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Quick and high performance direct power control for multilevel voltage source rectifiers

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ABSTRACT

The paper deals with the control of three-phase voltage source rectifiers (VSRs) with an arbitrary number of voltage levels. By means of an approach borrowed from the “Direct Torque Control” of AC drives, the paper presents an enhanced direct power control (DPC) strategy for VSRs which directly controls both active (P) and reactive (Q) line power by considering the values of their time derivatives. This control strategy can be applied both to the Neutral Point Clamped and to Cascaded H-bridge multilevel converters.

In every sampling interval the proposed control technique is able to select the most suitable converter voltage vector to obtain good dynamic response and to maintain P and Q within their respective reference bands. This result is achieved in the different operating conditions by means of a Dynamic Look-Up Table (D-LUT) of the converter voltage vectors, which are ordered on the basis of their influence on P and Q time derivatives. The mentioned D-LUT depends on the instantaneous operating point and is not predetermined.

Some significant operating conditions are numerically investigated in order to show the capability of the modified DPC technique to ensure good values of power quality indexes for the grid. Experimental results on a laboratory setup based on a three-level VSR show good accordance with the simulation ones.

1. Introduction

For many years, the achievement of high-level standards of power quality has been an essential need for power electric grids. This is mainly due to the simultaneous widespread deployment of distributed generation and of loads massively using power electronics. Among the solutions adopted to obtain high values of power quality indexes, the active front ends play an important rule. When in multilevel configuration, these voltage source rectifiers (VSRs) are particularly efficacious in interfacing either loads or renewable energy sources to the electric grid. As is well known, in addition to their intrinsic capability of bidirectional power flow and to the positive influence that they have at the load side, the VSRs are very useful at the grid side. In fact they contribute both to improve power-factor values and to reduce asymmetry and distortion of currents by controlling instantaneous active (P) and reactive (Q) power.

Many topologies of multilevel VSRs have been investigated in the technical literature and implemented in practice together with different control strategies (see e.g. [1–12]). Each control strategy is usually coordinated with the specific considered topology. This occurs because the multilevel topologies require increased complexity in the control due to some considerable accessory problems, e.g. voltage balance problem on the DC link or high number of selectable voltage vectors. The control strategies can be classified into two main categories: strategies based on a direct current control and strategies based on the selection of an appropriate converter voltage vector. The direct power control (DPC) technique belongs to this second group.

The main goal of the conventional DPC technique [1] (introduced by Akagi et al. [2]) is to carry out an appropriate selection of converter voltage vectors, by means of a preconceived look-up table (LUT), in order to follow the instantaneous references of P and Q power with a unity power factor [13–16].

Simplicity, versatility and good dynamic performance are the advantages of the traditional DPC techniques for several transportation and industrial applications. On the other hand, the switching frequency of DPC is not constant; moreover, another typical

