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Power Electronics Engineering

Elixir Power Elec. Engg. 37 (2011) 3893-3896

ISSN: 2229-712X

Application of matrix converter as the active power and voltage magnitude controller in power systems

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ARTICLE INFO

Article history:
Received: 14 June 2011;
Received in revised form: 19 July 2011;
Accepted: 29 July 2011;

Keywords
Active power control,
Matrix converter,
Power system compensation,
Voltage control.

ABSTRACT

The aim of this paper is to present control of voltage magnitude and active power flow by means of a matrix converter. The matrix converter based compensator acts as the power electronic interface connected in series with a transmission line. Such a power system compensator consists of two power transformers and a three-phase to three-phase matrix converter. The compensator adjusts the active power flow on the transmission line and the voltage Magnitude at the bus of the power system. Pulsed Width Modulation (PWM) technique is employed as the switching strategy. Performance of the matrix converter based compensator is evaluated in the Simulink/MATLAB environment.

Introduction

Owing to the environmental concerns and the growth of demand on electrical energy a considerable amount of attempt has being made to change the traditional concepts of power systems. In this regards the Flexible AC Transmission Systems (FACTS) technology has been introduced. FACTS are a family of power electronic represents a new concept of power transmission systems. In the newest products of these systems, the use of converter-based series and shunt compensators with fast response times play an important role, allowing the amount of power transfer through an existing line to increase. The recent FACTS devices such as UPFC use back-to-back converters with DC capacitor link, which provides an AC/DC/AC conversion. The DC capacitor increases size and volume of the system. The proposed compensator in this study can be considered as a new FACTS device providing the direct AC/AC conversion with no DC capacitor.

The matrix converter is an attractive topology of direct AC/AC power converter where factors such as the absence of electrolytic capacitors and reducing size and weight quality are fundamental. The drawbacks of the matrix converter are:

(1) The low voltage transfer ratio; and

(2) The strong coupling between the two AC sides of the converter.

The idea of using matrix converter in power system application was first introduced by Kazerani [1, 2]. In [3] this idea is developed. In these articles the matrix converter is replaced with the conventional back-to-back converter; but, series compensation with matrix converter was not investigated. In [4] the idea of application of a matrix converter as a series compensator is proposed; however, the objective was only to control the output voltage shift. Besides, the topology of 6 6 matrix converter with a 6-phase output transformer proposed in [4] seems not to be practical.

In this paper, a three-phase to three-phase matrix converter connected in series with the transmission line is proposed. The objectives are to control the active power flow on the transmission line and the voltage magnitude control at the bus. The switching strategy used in this study is based on PWM technique, which eliminates the undesired harmonic components. The rest of this paper is organized as follows: In section II, the fundamental of matrix converter and switching strategy is presented. In section III, the control of compensator will be described. Results and simulation are provided in section IV. Finally conclusions are given in section V.

Fundamental of matrix converter and PWM switching strategy

The Matrix Converter

The structure of a three phase to three phase matrix converter is shown in Fig. 1. This converter is composed of nine bidirectional semiconductor switch cells. Each input phase can be connected through one switch cell to the output phases.

A three-phase matrix converter has the ability to connect two three phase systems. The three-phase systems may have the different voltage amplitudes, different phase angles, and different frequencies.

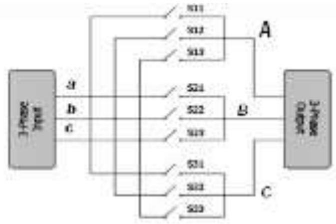

Figure 1: Three-phase matrix converter

Equation (1) shows this relation between the input and the output voltages of a matrix converter:

$$[V_o(t)]=[S(t)]\times[V_i(t)], \qquad (1)$$

Where:

$$[V_i(t)]=\begin{bmatrix} V_{im}\cos(\omega_i t) \\ V_{im}\cos(\omega_i t+\frac{2\pi}{3}) \\ V_{im}\cos(\omega_i t+\frac{4\pi}{3}) \end{bmatrix}, \qquad (2)$$

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$$\left[V_o(t)\right]=\begin{bmatrix} qV_{im}\cos(\omega_o t+\psi) \\ qV_{im}\cos(\omega_o t+\frac{2\pi}{3}+\psi) \\ qV_{im}\cos(\omega_o t+\frac{4\pi}{3}+\psi) \end{bmatrix}. \qquad (3)$$

In (2) and (3), V_{im} is the amplitude input voltages, q is the voltage transfer ratio, and ω_i,ω_o is the angular frequency of input/output voltages.

