Synchronisation methods for grid-connected voltage source converters

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Abstract: Four different synchronisation methods for a voltage source converter connected to a three-phase grid are investigated. The methods are adapted for use in a digital controller. The performance of the synchronisation methods is studied by response characteristics of phase-shift steps, frequency steps and low-frequency grid voltage harmonics. The low-pass filtering method can be used only if the frequency of the grid is constant and phase jumps do not occur. If phase jumps occur, the novel space vector filtering method is recommended. The extended space vector filtering method is adapted to handle frequency variations and is also preferred if fast frequency variations occur. This method even has a higher performance than the extended Kalman filter method, in spite of the large number of calculations that must be performed.

List of principal symbols

e_{g1}, e_{g2}, e_{g3} = grid phase voltages
e_1, e_2, e_3 = phase voltages in point of common connection (PCC)
e_α, e_β = grid voltage in $\alpha\beta$-coordinates in PCC
e_d, e_q = grid voltage in dq-coordinates in PCC
$\underline{e} = e_\alpha + je_\beta$ = grid voltage vector in PCC
i_d, i_q = grid current in dq-coordinates
i_α, i_β = grid current in $\alpha\beta$-coordinates
k = sample index
k_{ISVF} = integral gain
k_{PSVF} = proportional gain
L_g = short-circuit inductance of the grid
L_S = series inductance of the grid filter
R_g = short-circuit resistance of the grid
R_S = series resistance of the grid filter
T_S = sample time
$\boldsymbol{x}$ = state vector
$\boldsymbol{v}$ = process noise
$\boldsymbol{w}$ = sensor noise
$\boldsymbol{A}_{SVF}$ $\boldsymbol{B}_{SVF}$ $\boldsymbol{C}_{SVF}$ $\boldsymbol{D}_{SVF}$ = discrete state equation matrices
$\boldsymbol{R}(\theta)$ = rotation matrix
$\boldsymbol{V}$ = process noise covariance matrix
$\boldsymbol{W}$ = sensor noise covariance matrix
γ = forgetting factor
θ = transformation angle
$\Delta\theta$ = transformation angle deviation
ω_g = grid angular frequency
$\Delta\omega_g$ = grid angular frequency deviation
$\hat{}$ = estimated value

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1 Introduction

In almost all power electronic equipment connected to the grid, a phase-locked loop (PLL) is used to obtain an accurate synchronisation to the grid. The synchronisation algorithm must cope with the existing electrical environment [1], e.g. with harmonics, voltage sags and commutation notches. Another problem is grid frequency variations. In strong grids, the frequency variations are usually small, but larger frequency variations occur in autonomous grids. Furthermore, the synchronisation must handle measurement noise. An accurate zero voltage crossing detection is essential for the control of grid-commutated converters. Otherwise, the converter system can suffer from poor performance or even instability.

The firing angle unit for thyristor valves uses the zero voltage crossing as a reference; the zero voltage crossing must be accurately detected each half period of the grid [2]. A more demanding application is the grid connection of a forced-commutated voltage source converter (VSC) when vector current control is used [3]. The synchronisation must be updated not just at zero voltage crossings, but continuously under the whole period. In this case, a flux-based transformation angle detector (TAD) is used to obtain the rotating dq-coordinate system [3].

The classical synchronisator is an analogue PLL [4], designed around the IC chip 4046. Today, control systems of converters are often implemented by a computer. By using a software solution to the PLL, a flexible and cost effective solution is obtained. The analogue PLL function can be translated into a software PLL function [5], but the low update frequency from zero voltage detection is a disadvantage. Digital filters and controllers can, however, increase performance and make new methods feasible. If the input signal is noisy, a predictive digital filter can be used to find the zero voltage crossings for the PLL [6]. The calculation time is critical for a real-time control system, which results in a demand for fast algorithms.

In this paper, four synchronisation methods will be analysed. The complexity of the methods varies from a simple method adapted for stiff-grid applications to the extended Kalman filter (EKF) and a novel space vector filter (SVF), which can handle both phase angle steps and frequency steps. The performance of the synchronisation methods will be analysed based on three criteria: phase shift response, frequency step response and sensitivity to grid voltage harmonics. The maximum allowed frequency change is 1Hz/s in accordance with the IEC 1800-3. However, a good understanding of the performance is obtained by using frequency step responses.

2 VSC system connected to weak grid

When a VSC is connected to a weak grid, the voltage at the point of common connection (PCC) will vary and become a function of several variables: the grid voltage behind the impedance describing the grid, the grid current and the short-circuit parameters of the grid. A step in the power from the VSC (or another user of the grid at the PCC) results in a step change of the voltage vector at the PCC.

