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Extending the reactive compensation range of a direct AC–AC FACTS device for offshore grids

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ABSTRACT

The authors suggest to use hybrid modulation schemes to improve the reactive power compensation capabilities of the direct AC–AC FACTS device composed of a matrix converter and a permanent magnet machine. Because of the intrinsic limitations of the conventional matrix converter modulation schemes, the device has so far displayed a poor reactive power compensation capability when the output power factor is low. Even worse, the direct AC–AC FACTS device could not provide pure reactive power compensation. The paper presents an analysis demonstrating how the hybrid Three-Vector-Scheme extends the reactive compensation range beyond the level that the conventional indirect space vector modulation exhibits. The reactive power compensation capabilities of the FACTS device with both modulations are computed and compared analytically and finally verified by a simulation study.

1. Introduction

Large scale integration of wind energy will call forth an increased use of Flexible AC Transmission Systems (FACTS). For offshore AC grids, appropriate FACTS device should possess the two following features: high power density and high reliability. The direct AC–AC FACTS device composed of a matrix converter and a permanent magnet (PM) synchronous machine, see Fig. 1, is both compact and reliable mainly because the DC link capacitor is eliminated.

In [1,2] was introduced the idea of benefiting from the features of the matrix converter and provide power conditioning in drives and power conversion applications. A dedicated direct AC–AC FACTS device was presented in [3,4] for voltage compensation and reactive power support to the grid. The device can provide reactive power compensation like a STATCOM by controlling directly the input current fed to the grid, see Fig. 1. In addition active power control can be provided if there is a load on the shaft of the PM machine. The functioning of the device was experimentally verified in [1], however reactive power compensation capability was poor for low output power factor and could not perform pure reactive power compensation alone. The authors suggest in this paper to implement the hybrid modulation schemes presented in [5–8] to extend the reactive power compensation range of the FACTS while also enabling pure reactive power compensation. In [8] the FACTS device suggested here and in [4] is identified as a possible application for the hybrid modulation.

The reactive power compensation range of the AC–AC FACTS device depends on the modulation scheme of the matrix converter and also on the output power factor and current amplitude. The output conditions are determined by the PM machine. The approach used to model the PM machine is described in Section 2. The hybrid modulation schemes are modified versions of the conventional Indirect Space Vector Modulation (ISVM). In Section 3 the limitations that the ISVM causes on the reactive power compensation range of the FACTS device are analyzed.

The hybrid modulation can be used to extend the reactive power compensation at any low output power factor value, however for the sake of brevity, only the extreme case of zero output power factor corresponding to pure reactive power will be investigated. The hybrid Three-Vector-Scheme (3VS) features the highest overall current transfer ratio and is therefore chosen for the application of pure reactive power compensation. It is important to mention here that there exist other modulations that feature pure reactive input power [9,10]. However the 3VS is interesting as it is based on the ISVM and can thus provide a deeper understanding of the underlying mechanisms. In Section 4 the modifications made to the ISVM to obtain the 3VS are described and the reactive power compensation capability of the FACTS device with 3VS is computed and discussed. Finally in Section 5, the results of the simulation study carried out using Matlab Simulink to compare with the analytical findings, is presented. The notation used is explained in Table 1.

2. Modeling of the AC–AC FACTS device

A simple per-phase equivalent circuit of the FACTS device, depicted in Fig. 2, will be used to analyse how the PM machine influences the output of the matrix converter. In Fig. 2, the matrix

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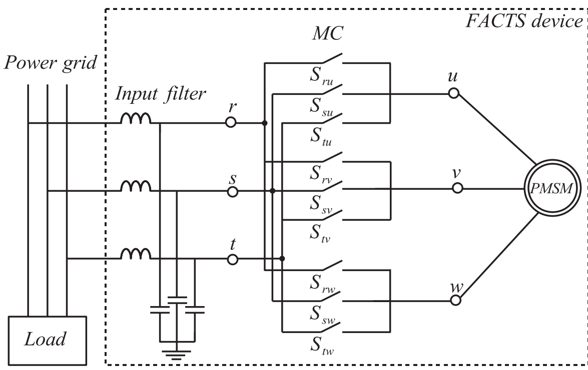

Fig. 1. The matrix converter-based FACTS device connected to the grid for reactive power compensation.

Table 1
Notation.

$\vec{Y}$	Phasor
$\hat{Y}$	Magnitude (peak value)
Y	Magnitude (RMS value)
Y_i/Y_o	Input/output variable of the matrix converter
δ_y	Phase angle of variable y
$\Phi = \delta_{voltage} - \delta_{current}$	Power factor angle
$q = \frac{\hat{V}_o}{\hat{V}_i}$	Voltage transfer ratio
$q_i = \frac{\hat{I}_i}{\hat{I}_o}$	Current transfer ratio
$q_n = \frac{q}{\frac{\sqrt{3}}{2}}$	Normalized modulation index
P/Q	Active/reactive power
T_s	Switching period
$d = \frac{\delta t}{T_s}$	Duty ratio
$\vec{u}/\vec{i}$	Active or zero voltage/current vectors
$\vec{v_{sp}}/\vec{i_{sp}}$	Voltage/current space vector
θ_{sp}	Angle of space vector
R	Armature resistance
X_s	Synchronous reactance
E	Excitation voltage
j	$j^2 = -1$

