Vector analysis and control of advanced static VAR compensators

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Abstract: The advanced static VAR compensator (now widely known as the static condenser or STATCON) uses a high power self-commutating inverter to draw reactive current from a transmission line. Two fundamentally different types of invertor can be used for this purpose, one providing control of output voltage magnitude and phase angle, and the other having only phase angle control. For each of these types, the governing equations are derived, and frequency domain analysis is used to obtain the relevant transfer functions for control system synthesis. Further analysis is provided to determine the response of the STATCON to negative sequence and harmonic voltage components on the transmission line. The results are illustrated with measured waveforms obtained from a scaled analogue model of an 80 MVAR STATCON.

1 Introduction

The advanced static VAR compensator (ASVC) is based on the principle that a self-commutating static inverter can be connected between three-phase AC power lines and an energy-storage device, such as an inductor or capacitor, and controlled to draw mainly reactive current from the lines. This capability is analogous to that of the rotating synchronous condenser and it can be used in a similar way for the dynamic compensation of power transmission systems, providing voltage support, increased transient stability, and improved damping [1, 2]. The ASVC inverter requires gate-controlled power switching devices such as GTO thyristors. GTOs are now available with ratings that are sufficiently high to make transmission line applications feasible. Consequently the ASVC has become an important part of the flexible AC transmission system (FACTS), introduced by Hingorani [3], and presently being promoted by the Electric Power Research Institute (EPRI).

The EPRI has recently commissioned the design and construction of a scaled model of an 80 MVAR ASVC for transmission lines [4]. The model represents an optimum power circuit configuration based on a voltage-sourced inverter, and includes the control system that would be applied to a fullpower installation. The control system has been designed to achieve fast dynamic control of the instantaneous reactive current drawn from the line. This capability ensures that the ASVC will function usefully during transmission line disturbances. The concept of instantaneous reactive current is a new one and will be explained in the following Sections.

In the course of this project, the dynamic behaviour of the ASVC has been studied in depth. This paper presents a simplified mathematical model of the ASVC that has made it possible to derive the transfer functions needed for control system synthesis. The resulting control system designs are briefly outlined and further analysis presented to show the behaviour of the ASVC when the line voltage is unbalanced or distorted. The analysis is based on a vectorial transformation of variables, first described by Park [5] for AC machine analysis, and later, using complex numbers, by Lyon [6] in the theory of instantaneous symmetrical components.

2 Derivation of ASVC mathematical model

2.1 Instantaneous reactive current

The main function of the ASVC is to regulate the transmission line voltage at the point of connection. It achieves this objective by drawing a controlled reactive current from the line. In contrast with a conventional static VAR generator, the ASVC also has the intrinsic ability to exchange real power with the line. As there are no sizeable power sources or sinks associated with the inverter and its DC-side components, the real power must be actively controlled to a value which is zero on average and which departs from zero only to compensate for the losses in the system.

The notion of reactive power is well known in the phasor sense. However, to study and control the dynamics of the ASVC within a subcycle time frame and subject to line distortions, disturbances and unbalance, we need a broader definition of reactive power which is valid on an instantaneous basis.

The instantaneous real power at a point on the line is given by

$$P = v_a i_a + v_b i_b + v_c i_c \quad (1)$$

The ASVC scaled model was designed and built at the Westinghouse Science and Technology Center through the combined efforts of several individuals. In particular, the authors would like to acknowledge the important contributions made by Mr. M. Gernhardt and Mr. M. Brennen.

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We can define the instantaneous reactive current conceptually as that part of the three-phase current set that could be eliminated at any instant without altering P.

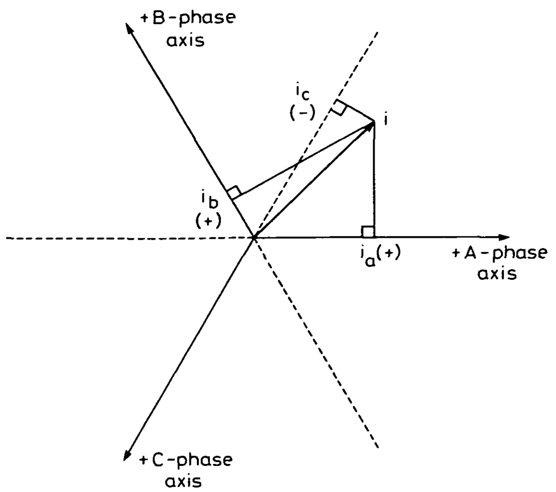

Fig. 1 *Vector representation of instantaneous three-phase variables*

The algebraic definition of instantaneous reactive current is obtained by means of a vectorial interpretation of the instantaneous values of the circuit variables, as explained in the following Section.

