \end{aligned} \tag{6}$$

where decaying to zero component $\tilde{i}_q$ has been neglected.

Important to note that second order model (6) is the same as for standard DC-DC converter, whose schematic diagram is show in Fig.2.

For controller design we introduce the following nonlinear transformation

$$p_d = 2u/V_{dc},\ \upsilon = E-u,\ z=V_{dc}^2. \tag{7}$$

In new coordinates system (6) can be rewritten as

$$\dot{z} = 2\left(\left(E-\upsilon\right)i_d - z/R_L\right)/C, \tag{8}$$

$$\dot{i}_d = \left(-Ri_d+\upsilon\right)/L, \tag{9}$$

where $R_L=V_d/i_L$ is virtual load resistance.

We assume that voltage control subsystem has cascaded structure with inner i_d current control loop and outer voltage loop. Such design procedure requires that inner loop is much faster than outer one providing two-time scale properties in order to establish a weak interconnection between current and voltage control subsystems.

According to (9), the proportional current controller is given by

$$\upsilon = L\left[\left(R/L\right)i_d^* - k_{id}\tilde{i}_d\right], \tag{10}$$

where $\tilde{i}_d=i_d-i_d^*$ – d-current regulation error and k_{id} is proportional gain of the controller.

From (9) and (10), the current error dynamics is computed as

$$\dot{\tilde{i}}_d = -\left(R/L+k_{id}\right)\tilde{i}_d - \dot{i}_d^*. \tag{11}$$

When conditions for two-time scale properties are satisfied then $\dot{i}_d^*\approx 0$ and therefore we conclude that

$$\lim_{t\to\infty}\tilde{i}_d=0 \tag{12}$$

for all $k_{id}>0$.

In order to achieve asymptotic DC-link voltage control, we introduce the following PI voltage controller

$$i^* = (C/2E)(-k_{v1}\tilde{z} + x_V),$$
$$\dot{x}_V = -k_{vi}\tilde{z}, \quad (13)$$

where k_{v1}, k_{vi} are proportional and integral gains of the PI voltage controller and $\tilde{z} = V_{dc}^2 - V^{*2}$.

Taking into account that current control loop is much faster than the voltage one, the voltage error dynamics is given by

$$\dot{\tilde{z}} = -\left(k_{v1} + \frac{2}{CR_L}\right)\tilde{z} + x_v - \frac{2}{CR_L}z^* - \frac{RC}{2E^2}\left(-k_{v1}\tilde{z} + x_v\right)^2 - \dot{z}^*,$$
$$\dot{x}_v = -k_{vi}\tilde{z}. \quad (14)$$

For small enough $RC/(2E^2)$ a term $\frac{RC}{2E^2}\left(-k_{v1}\tilde{z} + x_v\right)^2$ is negligible and in case $R_L = \text{const}$ and $z^* = \text{const}$ the equation (14) can be rewritten as

$$\dot{\tilde{z}} = -k_v\tilde{z} + \eta,$$
$$\dot{\eta} = -k_{vi}\tilde{z}, \quad (15)$$

where $\eta = x_v - \frac{2}{CR_L}z^*$ and $k_v = k_{v1} + \frac{2}{CR_L}$.

The approximated system (15) is linear and asymptotically stable, hence original nonlinear system (11), (14) is locally stable. From the analysis above it follows that $\lim_{t\to\infty}(\tilde{z},\eta)=0$ and therefore $\lim_{t\to\infty}\tilde{V}_{dc} = 0$.

The important issue of cascaded system design deals with the finding of a constructive mechanism to establish the two-time scale separation for subsystems (11) and (14). For second order linear subsystem (15), the standard tuning can be used:

$$k_{vi} = k_v^2/4, \; k_{vi} = \omega_{0v}^2, \quad (16)$$

where ω_{0v} is natural frequency of undamped oscillations of the voltage control loop.

Tuning according to (16) provides a damping factor $\zeta = 1$. The two-time scale separation for subsystems (11) and (14) is achieved if condition $\omega_{0i} \geq (2-3)\omega_{0v}$ is satisfied, where $\omega_{0i} = \left(R/L + k_{id}\right)^{-1}$.

Experimental Verification. This section reports the results of experiments and simulations to support the analytical findings. The following experiments has been conducted: a) testing of the three-phase AC-DC converter of the vector controlled induction motor drive; b) testing of the bidirectional DC-DC converter of the small size electric vehicle.

