Efficient Computer Simulation of STATCON

by

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1. Introduction

STATCONs are used for stabilizing bus voltages by exchanging reactive power with the network. Advantages of the STATCON compared to the conventional SVC are mainly the wider control range (reactive power capability proportional to bus–voltage) and the more compact design which offers easier relocatability. STATCONs usually consist of magnetic components such as reactors and transformers for network interfacing, self–commutated voltage–source converters and dc–capacitors. The number of converters or semiconductor devices connected in series or in parallel is determined by the power rating of the STATCON.

When developing basic control algorithms, it is not necessary to have an exact STATCON model, which contains every GTO or IGBT, diode and snubber circuit. A proper simplification leads to a much better understanding of system performance (including harmonics) and at the same time saves a large amount of engineering and simulation time and costs. The analysis of STATCON performance can be further simplified by using space vector representation [1] for line–side currents and voltages. This also enables an easy understanding of important instantaneous power quantities during transients. The modelling and analysis schemes presented in this paper can easily be applied to more complex STATCONs than the one presented and also to other FACTS elements that consist of voltage–source converters (e. g. UPFC).

At first space vectors and useful instantaneous power quantities in three–phase networks are introduced. The principle operation of a STATCON is described and it is shown how a STATCON consisting of a three–level voltage–source converter can be modelled efficiently with controlled voltage sources. The computer simulation results depict the transient and steady–state performance of such a STATCON by using space–vector representation and appropriate instantaneous power quantities.

The computer simulations were made with the NETOMAC–program [2], whose instruction set supports very much the ideas proposed in this paper.

2. Space vectors and power quantities

STATCONs are usually connected by only three conductors to the network at the PCC (point of common coupling in figure 1). Therefore the three line currents $i_a(t)$, $i_b(t)$ and $i_c(t)$ are linearly dependent on each other (their sum is always zero) and do not contain any zero sequence system. Without loosing information the line currents can be described by the two linear independent coordinates $i_\alpha(t)$ and $i_\beta(t)$ of the current space vector $\underline{i}(t)$:

$$\underline{i}(t) = i_\alpha + j i_\beta = \frac{2}{3}\left[i_a + \underline{a} i_b + \underline{a}^2 i_c\right] \; ; \; \underline{a} = e^{j2\pi/3} \quad (1)$$

In return the line currents can be derived from the current space vector coordinates by:

$$i_a(t) = i_\alpha(t)$$
$$i_b(t) = -\frac{1}{2} i_\alpha(t) + \frac{\sqrt{3}}{2} i_\beta(t)$$
$$i_c(t) = -\frac{1}{2} i_\alpha(t) - \frac{\sqrt{3}}{2} i_\beta(t) \quad (2)$$

The line voltages $v_a(t)$, $v_b(t)$ and $v_c(t)$ can also be represented by its space vector $\underline{v}(t)$. Only the information about a possible zero–sequence portion is lost by space vector representation. But since this possible zero–sequence portion in the line voltages can not create instantaneous power with the zero–sequence–free line currents it is totally suffincient to only look at the voltage space vector when analyzing the STATCON performance.

As shown in figure 2 the line current space vector $\underline{i}(t)$ can be split up into two components with respect to the voltage space vector $\underline{v}(t)$:

$$\underline{i}(t) = \underline{i}_{\parallel}(t) + \underline{i}_{\perp}(t) \quad (3)$$

The component $\underline{i}_{\parallel}(t)$ (called "i–parallel") has the same or the opposite direction with respect to the voltage space vector $\underline{v}(t)$; the component $\underline{i}_{\perp}(t)$ (called "i–perpendicular") is phase–shifted by plus or minus $\pi/2$. Only the component $\underline{i}_{\parallel}(t)$ can create instantaneous power $p(t)$ and therefore the energy, that is exchanged between the network and the STATCON. In steady–state the average value of $p(t)$ is the active power P used for covering losses in the STATCON. The component $\underline{i}_{\perp}(t)$ does not contribute to

