Control Strategy of Grid Connected Converter under Unbalanced Conditions

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Abstract— Current-controlled voltage source converters are widely used in grid-connected applications. The negative sequence component of the grid voltage causes pulsating components in powers transmitted through the converter and ripple of the dc voltage in the intermediate circuit. Two strategies of the current reference calculation for a dual current controller were developed and tested in the Matlab/Simulink environment and experimentally verified as well.

1. INTRODUCTION

In real situation, the three-phase grid voltage is distorted by high-order harmonics and by a negative sequence component, producing ripples in the voltage on the capacitors in the intermediate circuit and in the transferred active and reactive power too. The three-phase *ac* current is disturbed as well.

The object of the work is the control strategy of the positive and negative sequence of the *ac* converter current in order to eliminate high-order harmonics in the grid current, and ripple in powers flowing through the converter and in the voltage in the *dc* circuit as well. In the paper, two strategies of the current reference calculation for a dual current controller were developed and tested in the Matlab/Simulink environment and experimentally verified as well.

2. PROPOSED CURRENT REFERENCE CALCULATION BASED ON CONDITION OF ZERO *DC* VOLTAGE RIPPLE

Several control strategies aimed at minimum *dc* voltage fluctuation have been proposed, e.g., [1–4]. We have developed a new simplified method to calculate the reference currents for the dual current controller

$$\begin{bmatrix} i_d^p(t) \\ i_q^p(t) \\ i_d^n(t) \\ i_q^n(t) \end{bmatrix} = \begin{bmatrix} v_d^p & v_q^p & v_d^n & v_q^n \\ v_q^p & -v_d^p & v_q^n & -v_d^n \\ v_q^n & -v_d^n & -v_q^p & v_d^p \\ v_d^n & v_q^n & v_d^p & v_q^p \end{bmatrix}^{-1} \begin{bmatrix} \frac{2}{3}P_0^{out} \\ 0 \\ 0 \\ 0 \end{bmatrix} = \frac{2P_0^{out}}{3D} \begin{bmatrix} v_d^p \\ v_q^p \\ -v_d^n \\ -v_q^n \end{bmatrix}$$
$$= Y_0^{out}(e_d^p, e_q^p, e_d^n, e_q^n, P_0^{out}) \begin{bmatrix} v_d^p \\ v_q^p \\ -v_d^n \\ -v_q^n \end{bmatrix} \quad (1)$$

where $Y_0^{out}(e_d^p, e_q^p, e_d^n, e_q^n, P_0^{out})$ is a function of the measured grid voltages and of the active power at the terminals of the converter, which is usually influenced also by the output signal of the *dc* voltage controller.

Figure 1 displays a scheme of the grid connected converter and the dual current controller. The grid connected converter in Fig. 1 works as a *dc* source, although electric energy can be generally transferred through the grid- connected converter in both directions.

If the resistance R of the input filter is neglected, the determinant D in (1) may be calculated as

$$D = \left[u^{pn} + \sqrt{(u^{pn^2} - u_L^2)}\right]/2 \quad (2)$$

$$u^{pn^2} = e^{p^2} - e^{n^2} \quad u_L = 4\omega L P_0^{out}/3 \quad e^{p^2} = e_d^{p^2} + e_q^{p^2} \quad e^{n^2} = e_d^{n^2} + e_q^{n^2} \quad (3)$$

and the converter terminal voltages are calculated on the basis of the measured grid voltages

$$v_d^p = (e_d^p + K e_q^p)/D^{pn} \quad v_q^p = (e_q^p - K e_d^p)/D^{pn} \quad v_d^n = (e_d^n + K e_q^n)/D^{pn} \quad v_q^n = (e_q^n - K e_d^n)/D^{pn} \quad (4)$$