Three-phase AC-DC converter. The experiments have been carried out using the structure of induction motor drive system, shown in the Fig. 3. Experimental set-up includes: vector controlled rectifier (VCR) with connected via DC-link PWM inverter; two mechanically coupled induction motors with rated power of 2.2 kW; incremental encoder with resolution 1024 ppr for speed measurement; field-oriented vector control system for motor №2; TMS320F28335 based controller for control algorithms implementation; personal computer for processing, programming, interactive oscilloscope, data acquisition, etc. PWM frequency is set to 10 kHz for both converters. The sampling time is equal to 200 μs.

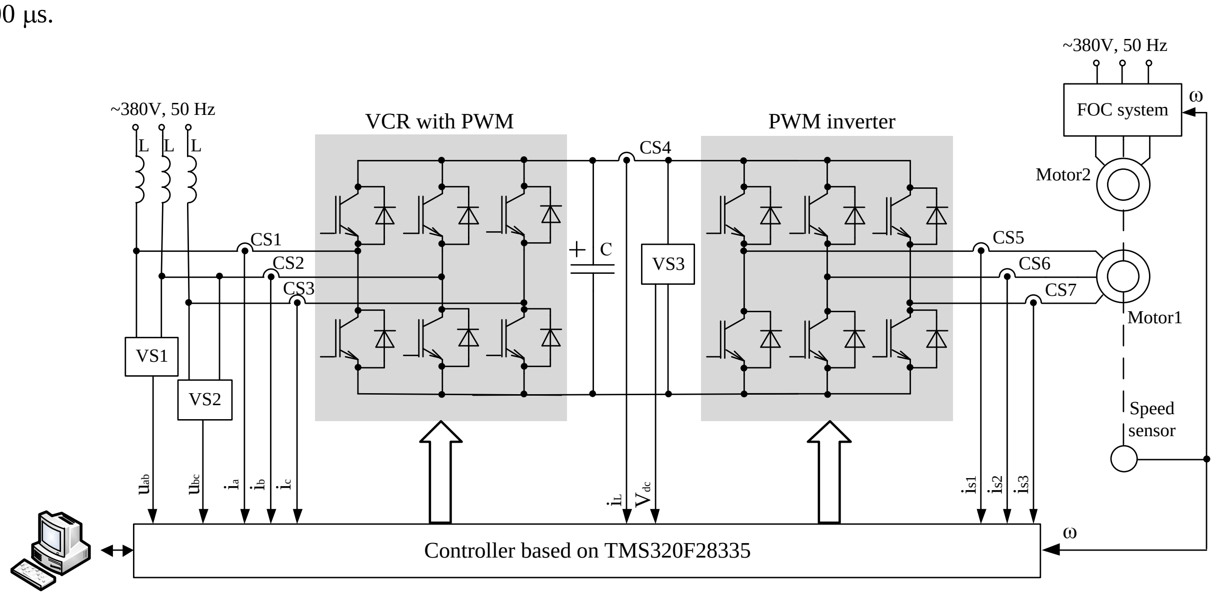
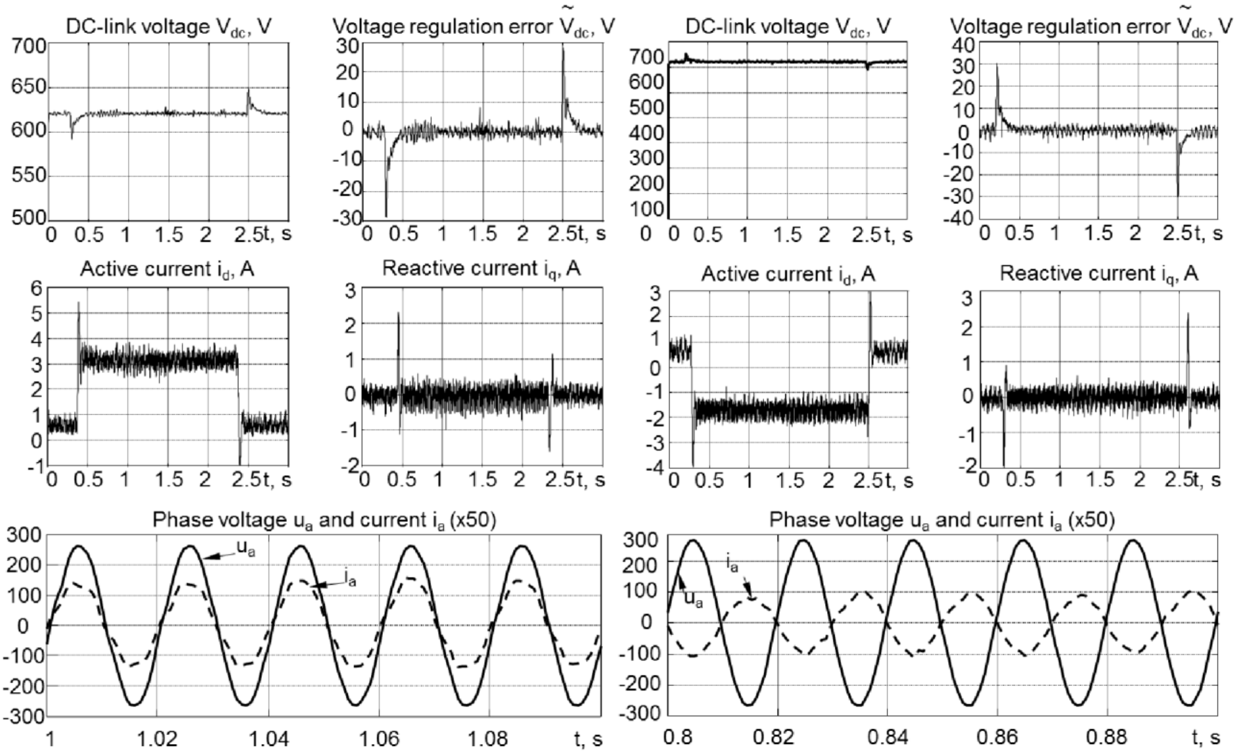