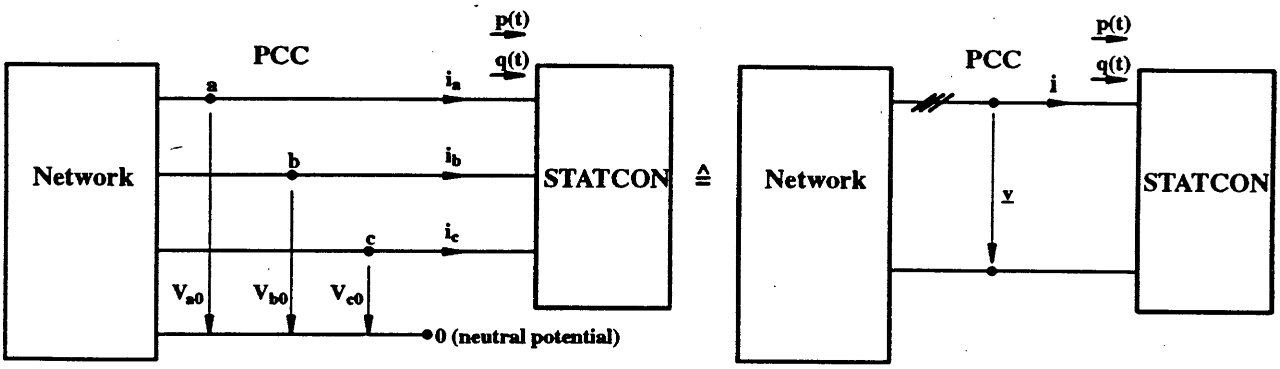

Fig. 1: three–phase (left) and single–phase (right) representation of network and STATCON

any power exchange. But under steady–state conditions its fundamental component carries the complete fundamental reactive power Q_f that is exchanged between the network and the STATCON. It is therefore useful to define an instantaneous quantity q(t), which is equal to the instantaneous power, that a minus $\pi/2$ phase–shifted voltage space vector would create with the current space vector $\underline{i}(t)$. Only the component $\underline{i}_\perp(t)$ contributes to q(t), which will be called "instantaneous nonactive power". When analyzing the transient STATCON–performance it is also useful to use the instantaneous complex power $\underline{s}(t)$.

The calculation of the power quantities can be looked up in the following equations (the superscript "*" denotes the complex conjugate space vector, the subscript "$_f$" denotes fundamental quantities):

– transient <u>and</u> steady–state conditions:

$$p(t) = \frac{3}{2}\mathrm{Re}\,\{\underline{v}(t)\,\underline{i}^*(t)\} = \frac{3}{2}\underline{v}(t)\,\underline{i}^*_\parallel(t) \quad (4)$$

$$q(t) = \frac{3}{2}\mathrm{Im}\,\{\underline{v}(t)\,\underline{i}^*(t)\} = \frac{3}{2}\underline{v}(t)e^{-j\pi/2}\,\underline{i}^*_\perp(t) \quad (5)$$

$$\underline{s}(t) = p(t) + jq(t) \quad (6)$$

– steady–state conditions:

$$Q_f = q_f(t) = \frac{3}{2}\mathrm{Im}\,\{\underline{v}_f(t)\,\underline{i}_f^*(t)\} = \frac{3}{2}\underline{v}_f(t)e^{-j\pi/2}\,\underline{i}^*_{\perp f}(t) \quad (7)$$

$$P = \frac{1}{T}\int_t^{t+T} p(t)\,dt \quad \text{(for covering losses)} \quad (8)$$

A detailed analysis of instantaneous power and instantaneous nonactive power is presented in [3].