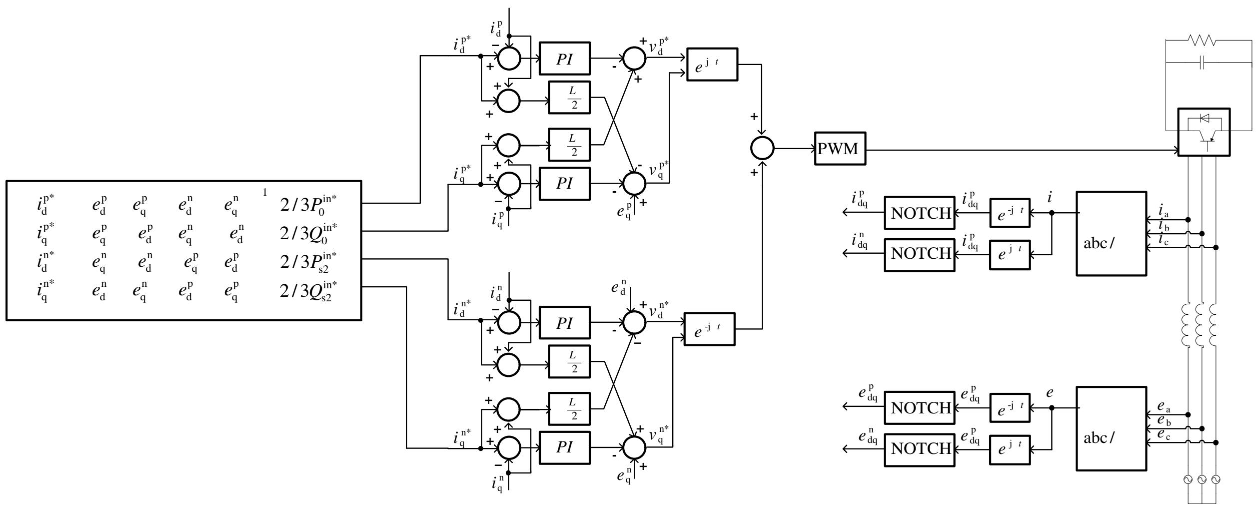

Figure 1: Scheme of grid connected converter and dual current controller.

$$K = \omega L Y_0^{out} \quad D^{pn} = 1 + K^2 \tag{5}$$

It is obvious that the calculation of the reference converter currents for the dual current controller based on the measured and control variables needs neither the solution of the set of nonlinear equations nor using the previous patterns of the calculated reference current in (1)–(5). The resistance R of the input filter and its dynamic behavior has been neglected in (1)–(5). But we may respect the losses produced in the line inductor modifying the power value P_0^{out} that is produced or at least modified by the output of the dc voltage controller.

3. PROPOSED CURRENT REFERENCE CALCULATION BASED ON DEMANDED INSTANTANEOUS POWERS EXCHANGES WITH GRID

The calculation of a converter reference current vector $\mathbf{i}$ can be based also on (6), where p is the instantaneous active and q reactive (non-active) power that should be exchanged between the converter and grid

$$\mathbf{s} = p + jq = 3/2 \left[\mathrm{Re}\left\{ \mathbf{v}\mathbf{i}^* \right\} + j\mathrm{Re}\left\{ \mathbf{v}(t - T/4)\mathbf{i}^* \right\} \right] \tag{6}$$

where $\mathbf{s}$ is called the complex power, $\mathbf{v}$, $\mathbf{i}$ stand for the voltage and current vectors in the SRF^p rotating by the synchronous speed $\omega = 2\pi/T$ in the positive direction, and T is the fundamental period.

In case of an unbalance voltage grid and considering that the current generated by the converter is also unbalanced, we can express the voltage and current vectors $\mathbf{v}$, $\mathbf{i}$ as follows

$$\begin{aligned} \mathbf{v} &= \mathbf{v}^p + \mathbf{v}^n e^{-j2\omega t} \\ \mathbf{v}' &= -j\left(\mathbf{v}^p - \mathbf{v}^n e^{-j2\omega t} \right) \\ \mathbf{i} &= \mathbf{i}^p + \mathbf{i}^n e^{-j2\omega t} \end{aligned} \tag{7}$$

where the superscripts p and n refer to the positive and negative sequences of the voltage and current vectors in the SRF^p and SRF^n, respectively that are constants in steady states.

The final formula for the converter reference current may be formulated as

$$\mathbf{i} = \frac{2}{3} \frac{j}{Im\left\{ \mathbf{v}'^* \mathbf{v} \right\}} \left(p\mathbf{v}' - q\mathbf{v} \right) = \frac{2}{3} \frac{j}{v^{p^2} - v^{n^2}} \left(p\mathbf{v}' - q\mathbf{v} \right) = \frac{2}{3} \frac{j}{v^{p^2}\left(1 - n^2\right)} \left(p\mathbf{v}' - q\mathbf{v} \right) \tag{8}$$

We will call this power control, in compliance with the term used in [6], the Instantaneous Active-Reactive Control (IARC).