Fig. 3. Functional diagram of experimental set-up with AC-DC converter

During experimental tests, DC voltage reference is equal to 620 V. Field oriented speed vector control algorithm is implemented in the same DSP controller and provide speed stabilization of the induction motor №1, while induction motor №2 serves as a loading machine. During the test, rated load torque of 15 Nm is applied to the motor №1 at time t = 0.25 s and removed at t = 2.5 s.

Experimental transients are shown in Fig. 4. As it follows from Fig.4, the proposed controller provides high dynamic performance of the DC-link voltage stabilization for bi-directional energy flow. Input current i_q is controlled on zero level.



a) b)

Fig. 4. Experimental transients of vector controlled AC-DC converter; a) consumption mode; b) recuperation mode

DC-DC boost converter. The experiments have been carried out using the setup whose functional diagram is shown in Fig. 5. Batteries bank with $E = 50\,V$ provides input voltage for DC-DC booster converter loaded by controlled resistive load. The converter parameters has been computed as L=0.011 H, R=0.5 Ω, C=500 μF, controller coefficients are equal to $k_{id} = 2000$, $k_v = 200$, $k_{vi} = 20 \cdot 10^3$, sampling time is set at 20 μsec. During the tests $V^* = 100V$, $V_{dc}(0) = 52$ V. The load current $i_L = 1$ A was applied at moment of time $t_1 = 0.1$ s, and it was removed at $t_2 = 0.2$ s by switching on and off the transistor S_3.

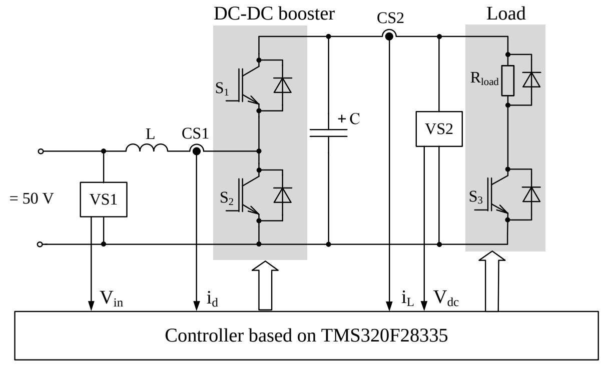


Fig. 5. Functional diagram of experimental set-up with DC-DC boost converter

Transients in Fig.6 compare the simulation results a), b) and results of the experimental test c). During simulations average model is used for switching and control part (Fig. 6.a), while transients in Fig.6 b) corresponds to switching converter with continuous time controller implementation. The controller's coefficients are chosen so that the switching function doesn't reach its limits.

As it follows from the transients in the Fig.6, the resulting dynamics obtained by simulation and experimentally are quite similar. Asymptotic voltage regulation is achieved with fast transients and desired dynamics according to solutions of dynamic system (14).