In (1) [S(t)] is the switching matrix and the elements of S(t) are determined by switching strategy. A number of switching strategies have been proposed for matrix converter [5,6,7,8]. In order to regulate the voltage magnitude at the of the matrix converter output bus, magnitude of converter output voltage must be controlled. This can be achieved by adjusting the voltage transfer ratio, q.

We may like to control the power flow in a AC transmission line to enhance power transfer capacity and or to change power flow under dynamic conditions (subjected to disturbances such as sudden increase in load, line trip or generator outage) to ensure system stability and security. Assuming the line to be lossless in Fig. 2 and ignoring the line charging, the power flow (P) is given by

$$P=\frac{V_1V_2}{X}\sin(\theta_1-\theta_2), \qquad (4)$$

where X is the series line reactance.

The power flow in a lossless transmission line with a matrix converter (see Fig. 3) is given by

$$P=\frac{qV_1V_2}{X}\sin(\theta_1-\theta_2+\psi). \qquad (5)$$

To regulate the active power flow on the transmission line, the phase-angle of the converter output voltage must be adjusted. This can be achieved by adjusting the ψ.

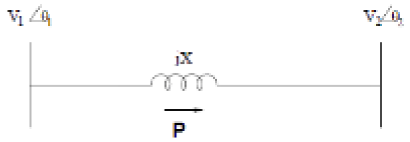

Figure 2: A transmission line carrying power.

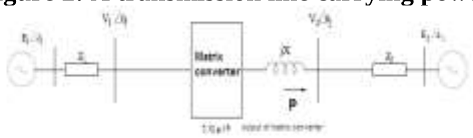

Figure 3: Single line diagram transmission line including matrix converter.

PWM Switching Strategy for Matrix Converter

The switching strategy presented in this paper is based on the PWM switching strategy.

The modulation problem assumes that a set of sinusoidal output voltages is required. This set can be represented as (3). There is also a constraint equation for Matrix Converters:

In order to avoid open and short circuit conditions, one and only one of the input phases must be connected to every output phase at any instant:

$$S_{j1}(t)+S_{j2}(t)+S_{j3}(t)=1 \qquad (6)$$
$$j=1,2,3.$$

Thus the switching matrix S(t) should be determined such that (1) as well as the constraint equation is satisfied. The problem was treated by Venturini [9], who found two solutions for [S(t)].The solutions are expressed in (5) and (6).

$$\frac{1}{3}\begin{bmatrix} 1+2q\cos(\omega_m t+\psi) & 1+2q\cos(\omega_m t-\frac{2\pi}{3}+\psi) & 1+2q\cos(\omega_m t-\frac{4\pi}{3}+\psi) \\ 1+2q\cos(\omega_m t-\frac{4\pi}{3}+\psi) & 1+2q\cos(\omega_m t+\psi) & 1+2q\cos(\omega_m t-\frac{2\pi}{3}+\psi) \\ 1+2q\cos(\omega_m t-\frac{2\pi}{3}+\psi) & 1+2q\cos(\omega_m t-\frac{4\pi}{3}+\psi) & 1+2q\cos(\omega_m t+\psi) \end{bmatrix} \qquad (7)$$

$$\text{for } \omega_m=\omega_o-\omega_i$$

$$\frac{1}{3}\begin{bmatrix} 1+2q\cos(\omega_m t+\psi) & 1+2q\cos(\omega_m t-\frac{2\pi}{3}+\psi) & 1+2q\cos(\omega_m t-\frac{4\pi}{3}+\psi) \\ 1+2q\cos(\omega_m t-\frac{2\pi}{3}+\psi) & 1+2q\cos(\omega_m t-\frac{4\pi}{3}+\psi) & 1+2q\cos(\omega_m t+\psi) \\ 1+2q\cos(\omega_m t-\frac{4\pi}{3}+\psi) & 1+2q\cos(\omega_m t+\psi) & 1+2q\cos(\omega_m t-\frac{2\pi}{3}+\psi) \end{bmatrix} \qquad (8)$$

$$\text{for } \omega_m=\omega_o+\omega_i$$

Using these solutions the maximum value of input to output voltage ratio, q, that the converter can achieve is 50%. The modulation algorithm represented by (5) and (6) is suitable for real time implementation. For an input and output frequency of 50 Hz and a modulation frequency of 100 Hz (6) and frequency modulation ratio of 12, the switching frequency of the matrix converter is about 1200 Hz. Fig. 4 shows creating of switching functions based on PWM technique.