We can separate (8) into the reference current vectors for the positive (in SRF^p) and negative (in SRF^n) paths of the dual current controller

$$\mathbf{i}^n = \frac{2}{3} \frac{-1}{v^{p^2}\left(1 - n^2\right)} \left(p + jq \right) \mathbf{v}^n \quad \mathbf{i}^p = \frac{2}{3} \frac{1}{v^{p^2}\left(1 - n^2\right)} \left(p - jq \right) \mathbf{v}^p \tag{9}$$

If only $\mathbf{i}^p$ is used for calculation of the reference currents, it means that the current control in the negative branch of the whole controller is not in operation, the converter current vector $\mathbf{i}^p$ (9) is balanced because it is a replica of the voltage positive sequence $\mathbf{v}^p$. In [6] this option is called the Balanced Positive Sequence Control (BPSC).

It is well known that if the Instantaneous Reactive Power (IRP) theory is used for the reference current calculation instead, the current vector $\mathbf{i}$ is, in case of an unbalanced voltage $\mathbf{v}$, also unbalanced and non-sinusoidal [5].

4. VERIFICATION OF PROPOSED STRATEGIES

Figures 2–3 show the results of simulation of the algorithm proposed in the 2nd paragraph (zero *dc* voltage ripple) in the Matlab/Simulink environment. The grid voltage contains the positive symmetrical component (1 in the p.u. system), negative symmetrical component (0.5 p.u.), 5th harmonic (0.2 p.u.), and the voltage magnitude is modulated by the subharmonic signal (0.2 p.u.) with the frequency 5 Hz. The converter switching frequency was 2400 Hz, and the grid filter inductance L =0.1 p.u. with $R = 0.02$ p.u. In the instant 0.3 s the reference *dc* voltage was increased by 10%, in 0.5 s the power consumed from the *dc* capacitor was increased from zero to the value 0.3 p.u. In the time interval $< 0.7, 0.8 >$ s the voltage drop from 1 p.u. to 0.1 p.u. in the phase a was applied.

Figures 2 and 3 show that there are no fluctuations in the *dc* voltage in steady states, which would result from the occurrence of the huge negative symmetrical component (0.5 p.u.) and other detrimental components in the grid voltage if only a single current controller that was not able to control precisely both the current symmetrical components was used.

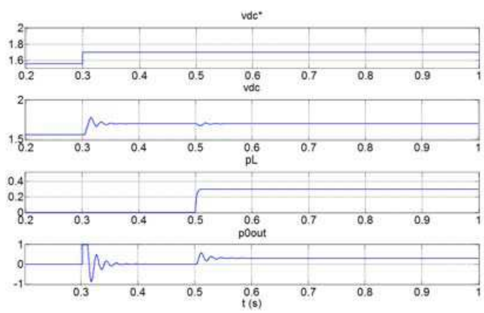

Figure 2: Results of simulation of proposed algorithm (1)–(5): dc voltage, load power and output of dc voltage controller (p.u.).

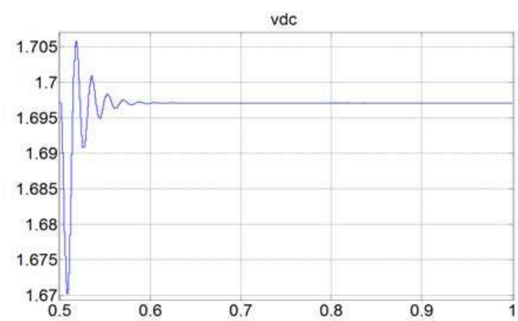

Figure 3: Results of simulation of proposed algorithm (1)–(5): detail of dc voltage from Fig. 2 in time interval $< 0.5, 1 >$.

The following Fig. 4 shows results of the simulation of the algorithm proposed in the 3rd paragraph (demanded instantaneous power exchanges with grid) in the Matlab/Simulink environment. A detailed scheme of a PWM converter and the dual current controller was simulated. The options IARC, IRP, BPSC of the control strategy were implemented.