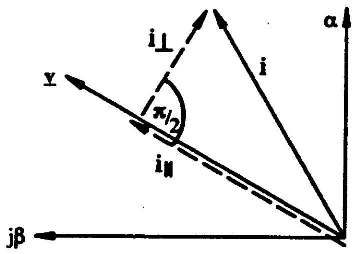

Fig. 2: line current space vector components

3. Principle operation of STATCON

As shown in Figure 3 the voltage–source type STATCON consists of a magnetic structure (transformers, reactors), one or more converters (here only one converter having a three–phase transformer connection is depicted) and one or more dc–capacitors. The function of the power electronics in the converter is to create line–side voltages using the voltages across the dc–capacitor(s). The information how to use the capacitor–voltage(s) is contained in the switching signals, which are derived in the control unit and output to the self–commutated power electronic devices via the drive unit.

4. Modelling of the STATCON converter

Since the converter builds up voltages at the line side it can be most easily thought of as a set of controlled voltage sources. The proper modelling will now be presented for a three–level converter (figure 4a). Although a detailed modelling can be done with NETOMAC (e. g. for getting the results presented in [4]), the following method has advantages, since the transient and steady–state STATCON perfomance can be analyzed in detail while saving a lot of time.

Depending on the switching states of the power electronics (here: GTOs), each terminal ν=a, b, c is either connected to

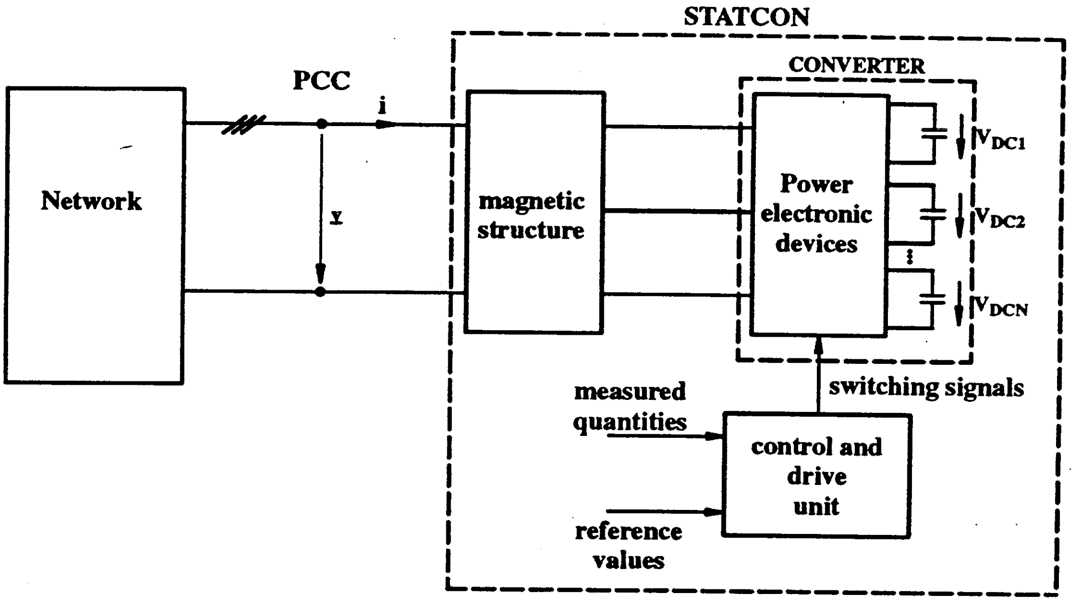

Fig. 3: STATCON components

the upper potential point L_+, the medium potential point M or the lower potential point L_- of the dc–capacitors. These possible switching states of each inverter leg v=a, b, c are denoted by [+], [0] and [–] in figure 4b. The voltages between the line–side converter terminals v and the medium potential point M depend on these switching states according to:

$$v_{vM} = \begin{cases} V_{DC1} \; ; \; S_v = [+] \\ 0 \; ; \; S_v = [0] \\ -V_{DC2} \; ; \; S_v = [-] \end{cases} \tag{9}$$

Figure 5 depicts such a voltage for one–pulse (each GTO is turned on and off once per line period) and three–pulse modulation.