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Nomenclature

List of symbols

α_λ, β_λ axes delimiting the 60-degree sector (λ) of the voltage complex plane
$\Delta P_{inner} = \frac{1}{2} P_{slope,WC} \cdot T_s$ integer numbers that represent the "distance" of the voltage vector to be applied from v_{c1}
$\gamma^p_{r,\max}$, $\gamma^p_{h,\max}$ upper limits of γ_r, γ_h within performance vectors domain
$\gamma^p_{r,\min}$, $\gamma^p_{h,\min}$ lower limits of γ_r, γ_h within performance vectors domain
δ duty cycle of the first voltage vector
ΔP_{inner} active power inner hysteresis band
ΔP_{outer} active power outer hysteresis band
ΔQ reactive power hysteresis band
Δr_1, Δh_1 real numbers defining the vector Δv
Δ_{slope} estimator of the average increment of active power derivative magnitude
$\Delta v(\Delta P_{outer} = 2 \cdot \Delta P_{inner})$ "distance vector" of v_{c1} from v_c^*
λ integer number denoting one of the 60-degree sectors of the complex voltage plane
φ instantaneous phase angle of $\mathbf{V}_p^{(1)}$ "reduced" to the interval $(0, \pi/3)$
ψ $(\psi = \omega t)$ instantaneous phase angle of $\mathbf{V}_p^{(1)}$
σ sector of $\mathbf{V}_p^{(1)}$
ω grid angular frequency
D_S, D_E *sorted* vectors domain and *existing* vectors domain
D_{ES}, D_P *existing sorted* vectors domain and *performance* vectors domain
$\mathbf{i}$ grid current space vector
i_k kth-phase line current
L_F,R_F inductance and resistance of the input filter of the voltage source rectifier
m number of voltage source rectifier voltage levels
r, h integer coefficients of the converter voltage vectors $\mathbf{v_c}$ for a generic sector $\bar{\lambda}$
r^*, h^* indexes of the voltage vector $\mathbf{v}_c^*$
r_1, h_1 indexes of the converter voltage vector $\mathbf{v}_{c1}$
s_k switching functions of the kth converter phase
v_k kth-phase supply voltage
$v_{c,k}$ kth-phase converter voltage
v_{dc} total DC-link voltage
$v_{O,O'}$ voltage between O and O'
P, Q actual active and reactive power
P^*, Q^* reference active and reactive power
$\dot{p}$, $\dot{q}$ power derivatives, in pu, imposed by the generic converter voltage vector v_c
$\dot{p}_1$, $\dot{q}_1$ the power derivatives, in pu, imposed by the converter voltage vector v_{c1}
$\mathbf{P}_{cmx}$ instantaneous line *complex power* (corresponding to $\mathbf{V}_p^{(1)}$)
$P_{slope,WC}$ minimum obtainable active power slope in the worst case
T_s sampling time
$\mathbf{v}$ grid voltage space vector
$\mathbf{v}_{\alpha,\lambda}$, $\mathbf{v}_{\beta,\lambda}$ smallest converter voltage vectors along the axes α_λ, β_λ delimiting the 60-degree sector λ
$\mathbf{v}_c$ converter voltage space vector
$\mathbf{v}_{c1}$ approximated zero-slope converter voltage vector
$\mathbf{v}_c^*$ voltage vector which sets both active and reactive time derivatives to zero
$\mathbf{V}_p^{(1)}$ space vector of positive (forward) sequence of the line voltages at the fundamental harmonic
x_p, x_q positive real numbers evaluated by Phase-Locked Loop routine

drawback is the non-uniform behavior in tracking the power reference in the whole range of operating conditions. These drawbacks of conventional DPC have been overcome in the literature using different approaches [17–25]. The most effective solutions are based on a predictive current approach [17,18], or the sinusoidal pulse width modulation technique (PWM) or space vector modulation [19–25]. In each of these solutions the control tries to follow the power reference in a specific way. However these control techniques are always based on the selection of a proper conduction state of the converter, linked to a static and predetermined LUT, which does not take into account the actual operating condition of the system. As a consequence the performance of these modified DPCs are not uniform in all the operating conditions. In addition, when multilevel converter topologies are used, the problem of a suitable selection of the voltage vector is really complex and it has been usually solved by referring only to a reduced number of voltage vectors; this implies that not even optimized vectors are selected. Moreover, the different DPC algorithms proposed in the literature are valid only for a given number of voltage levels of VSRs.

The paper deals with a modified DPC strategy that uses a virtual dynamic LUT (D-LUT) strictly linked to the operating conditions, in order to achieve a direct control on time-derivative values of both P and Q. The proposed DPC technique is based on a simultaneous action of two hysteresis controllers (single- and/or double-band controllers), which give the entry values of LUTs for a quick selection of the most suitable converter voltage vector. Instead of the static LUTs of conventional DPCs, the modified control strategy consists of appropriately sorted lists of vectors that are dynamically built, starting from the knowledge of the instantaneous state of the grid. In each sampling interval the choice of the converter voltage is suggested by the desired time-derivative values of both P and Q.

A "variable duty cycle" is also introduced to reduce ripple of the main lines' quantities; by means of a predictive evaluation of the system state, the converter voltage vector is properly changed within a sampling interval, in order to reduce P and Q deviations from their reference values.

Moreover, the DPC algorithm presented in this paper refers to VSRs with an arbitrary number of voltage levels (even if the examples refer to a seven-level VSR). The main purpose of this particularization is to illustrate in detail the procedure for the dynamic construction of ordered lists of converter voltages suitable to quickly follow P and Q reference values.

Simulation and comparative analysis are provided in order to appreciate the capabilities of the proposed control and to underline the better performance obtained with respect to conventional DPC techniques. Finally, experimental tests are carried out on a laboratory multilevel VSR in order to validate theoretical simulated results.

2. Multilevel VSR model

The following investigations refer to multilevel VSRs, connected to a three-phase grid through a R_F, L_F filter, as schematically represented in Fig. 1.

The mathematical relations of this section and the control procedure of Section 3 could be considered valid either for diode-clamped or flying capacitors or cascaded H-bridge converter