The VSC connected to a weak grid and the vector current controller are shown in Fig. 1. The transformation angle $\theta(t)$ is used to transform grid currents and grid voltages needed in the vector current controller into the dq-coordinate system. The d-axis of the rotating dq-coordinate system is synchronised with the grid flux vector. The reference voltages from the current controller are transformed back to three-phase values. The synchronisation must have a high performance due to the structure of the vector current controller. A phase shift in the synchronisation will result in steady-state errors, and the cross-coupling current gain will increase. In addition, poor performance or instability can occur if the synchronisation is sensitive to noise or reacts too distinctly to phase steps.

3 TAD based on low-pass filtering of grid voltage

A simple method is obtained by low-pass filtering (LP filtering) the grid voltage vector, and the method is denoted by LP-TAD. A first-order Butterworth filter is utilised. The cut-off frequency is tuned to between 0.1 and 25Hz. The phase lag of a first-order filter depends on the grid frequency and the cut-off frequency. The desired phase lag of 90° occurs at an infinite frequency. The phase lag will, thus, be less than 90° due to the grid frequency of 50 or 60Hz. The phase lag increases when the cut-off frequency decreases. By using a coordinate transformator, the LP-filtered grid voltage vector can be rotated by an angle $\Delta\theta$ so that the phase lag becomes 90°. Fig. 2 shows a diagram of the LP-TAD. Due to the extensive calculation time of trigonometric functions of the DSP, the transformation angle itself is not used. The sine and cosine of the transformation angle are obtained by dividing the LP-filtered α- and β-voltage components by the length of the LP-filtered voltage vector. The correct phase lag is obtained by using the rotation matrix $\boldsymbol{R}$.

Two calculated step responses to a 10° phase-shift in the grid voltage vector are presented in Fig. 3. The grid frequency is 50Hz and the cut-off frequency is 0.5Hz or 5.0Hz. Coordinate transformation is not used to correct the phase-shift. Different steady-state angle errors, due to different cut-off frequencies, can be observed. The phase-shift errors are approximately 1° and 6° for cut-off frequencies 0.5 and 5Hz, respectively. Unfortunately, the detector characteristics are undamped and oscillate. The damping is increased by a higher cut-off frequency. This behaviour makes the detector unsuitable for applications where phase jumps can occur. In practice, every grid-connected VSC is exposed to grid phase jumps due to short circuits in other nodes of the grid [7]. The LP-TAD is also sensitive to grid frequency deviations.

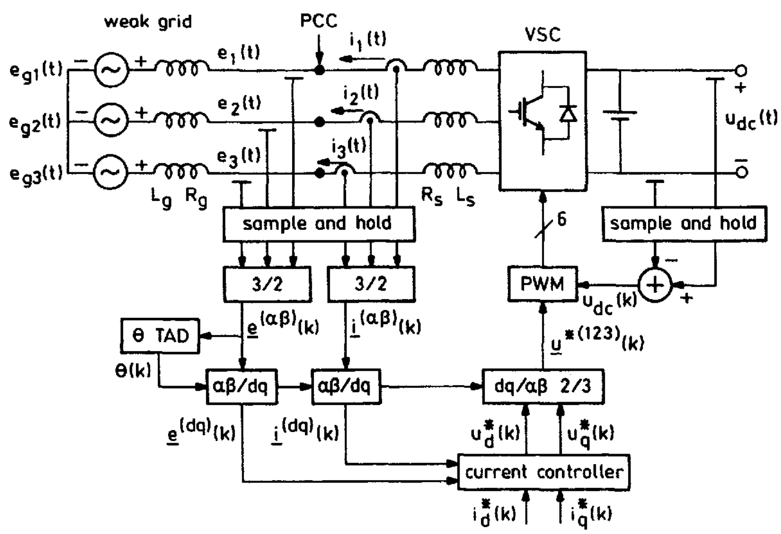

Fig. 1 *VSC system diagram cosisting of VSC, grid filter, weak grid and vector current controller*

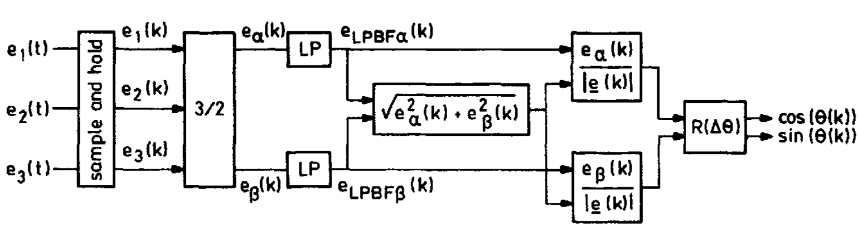

Fig. 2 *Diagram of LP-TAD*