2.2 Vector representation of instantaneous three-phase quantities

A set of three instantaneous phase variables that sum to zero can be uniquely represented by a single point in a plane, as illustrated in Fig. 1. By definition, the vector drawn from the origin to this point has a vertical projection onto each of three symmetrically disposed phase axes which corresponds to the instantaneous value of the associated phase variable. This transformation of phase variables to instantaneous vectors can be applied to voltages as well as to currents. As the values of the phase variables change, the associated vector moves around the plane describing various trajectories. The vector contains all the information on the three-phase set, including steady-state unbalance, harmonic waveform distortions, and transient components. Fig. 2 provides a graphical illustration of the vector trajectory that would develop in the case of a three-phase set with severe harmonic distortion. The diagram shows the vector trajectory and relates it back to the actual phase-variable waveforms.

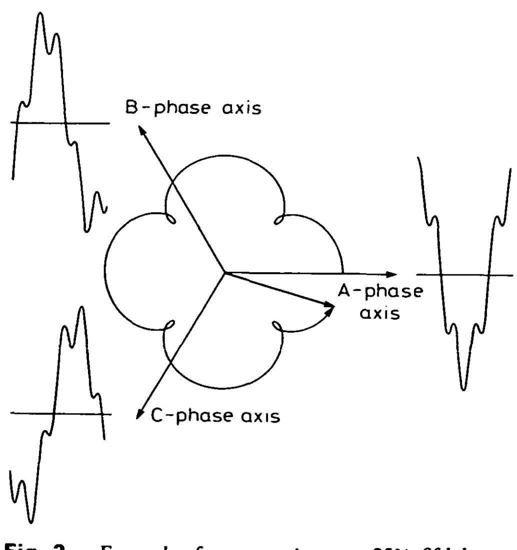

Fig. 2 *Example of vector trajectory: 25% fifth harmonic*

In Fig. 3, the vector representation is extended by introducing an orthogonal co-ordinate system in which each vector is described by means of its ds- and qs-components. The transformation from phase variables to ds and qs co-ordinates is as follows:

$$[c] = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \quad [c]^{-1} = \tfrac{3}{2}[c]_t$$

$$\begin{bmatrix} i_{ds} \\ i_{qs} \\ 0 \end{bmatrix} = [c]\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad \begin{bmatrix} v_{ds} \\ v_{qs} \\ 0 \end{bmatrix} = [c]\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{2}$$

Fig. 3 shows how the vector representation leads to the definition of instantaneous reactive current. In the diagram, two vectors are drawn, one to represent the transmission line voltage at the point of connection and the other to describe the current in the ASVC lines.

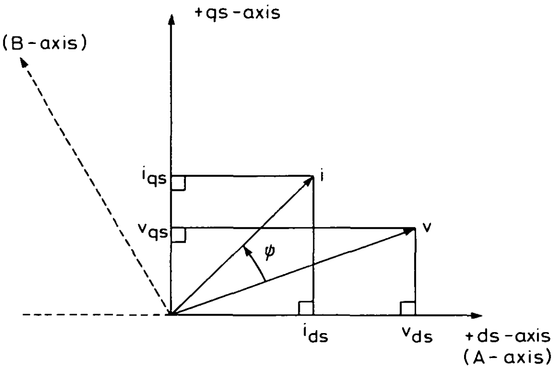

Fig. 3 *Definition of orthogonal co-ordinates*

Using eqns. 2, the instantaneous power given by eqn. 1 can be rewritten in terms of ds and qs quantities as follows:

$$P = \tfrac{3}{2}(v_{ds}\, i_{ds} + v_{qs}\, i_{qs}) = \tfrac{3}{2}\,|v|\,|i|\cos(\phi) \tag{3}$$

where ϕ is the angle between the voltage and the current vectors. Clearly, only that component of the current vector which is in phase with the instantaneous voltage vector contributes to the instantaneous power. The remaining current component could be removed without changing the power, and this component is therefore the instantaneous reactive current. These observations can be extended to the following definition of instantaneous reactive power:

$$Q = \tfrac{3}{2}\,|v|\,|i|\sin(\phi) = \tfrac{3}{2}(v_{ds}\, i_{qs} - v_{qs}\, i_{ds}) \tag{4}$$

where the constant 3/2 is chosen so that the definition coincides with the classical phasor definition under balanced steady-state conditions.

Fig. 4 shows how further manipulation of the vector co-ordinate frame leads to a useful separation of variables for power control purposes. A new co-ordinate system is defined where the d-axis is always coincident with the instantaneous voltage vector and the q-axis is in quadrature with it. The d-axis current component, i_d, accounts for the instantaneous power and the q-axis