Modeling of A Square-Wave-Controlled Cascaded Multilevel STATCOM by Analytical Approach

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Abstract: In recent years, multilevel converters have become increasingly popular in high-power transmission/distribution systems and in industry application. The aim of this paper is to present an analytical, state space model of an indirect, voltage-controlled cascaded-type multilevel static synchronous compensator (STATCOM) with “square wave control.” The multilevel converter model is segmented into a dynamic and static part in order to accurately represent all internal feedback connections. Each voltage component is analyzed in detail and described mathematically by an averaged expression with an equivalent capacitance. The STATCOM model is linearized and linked with a DQ frame ac system model and the controller model, and implemented in MATLAB. The controller gains are selected by analyzing the root locus of the analytical model to give optimum responses. The model is very accurate in the sub synchronous range, and it is adequate for most control design applications and practical stability issues below 100 Hz. Furthermore, the developed model can be used for multilevel cascaded converters which exchange real power.

A suitable and accurate analytical model of an indirectly controlled cascaded multilevel STATCOM with square-wave control is presented in this paper. The converter voltage components are analyzed in detail for a single-cell and the results are then generalized for a multilevel cascaded converter. The converter ac voltage waveform is of a nonlinear, discrete, and dynamic nature, which is described mathematically by appropriate averaged expressions. The dynamic, analytical state-space model is built of subsystems to enable model application to a wide range of system configurations and various dynamic studies. The developed STATCOM model is linearized and implemented in MATLAB. Eigen values studies are conducted for each particular test system in order to select optimum open-loop controller gains.

Index terms— STATCOM; Static VAR Compensator; Pulse-Width Modulation; Matlab / Simulink.

I. INTRODUCTION

In recent years, multilevel converters have become increasingly popular in high-power transmission/distribution systems and in industry applications. In contrast to a conventional two-level voltage-source converter (VSC) that works with pulse width modulation (PWM), such multilevel converters use a number of (low voltage) series-connected capacitors to generate high ac voltage. This allows higher power-handling capability with reduced switching power losses and harmonic distortion. The main types of multilevel converters are diode clamped, flying capacitor, and cascaded inverter.

By comparing these different topologies, while considering the harmonic level, losses, and component costs, the cascaded multilevel converter with “square wave control” is found to be the optimum solution for static synchronous compensator (STATCOM) applications. The modular structure of this converter, with a number of identical H-bridges, makes this converter very flexible in terms of power-handling capability. The use of “square wave control” results in a single switch on and off per cycle for each switch, which brings benefits of low switching losses. In addition, since the control angle at each capacitor can be used to cancel one harmonic, low harmonic distortion can be achieved.

The dynamics of such complex converters are mostly analyzed by using Electromagnetic Transients Program (EMTP)-type programs, such as PSCAD/EMTDC. However, these simulators provide only trial-and-error-type studies in the time domain. The demanding analysis and design tasks become very time-consuming since a labored search has to be executed to find the best solution. Alternatively, a suitable and accurate analytical system model would provide faster design routes. This type of model would provide the ability to use dynamic systems-analysis techniques (e.g., eigenvalues and frequency-domain methods) and modern control design theories, resulting in shorter design time and advanced controller configurations. Compared to conventional VSCs, the analytical modeling of multilevel converters is more challenging.

A conventional PWM-controlled VSC has a fixed structure and the switching frequency is high which implies that intervals between switching’s are short and conventional averaging approaches can represent converter dynamics.
A multilevel converter with square-wave control, on the other hand, fundamentally changes its structure as the capacitors are switched in and out of the current path and, therefore, these changes may have a significant influence on the system dynamics.

Further, each cell is switched only twice per cycle and, therefore, variables may undergo notable excursions within a single conduction interval. One of the primary challenges in the dynamic modeling of a square-wave converter is therefore the adequate dynamic representation of cell variables between the switching instants. The multilevel converter model is in convenient state space form but it adopts overly simplified equivalent capacitance which is only valid for a particular number of levels and does not consider firing angles on individual cells. Similarly, the state-space model is of little practical use, since the equivalent capacitance has to be tuned for every change in converter parameters, using identification methods.

The researchers in developed a frequency-domain model of a square-wave controlled converter. Since it only considers a single cell with uncontrollable, full 180 conduction periods, this model does not address the aforementioned modeling challenge. The research presented in represents the structure of a multilevel converter at a wide range of frequencies in order to provide a model for phasor studies and harmonic analysis. However, this is essentially a static model, and it completely ignores the control influence.