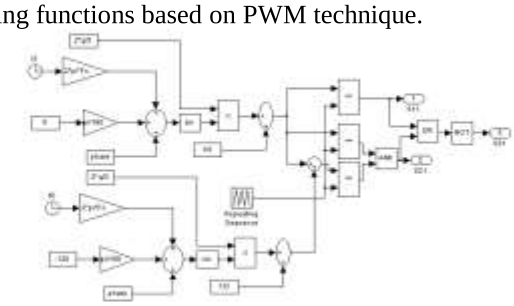

Figure 4: Matrix converter switching generation.

Control of matrix converter

The objective is to investigate the control of matrix converter in the power system. The control strategy makes it possible to control the magnitude and phase-angle of the output voltage of the matrix converter.

The main function of the series FACTS steady-state controller is to control power flow. For the shunt FACTS steady-state controller, its main function is to achieve the reactive compensation and bus voltage control. The proposed compensator based on the matrix converter is able to control both power flow and bus voltage.

Based on (6), amplitude and phase-angle of the fundamental component of is expressed in terms of q and :

$$S_{11}=\frac{1}{3}(1+2q\cos(\underbrace{\omega_m t+\psi}_{\delta(t)})). \qquad (9)$$

Magnitude of the matrix converter output voltage is controlled by regulating q of the converter switches. A temporary change in the output frequency of the converter, changes both frequency and phase-angle of matrix converter output voltage .

The converter output side is connected to a system whose voltage frequency is assumed to be constant (50 Hz). Hence the converter output frequency is not changed ( ). Therefore, to regulate the active power flow on the transmission line, the phase-angle of the converter output voltage must be controlled ( ).

In this paper a closed loop control system is developed to enable independent control the magnitude and phase-angle of the output voltage based on PWM switching strategy. Fig. 5 shows a block diagram of the closed loop controller.

Phase-angle controller

The objective is to control the matrix converter output voltage phase-angle to accommodate real power demand. The output phase-angle variable is measured with respect to voltage angle of the slack bus in the system. A Proportional-Integral (PI) controller is used to control phase-angle.

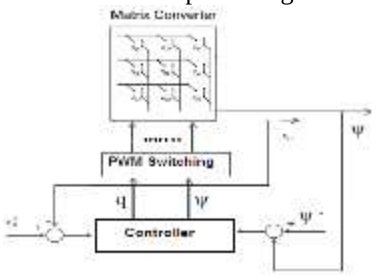

Figure 5: Matrix converter switching generation.

The reference and measured values of the voltage phase-angle are compared, and the controller adjusts the for the converter switches in order to set the phase-angle to its reference value. The error is given as follows:

$$e=\psi^{*}-\psi \tag{10}$$

The controller operation is given by

$$\psi=K_p e+K_I\int e\ . \tag{11}$$

Where and denote proportional and integrating coefficients of the magnitude controller, respectively.

Magnitude controller

The objective is to control the matrix converter output voltage magnitude. The output voltage magnitude variable is . A Proportional-Integral (PI) controller is used for the voltage magnitude control. The reference and measured values of the voltage magnitude are compared, and the controller adjusts the q for the converter switches in order to set the magnitude to its reference value. Based on (3), magnitude of the matrix converter output voltage can be written as:

$$V_o=qV_i,\ 0\le q\le 0.5 \tag{12}$$

The error e is:

$$e=v_o^{*}-v_o\ . \tag{13}$$

The controller operation is given by

$$q=K_p e+K_I\int e\ . \tag{14}$$

Where and denote proportional and integrating coefficients of the magnitude controller, respectively. The detailed representation of Fig. 5 is depicted in Fig. 6. The system consist a real power controller (see Fig. 6).

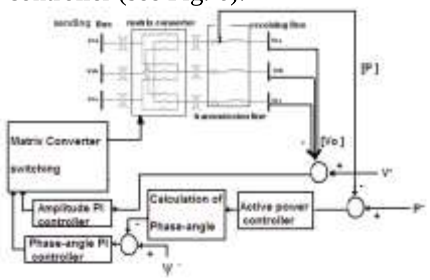

Figure 6: Matrix converter switching generation

This controller determines the reference value of ψ based on the required value of real power on transmission line.