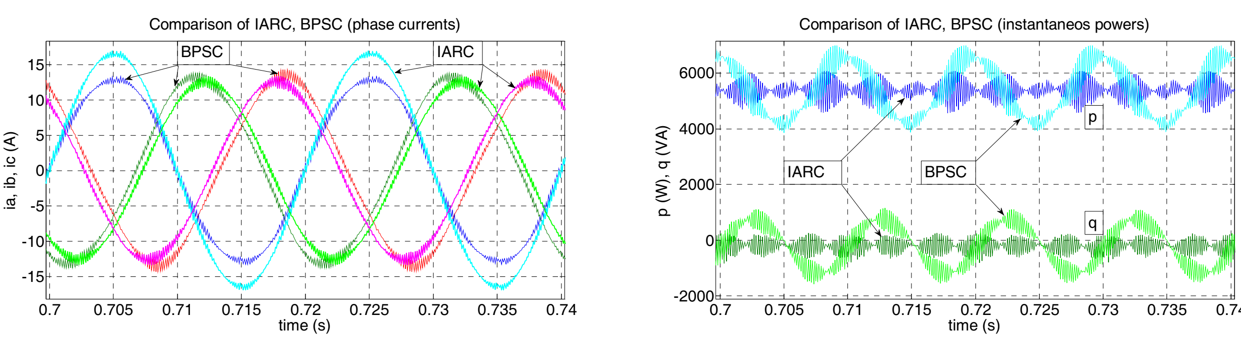

Figure 4: Comparison of responses of phase currents and active and reactive powers in steady state and unbalanced conditions for IARC and BPSC strategies.

We have compared the discussed strategies IARC, IRP, BPSC also through experimentations.

The following figures show phase voltages, currents, and instantaneous active and reactive power responses (calculated by (6)) captured by the dSPACE™ control system and processed in Matlab™.

Figures 5 and 6 show the captured grid voltage, current and power transient responses under unbalanced conditions with the voltage unbalance factor $n = |v^n|/|v^p| = 0.23$. We can recognize a good compliance in steady state, while during the transient process the instantaneous power waveforms approach the reference values in the horizon of about three quarters of the fundamental period in Fig. 6 due to the current transients shown in Fig. 5.

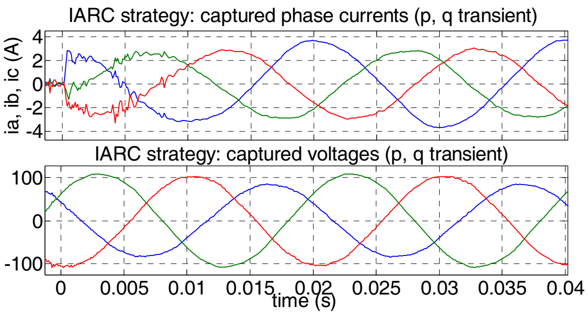

Figure 5: Captured grid voltage and current transient responses following their reference jumps under unbalanced conditions (IARC strategy).

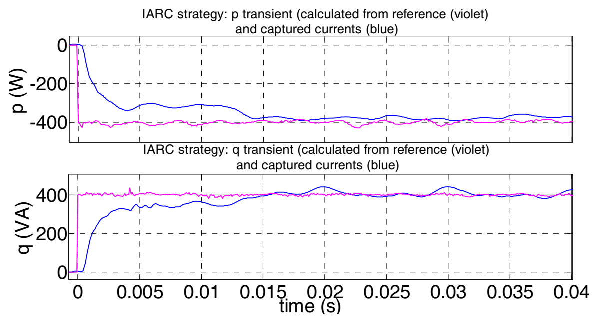

Figure 6: Captured active and reactive instantaneous power transients related to Fig. 5 under unbalanced conditions.

5. CONCLUSION

An unbalanced and disturbed grid voltage causes a wrong function of grid-connected inverters in terms of the grid current and active and reactive power disturbances as well as the ripple in the *dc* voltage.

A new simple dual current control algorithm was developed and tested in the Matlab/Simulink environment with good results.

An option of the Instantaneous Active-Reactive Control (IARC) of the grid-connected converter based on an alternative definition of the reactive (non-active) instantaneous power was also proposed, simulated and experimentally verified. A comparison of this strategy with the IRP and Balanced Positive Sequence Control (BPSC) strategies was carried out as well.

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