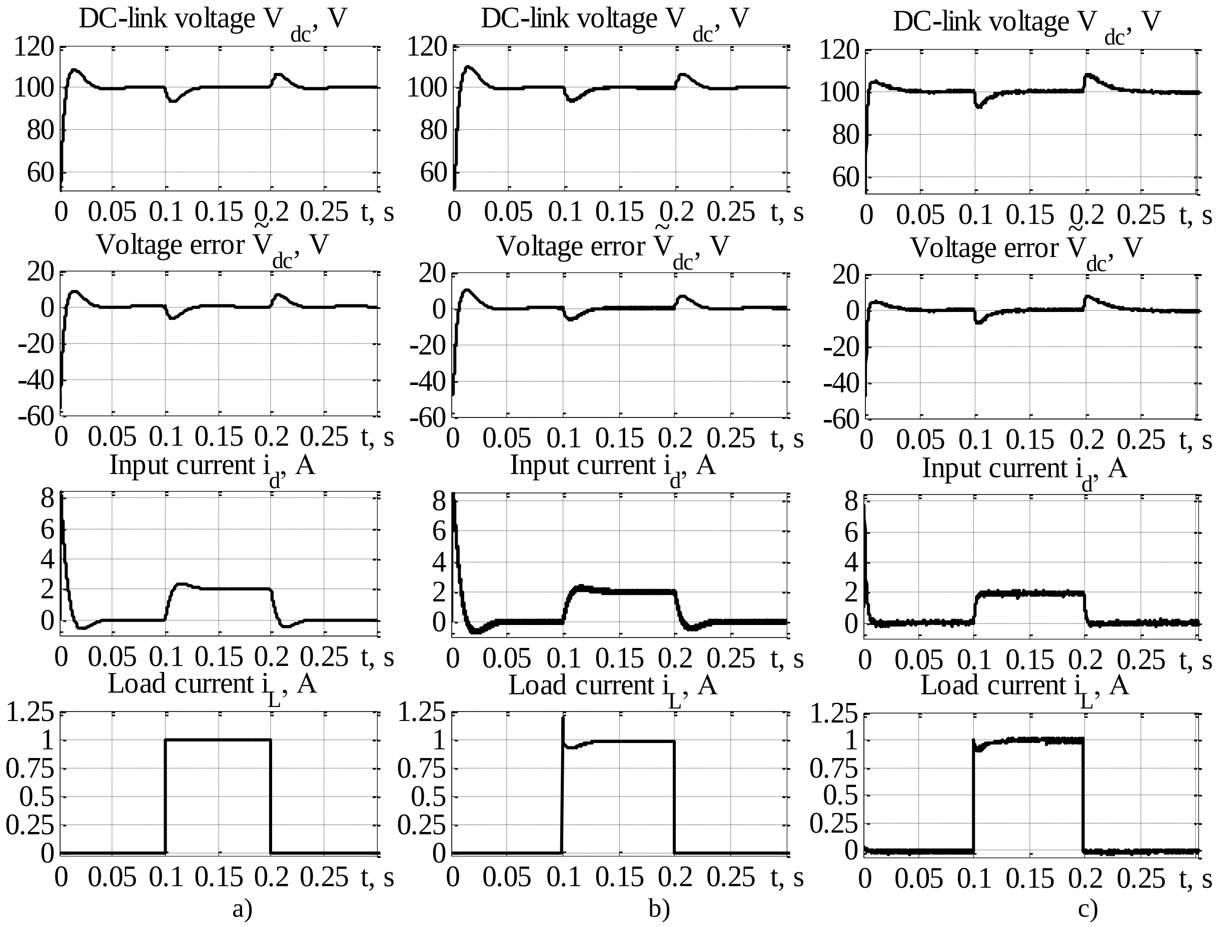


Fig. 6. Comparison of the transients obtained in simulation of continuous system (a), discrete model in MatLAB SimPowerSystems (b) and experimental results (c)

Conclusion. In this paper, a theoretical solution of the voltage source AC-DC and DC-DC converters control problem is presented. The DC-voltage and input reactive power nonlinear controllers are designed for three-phase AC-DC converter. It is shown that if decoupling vector control is applied the reactive component of the line current vector exponentially decays to zero. As result equivalent voltage dynamics for both converters is the same. We present a design of the simple feedback linearizing voltage controller, which is based on two time-scale separation approach and reasonable approximation of the resulting locally asymptotically stable error dynamics. This controller does not requires the exact information about parameters L, C and robust with respect of uncertainties in resistance R. However, tuning of the control loops is needed to achieve the two time-scale separation properties; dynamic performance of the voltage regulation depends from the achievable dynamics of current regulation. Simulation and experimental results proof the effectiveness of the theoretical findings.

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