Simulation results

The test system taken for simulation is shown in Fig. 3. The converter is controlled by the control system of Fig. 6. It regulates magnitude and phase-angle of the converter output voltage that control real power of the transmission line. The studies are conducted in time-domain in the SIMULINK/MATLAB software environment. The generators in the system are modeled as three-phase ideal voltage sources in series with an R-L branch in each phase and the dynamic of synchronous machines are neglected. The base values of the system line voltages and power are, respectively, $V_{ab}=720$ v and $S=100$ KVA . The gains of the controllers are found by trial and error method for best response for the test system considered in this paper. Parameters of the system of Fig. 3 are listed in Table I. The system is initially operating at a steady-state condition.

Control of Active Power Flow on the Transmission line

The performance of the system of Fig. 3 in response to a step change is tested. In this case P_{ref} was subjected to a step change from 0 to 1 at time 0.1. The active power flow in this case is shown in Fig. 7 which has an overshoot of about 5%. The system was initially operating at P=0.8 pu. The objective --of the compensator was to set the transmission line real power to the value of P=1.0 pu. Results illustrate that the transmission line real power track the corresponding references.

Magnitude Control

Fig. 8 shows the system response to a step change in the reference of magnitude of the converter output voltage. In this case V_{ref} was subjected to a step change from 0 to 0.9 at time 0.1. The matrix converter output voltages follow the desired reference because the magnitude controller regulates the voltage ratio q. The voltage magnitude in this case is shown in Fig. 8 which has an overshoot of about 6%. The system was initially operating at V=1.1 pu. The objective of the compensator was to set magnitude of the converter output voltage to the value of V=0.9 pu. Results shown in Fig. 8 illustrate that the magnitude of output voltage faithfully track the corresponding references.

Control of Active Power Flow and Voltage Magnitude

Performance characteristic of the compensator for step changes in both the real power and voltage magnitude references, are shown in Fig. 9 and Fig.10, respectively. These figures show that the compensator has set the control parameters to their corresponding desired reference values. In this case P_{ref} was subjected to a step change from 0 to 1 at time 0.08 and V_{ref} was subjected to a step change from 0 to 1 at the same time. The system was initially operating at V=1.1 pu and at P=0.8 pu. The objective of the compensator was to set magnitude of the converter output voltage to the value of V=1.0 pu and the real power on the transmission line to P=1.0 pu. Results illustrate that the transmission line real power and the magnitude of output voltage faithfully track the corresponding references.

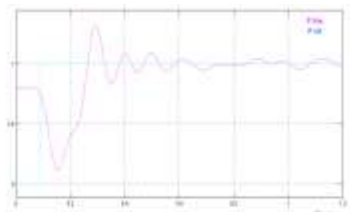

Figure 7: Active power flow through the line for a change in active power reference from 0 to 1.0 p.u

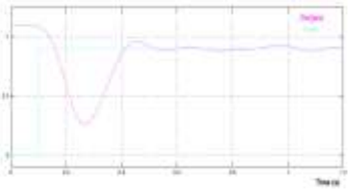

Figure 8: Magnitude of voltage for a change in voltage reference from 0 to 0.9 p.u .

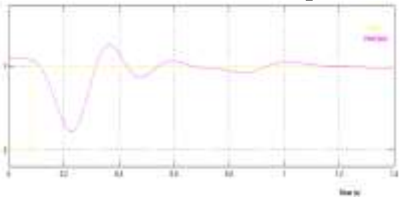

Figure 9: Magnitude of voltage for a change in voltage reference from 0 to 1.0 p.u .

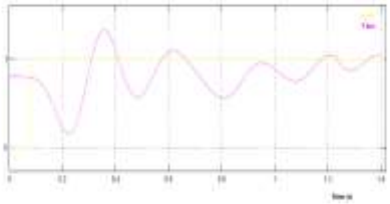

Figure 10: Active power flow through the line for a change in active power reference from 0 to 1.0 p.u

Conclusion

This paper presented a controller of voltage magnitude and active power flow for the series connected matrix converter based compensator. The proposed compensator provides a direct AC/AC conversion and reduced control complexity owing to absence of DC link. PWM technique is employed for switching of matrix converter. The compensator has been tested with the step change in reference real power and voltage magnitude. Matrix converter based compensator is capable of controlling the active power flow on the transmission line and the voltage magnitude at the bus of the power system. Performance of the compensator is evaluated based on digital time domain simulation in the SIMULINK/MATLAB environment.

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Table 1: System Parameters

Parameters	Values
Power system frequency	50 Hz
Z_1	0.01+j0.15 pu
Z_2	0.01+j0.62 pu
Gains for voltage control loop	K_p=0.01 ,K_I =1.0
Gains for line active power control loop	K_p=0.0001 ,K_I = 0.001
Switching frequency	1200 Hz