The currents flowing to the three potential points of the dc–capacitors can be calculated by taking into account the phase currents i_v and the switching states:

$$i_{L+v} = \begin{cases} i_v \; ; \; S_v = [+] \\ 0 \; ; \; \text{else} \end{cases}$$
$$i_{M} = \begin{cases} i_v \; ; \; S_v = [0] \\ 0 \; ; \; \text{else} \end{cases}$$
$$i_{L-v} = \begin{cases} i_v \; ; \; S_v = [-] \\ 0 \; ; \; \text{else} \end{cases} \tag{10}$$

$$i_{L+} = \sum_{v=a,b,c} i_{L+v}$$
$$i_M = \sum_{v=a,b,c} i_{Mv}$$
$$i_{L-} = \sum_{v=a,b,c} i_{L-v} \tag{11}$$

The capacitor voltages are calculated using:

$$V_{DC1} = V_{DC1,t=0} + \frac{1}{C} \int_0^t i_{L+}(t)\, dt$$
$$V_{DC2} = V_{DC2,t=0} + \frac{1}{C} \int_0^t [-\, i_{L-}(t)]\, dt \tag{12}$$

With these dependencies a simple voltage–source model for the three–level converter can be developed in time domain (figure 4c).

In this model the power electronics of the converter and their interconnections are assumed to be ideal (no losses, no delay times, no energy storage devices). A closer approximation to practice is to connect resistors representing the switching losses in series to the voltage sources. But since the converter losses dampen the transients and therefore lead to a more secure operation with respect to overcurrents it is safer to neglect them in the model and look for a converter control scheme that provides optimal performance for the lossless converter.

When using the simulation program NETOMAC, the voltage sources are contained in the network data and the capacitor voltages are calculated in the controller part of the program. The simulations should be performed in the instantaneous value mode of NETOMAC in order to obtain full information about transient and steady–state operating conditions (e. g. harmonics). It is also possible to test control algorithms for medium potential control (=balancing of the capacitor voltages V_{DC1} and V_{DC2}).

The idealizations presented here are a good and simple approximation to practice and at the same time give important information about the STATCON performance under steady–state and transient conditions.