Moreover, since the model neglects the transfer of active power, it cannot be used for dynamic modeling. This paper aims to develop a dynamic analytical model of a multilevel-cascaded STATCOM converter that is convenient for system stability studies and for the analysis of interactions with ac systems. We attempt to establish generic modeling principles that are applicable for a range of multilevel-cascaded converters, even those which exchange real power. A modular modeling approach is adopted to represent the complexity of the system with the benefit that each individual subsystem can be analyzed independently.

This analytical model employs all parameters and variables with physical meaning and, therefore, it can study variations in ac and dc system structures.

II. STATCOM

In 1999 the first SVC with Voltage Source Converter called STATCOM (Static Compensator) went into operation. The STATCOM has a characteristic similar to the synchronous condenser, but as an electronic device it has no inertia and is superior to the synchronous condenser in several ways, such as better dynamics, a lower investment cost and lower operating and maintenance costs. A STATCOM is build with Thyristors with turn-off capability like GTO or today IGCT or with more and more IGBTs. The static line between the current limitations has a certain steepness determining the control characteristic for the voltage.

The advantage of a STATCOM is that the reactive power provision is independent from the actual voltage on the connection point. This can be seen in the diagram for the maximum currents being independent of the voltage in comparison to the SVC. This means, that even during most severe contingencies, the STATCOM keeps its full capability.

In the distributed energy sector the usage of Voltage Source Converters for grid interconnection is common practice today. The next step in STATCOM development is the combination with energy storages on the DC-side. The performance for power quality and balanced network operation can be improved much more with the combination of active and reactive power.

![Figure 1: STATCOM operation in a power system](image)

The charged capacitor $C_{dc}$ provides a DC voltage, $U_{dc}$, to the converter, which produces a set of controllable three-phase output voltages, $U$, in synchronism with the AC system. The synchronism of the three-phase output voltage with the transmission line voltage has to be performed by an external controller. The amount of desired voltage across STATCOM, which is the voltage reference, $U_{ref}$, is set manually to the controller. The voltage control is thereby to match $U_T$ with $U_{ref}$ which has been elaborated. This matching of voltages is done by varying the amplitude of the output voltage $U$ which is done by the firing angle $\alpha$.
The controller. The controller thus sets $U_T$ equivalent to the $U_{ref}$. The reactive power exchange between the converter and the AC system can also be controlled. This reactive power exchange is the reactive current injected by the STATCOM, which is the current from the capacitor produced by absorbing real power from the AC system.

$$I_q = \frac{U_T - U_{eq}}{X_m}$$

Where $I_q$ is the reactive current injected by the STATCOM

$U_T$ is the STATCOM terminal voltage

$U_{eq}$ is the equivalent Thevenin voltage seen by the STATCOM

$X_m$ is the equivalent Thevenin reactance of the power system seen by the STATCOM

If the amplitude of the output voltage $U$ is increased above that of the AC system voltage, $U_T$, a leading current is produced, i.e. the STATCOM is seen as a conductor by the AC system and reactive power is generated. Decreasing the amplitude of the output voltage below that of the AC system, a lagging current results and the STATCOM is seen as an inductor. In this case reactive power is absorbed. If the amplitudes are equal no power exchange takes place.

A practical converter is not lossless. In the case of the DC capacitor, the energy stored in this capacitor would be consumed by the internal losses of the converter. By making the output voltages of the converter lag the AC system voltages by a small angle, $\delta$, the converter absorbs a small amount of active power from the AC system to balance the losses in the converter. The diagram in Figure below illustrates the phasor diagrams of the output voltage at the terminal, the converter output current and voltage in all four quadrants of the PQ plane.

![Figure 2: Phasor diagrams for STATCOM applications](image)

The mechanism of phase angle adjustment, angle $\delta$, can also be used to control the reactive power generation or absorption by increasing or decreasing the capacitor voltage $U_{dc}$, with reference with the output voltage $U$.

Instead of a capacitor a battery can also be used as DC energy. In this case the converter can control both reactive and active power exchange with the AC system. The capability of controlling active as well as reactive power exchange is a significant feature which can be used effectively in applications requiring power oscillation damping, to level peak power demand, and to provide uninterrupted power for critical load.

### A. Characteristics of STATCOM

The derivation of the formula for the transmitted active power employs considerable calculations. Using the variables defined in Figure below and applying Kirchhoff’s laws the following equations can be written:

$$P = \frac{U_T U_1}{X_1} \sin \alpha - \frac{U_T U_1 \sin \delta}{(X_1 + X_2)} U_T$$

![Figure 3: Two machine system with STATCOM](image)
With these concepts of STATCOM, it is thus important to utilize these principles in accommodating shunt compensation to any system. Since this thesis only reflects on the voltage control and power increase, the requirements of the STATCOM would be further elaborated.