converter is represented by a black box which transforms the grid voltage modeled by a sinusoidal voltage source, $\vec{V}_i = V_i\angle 0$, into the output voltage, $\vec{V}_o = V_o\angle 0$ which corresponds to the terminal voltage of the PM machine. The matrix converter fully controls the output voltage phase angle. The output voltage and the input voltage are therefore both set to have zero phase angles for simplicity. The input filter which is needed to avoid the current harmonics from polluting the grid, is neglected as it influences the fundamental frequency operation very little. The output current amplitude and phase angle are calculated as:

$$I_o = \sqrt{\left(\frac{V_oR - ER\cos\delta_E + EX_s\sin\delta_E}{R^2 + X_s^2}\right)^2 + \left(\frac{ER\sin\delta_E - V_oX_s + EX_s\cos\delta_E}{R^2 + X_s^2}\right)^2} \quad (1)$$

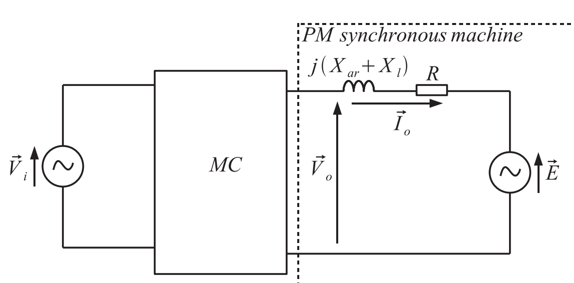

Fig. 2. The per-phase simplified representation of the matrix converter-based reactive power compensation device.

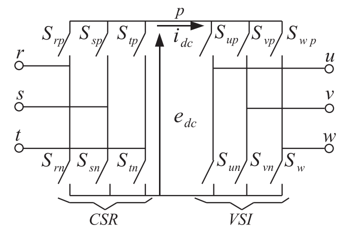

Fig. 3. The indirect matrix converter.

$$\Phi_o = -\tan^{-1}\left(\frac{ER\sin\delta_E - V_oX_s + EX_s\cos\delta_E}{V_oR - ER\cos\delta_E + EX_s\sin\delta_E}\right) \quad (2)$$

In the particular case of no load on the rotor shaft of the PM machine, no active power is transferred through the matrix converter, the output power factor zero, corresponding to the FACTS device providing pure reactive power compensation.

3. The indirect space vector modulation

3.1. Description of the indirect space vector modulation

The conventional ISVM considers the matrix converter to be of the indirect form, see Fig. 3 and breaks the modulation down into the basic Voltage Source Inverter (VSI) space vector modulation and Current Source Rectifier (CSR) space vector modulation, as is represented in Fig. 4. With every switching interval, T_s, new duty ratios are calculated for both modulations. Eqs. (3) and (4) are used for calculating the duty ratios d_{rs} and d_{rt} corresponding to the case of the input current space vector $\vec{i}_{i,sp}$ lying in the sector formed by the active vectors $\vec{i}_{rs}$ and $\vec{i}_{rt}$. The subscripts of the vectors and duty ratios correspond to the applied pulse. In a CSR only one upper switch and one lower switch is ON, represented respectively by the first and second letter in the subscript.

$$d_{rs} = \frac{t_{rs}}{T_s} = \frac{\hat{I}_i\sin(\pi/6 - \theta_{i,sp})}{i_{dc}} \quad (3)$$

$$d_{rt} = \frac{\hat{I}_i\sin(\pi/6 + \theta_{i,sp})}{i_{dc}} \quad (4)$$

Similarly when the output voltage space vector $\vec{v}_{o,sp}$ is lying in the sector formed by the active vectors $\vec{u}_{pnn}$ and $\vec{u}_{ppn}$ the duty ratios are calculated as in Eqs. (5) and (6). The upper and lower switches in a leg of the VSI are complementary. The subscript indicates whether the upper (p) or lower (n) switch is ON.

$$d_{pnn} = \sqrt{3}\frac{\hat{V}_o\sin(\pi/3 - \theta_{o,sp})}{e_{dc}} \quad (5)$$

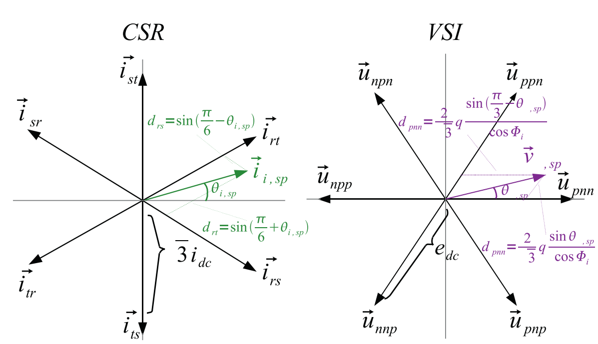

Fig. 4. ISVM of the CSR part (left) and of the VSI part (right): in the complex plane are represented the current and voltage reference space vectors $\vec{i}_{i,sp}$ and $\vec{v}_{o,sp}$ as well as the active vectors used to build the input current ($\vec{i}_{rt}, \vec{i}_{st}$...) and the output voltage ($\vec{u}_{pnn}, \vec{u}_{ppn}$..).