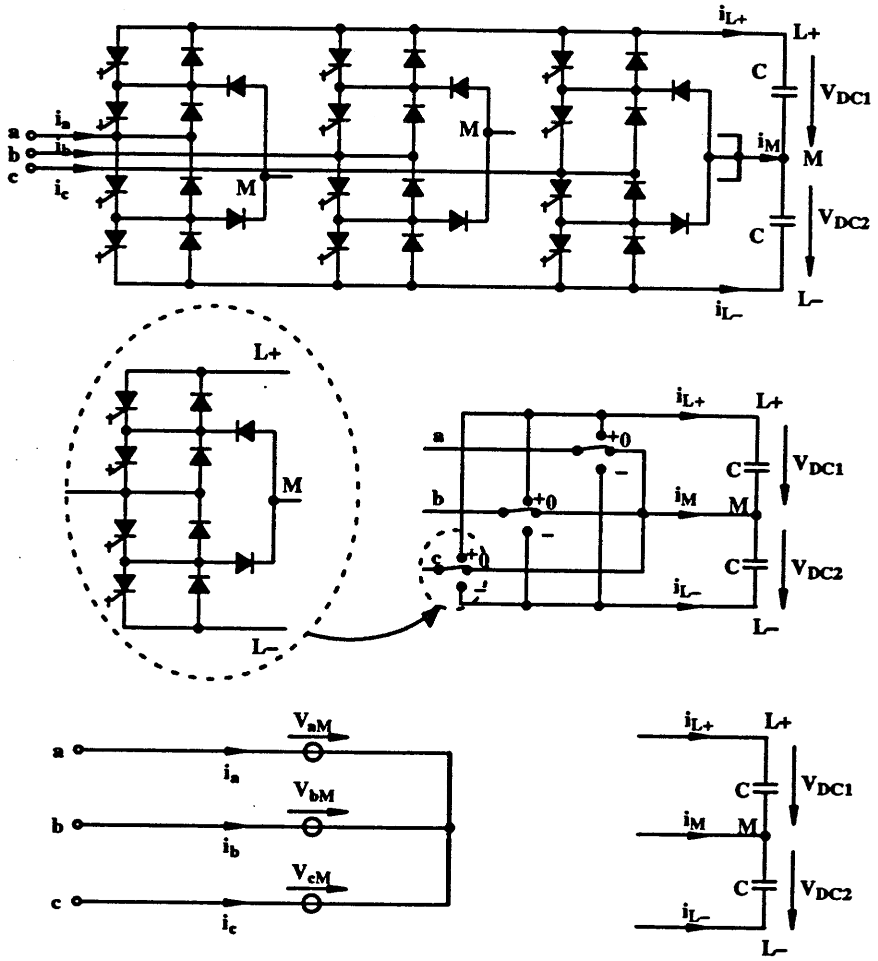

Fig. 4: a) three–level voltage–source converter; b) switch model; c) voltage–source model

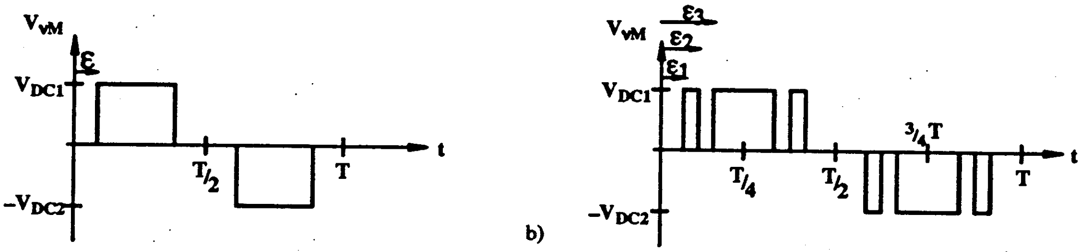

Fig. 5: a) fundamental–frequency switching (one–pulse modulation); b) three–pulse modulation (the angles ε denote each degree of freedom)

6. Computer simulation results

The simulation results presented in figure 6 were obtained using the model for the three–level converter presented in chapter 5. The STATCON has a power rating of +/–8MVAr, the relative short circuit voltage of the transformer is 12% (at 8 MVAr) and the transformer damping R/X=1/25. For simplicity the network is assumed to be ideal (line voltages purely sinusoidal, short circuit impedance equal to zero). The RMS–value of the line–to–line network voltages is 15kV and the RMS–value of the converter–side line–to–line transformer–voltages 3.3kV (under no–load conditions = no reactive power is exchanged with the network).

The STATCON–control consists of a simple nonactive power controller (P–controller), whose output only effects the phase δ of the converter voltages with respect to the line voltages (lower track in figure 6a).

The pulse pattern is fixed and optimized such that the combined RMS–value of fifth and seventh harmonic in the line–side converter voltages is minimized and at the same time the 11th and 13th harmonic are cancelled (three–