III. ANALYTICAL STATCOM SYSTEM MODEL

A. Model Structure

The STATCOM system consists of the multilevel converter, a transformer, a control system with phase-locked loop (PLL), and it is connected with an ac system. The STATCOM model schematic diagram is shown in Fig. 7 with all linking variables between the subsystems. It can be seen that the STATCOM model is segmented in two main subsystems: 1) an ac system and 2) a dc system, which is a conventional approach with converter modeling. Each subsystem is represented as a stand-alone state-space model, and the dc system includes the converter model, the controller model, and the PLL model. The final state-space model can be written in the following matrix:

\[
\begin{align*}
\dot{x} &= A_x x + B_u u_{\text{ref}} \\
y &= C_x x + D_u u_{\text{ref}} \\
A_x &= \begin{bmatrix} A_{\text{DC}} & B_{\text{DC,AC}} \end{bmatrix} \\
B_u &= \begin{bmatrix} -A_{\text{AC}} & C_{\text{AC}} \end{bmatrix} \\
C_x &= \begin{bmatrix} 0_{\text{AC}} & 1_{\text{AC}} \end{bmatrix} \\
u_{\text{ref}} &= \begin{bmatrix} V_{\text{ref,AC}} \\
V_{\text{AC}} \end{bmatrix} \\
y &= \begin{bmatrix} 0_{\text{AC}} \\
V_{\text{AC}} \end{bmatrix}.
\end{align*}
\]

In above equations, \(x\) is the state-variable vector, \(u_{\text{ref}}\) represents the input variable vector (including reference voltage \(V_{\text{ref,AC}}\) and disturbance voltage \(V_{\text{Grid}}\)), and \(y\) stands for the output variable vector.

B. AC Model

Assuming a symmetrical and balanced ac system, the ac grid can be modeled as a single-phase dynamic system as shown in Fig. 8. The instantaneous circuit variables are used as the states. Since the ac grid voltage \(V_{\text{ac}}\) cannot be measured directly in a state-space model, an artificial capacitance \(C_{\text{Ac}}\), which has a very small value (no dynamic effects to the system), is used to accommodate state-space modeling. It is shown in...
Conduction losses are dominant in a converter with square-wave control and, therefore, the converter losses are represented in the model as a series-connected resistance $R_{\text{losses}}$. The final model is subsequently converted to dq the rotating frame using Park’s transformation as described.

C. Converter Model

The final STATCOM model is presented in the dc sub model and the ac voltage is the sum of dynamic and static voltage components (31)–(34). Since these expressions are strongly nonlinear, they are linearized in a usual manner. The linearized STATCOM model is linked with the PLL and the controller model, as shown in the next section, to create the final dc model.

D. Controller and PLL

The STATCOM system uses indirect control, which consists of a proportional plus integral (PI) controller, to regulate the ac voltage as seen in Fig. 7. The “PI” controller produces the phase angle $\phi_{\text{ref}}$, which is common for all cells. The reference $v_{\text{ref}}$ signal is provided by an external or a system control. The delay filter in Fig. 7 is introduced to represent firing control circuit delay and does not represent actual system dynamics.

This filter accounts for the delay in the signal transfer in a discrete system, and the delay time constant is determined by $\tau = \frac{1}{(50 \times 3 \times 2 \times X)}$, where 50 represents the fundamental frequency, “3” is the number of branches, and “2” considers two switching’s per cycle per branch. The main role of the PLL is to synchronize the converter firing signals with the ac system. The latest D-Q-Z type, which has the advantage of accurate phase information even with a distorted ac system voltage waveform, is used here.

IV. MATLAB DESIGN OF CASE STUDY AND RESULTS

![Diagram of STATCOM system](image)

Figure 7: Block diagram of statcom

![Waveforms](image)

Figure 8: (a) Source voltage (b) Angle (c) Source current

![Output waveform](image)

Figure 9: Output waveform of voltage
V. CONCLUSION

A suitable and accurate analytical model of an indirectly controlled cascaded multilevel STATCOM with square-wave control is presented in this paper. The converter voltage components are analyzed in detail for a single-cell and the results are then generalized for a multilevel cascaded converter. The converter ac voltage waveform is of a nonlinear, discrete, and dynamic nature, which is described mathematically by appropriate averaged expressions. The dynamic, analytical state-space model is built of subsystems to enable model application to a wide range of system configurations and various dynamic studies. The developed STATCOM model is liberalized and implemented in MATLAB. Eigenvalues studies are conducted for each particular test system in order to select optimum open-loop controller gains. The validity and accuracy of the proposed model is verified against nonlinear PSCAD simulations, and good matching is observed in the time domain for a range of outputs and for three different test systems. The model is also tested in the frequency domain and it is concluded that the presented model can be used for dynamic studies below 100 Hz.

REFERENCES