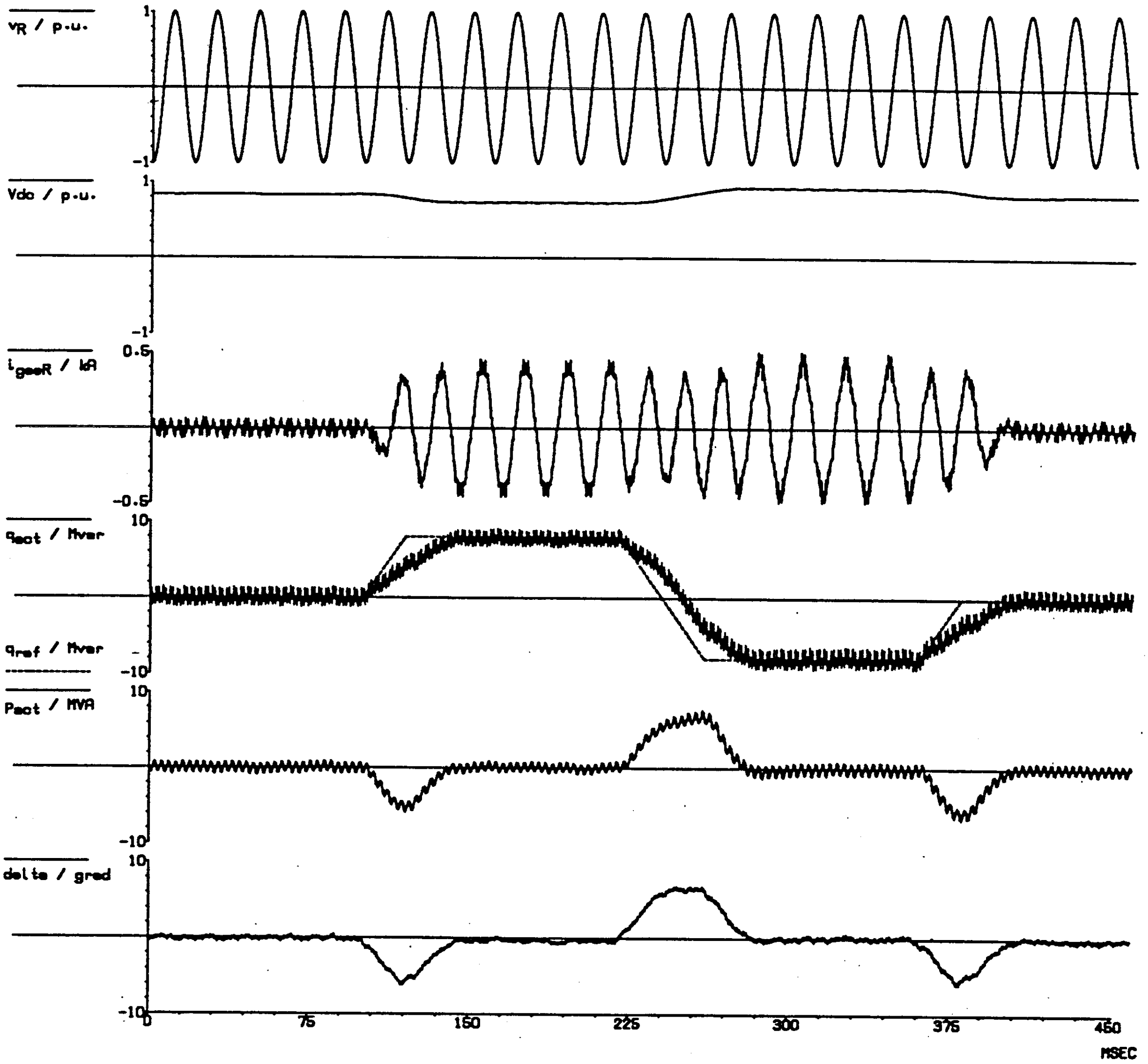

Fig. 6a: time dependency of important network and STATCON quantities under transient and steady-state conditions (discussion see text)

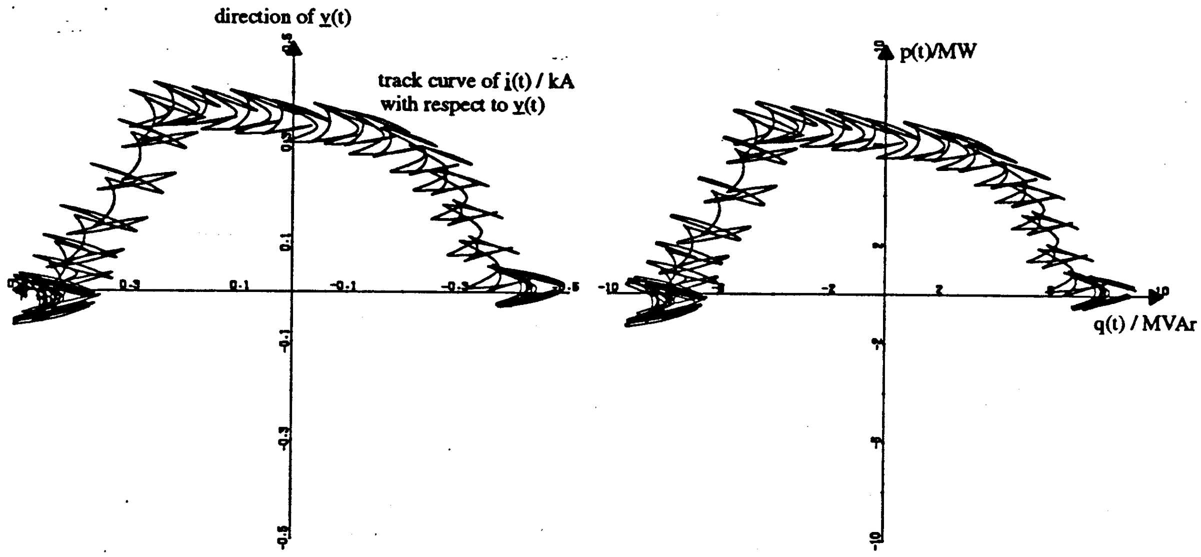

Fig. 6b: track curves of line current space vector (left) and instantaneous complex power s(t) during a change from inductive to capacitive mode of the STATCON. The track curves start at t=0.21s and end at 0.30s (compare with figure 6a). The movement is counterclockwise.

pulse modulation as described in figure 5b). With such a control mode the capacitor voltages must be smaller in the inductive mode (STATCON appears like a reactor) and higher in the capacitive mode compared to no–load conditions. When changing the amount of exchanged reactive power, the energy stored in the capacitors therefore has to change, too.

Figure 6a shows the time dependency of important quantities when the reference value for the nonactive power is changed from 0 to +8MVAr and then to –8MVAr. The upper track shows the network line–to–neutral voltage, below one of the dc–capacitor–voltages, one line current, the reference and actual value of the instantaneous nonactive power q(t), the instantaneous power p(t) and the bottom track depicts the angle δ.

In order to have a good overview over STATCON performance it is very useful to look at the relative movement of the line current space vector $\underline{i}(t)$ with respect to the line–voltage space vector $\underline{v}(t)$. The resulting track curve for a change from +8MVAr to –8MVAr is shown in figure 6b. As mentioned in chapter 2 only $i_{\perp}(t)$ contributes to fundamental reactive power under stationary conditions and the quantity $i_{\parallel}(t)$ carries the instantaneous power p(t) beeing exchanged between the network and the STATCON (equations (4) and (5)). Therefore the track curve of the instantaneous complex power $\underline{s}(t)$ must have exactly the same shape as the line current space vector track curve. This can be recognized when comparing figure 6b with figure 6a. Since the line current space vector contains total information about the line currents (three–phase network–STATCON connection), figure 6b depicts the essential information about the transient performane of the STATCON. Such a figure is very useful for controller–design and testing, since the task of the controller is to guide the current space vector as quickly and as smooth as possible into its new position relative to the voltage space vector. A bad controller design can for example result in a high overshoot of the current space vector magnitude, which may provoke a security shut–down of the converter in practice. The figures also show the line current distortion resulting from the nonsinusoidal converter voltages.

7. Conclusion

By using proper voltage source representation of the STATCON–converter as outlined in this paper, the simulation model is small and simulation time minimized. Space vector representation of three–phase currents and voltages simplifies the understanding of instantaneous power quantities. They are very important when analyzing transient performance of the STATCON. The NETOMAC simulation program supports the usage of controlled voltage sources and offers the drawing of space vector and instantaneous complex power track curves.

The ideas presented in this paper help to reduce the overall time spent for computer simulation when designing a STATCON. They can be extended to more complex STATCONs and also other FACTS elements consisting of voltage–source converters.

Space vector representation is in general a powerful tool to analyze three–phase systems.

8. References

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