Fast Equivalent Modeling of Cascaded Static Synchronous Compensator Under Higher Voltage

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Abstract: Cascaded STATCOM including huge number of sub-modules under higher voltage needs rapid modeling to analyze efficiently. This paper presents a discrete iterative algorithm based on equivalent modeling method, which can greatly simplify mathematical model of STATCOM under higher voltage. According to the mathematical properties of the sub-module DC capacitor, it is equivalent to a historical series branch voltage source with an equivalent resistance. By simplifying IGBT to equivalent variable resistor, H-bridge is simplified to an equivalent branch with PWMs. Control system can calculate each IGBT PWM pulse signal by embedding to the equivalent electric circuit. Created an iterative calculation algorithm for the equivalent circuit, and evaluated the two basic errors that are algorithm error and parameter error. By comparing ±100MVar STATCOM’s waves between field data and simulation data, it is proved correct that the rapid equivalent modeling method. In-depth comparison of the key parameters of the theory and simulation instructions, it is very close between the theory and the practice, and methods can greatly simplify the analysis and simulation calculations.

1. Introduction
The cascaded STATCOM contains a large number of power modules, so the mathematical model is very complex and the simulation speed is extremely slow [1]-[3]. Therefore, for the characteristics of cascaded STATCOM with large-capacity, fast equivalent modeling is needed. A series of studies have been carried out in terms of equivalent modeling at home and abroad. As in the literatures [4]-[6], the matrix simplification method is used to study the rapid modeling of the H-bridge sub-module, the half-bridge sub-module and the clamped double sub-module of the flexible HVDC transmission system. The traditional module experiment is testing modules one by one. Obviously, that test is insufficient, especially in the distributed new energy field including thousands of photovoltaic converters and wind power converters consisting of H-bridges.

In this paper, the high-speed equivalent model of high-voltage STATCOM is constructed by discretization iterative method for the actual characteristics and requirements of cascaded STATCOM, and the comparison of the original model and equivalent model is present. Through the comparison of experimental and simulation data, the modeling method of this paper is in line with engineering practice. The comparison between the calculation error and the calculation time before and after the equivalent is used to illustrate the rapidity and accuracy of the modeling method.
2. **Principle of Electromagnetic Transient Quick Equivalent Modeling.**

Take AB converter chain as an example to illustrate the algorithm in the electromagnetic transient simulation tool. First of all, the converter chain is equivalent to the chain circuit of switches, capacitors, resistors, etc. The preliminary calculation circuit is shown in figure 1 (a) and (b).

![Preliminary calculation circuit in the electromagnetic transient simulation tool](image)

(a) the preliminary calculation circuit in the electromagnetic transient simulation tool

![Standard circuit in electromagnetic transient simulation tool](image)

(b) Standard circuit in electromagnetic transient simulation tool

![A standard circuit with three nodes as an example](image)

(c) A standard circuit with three nodes as an example

Fig. 1 Calculation Method of EMTP Simulation Tools

FIG. 1(c) illustrates the principle by taking the three-node point network as an example. If the injection current of each node is, and, and, and the resistance between nodes is and, it is easy to write the voltage equation of its nodes as

\[
\begin{bmatrix}
I_1 \\
I_2 \\
I_3
\end{bmatrix} =
\begin{bmatrix}
1/R_{01} & -1/R_{01} & 0 \\
-1/R_{01} & 1/R_{01} + 1/R_{12} & -1/R_{12} \\
0 & -1/R_{12} & 1/R_{12}
\end{bmatrix}
\begin{bmatrix}
U_0 \\
U_1 \\
U_2
\end{bmatrix}
\]

(1)

The method proposed in this paper is to treat the converter chain as a cascade circuit as shown in figure 2. The voltage of each node is related to the resistance, current, current and independent voltage source voltage, and the calculation process of each power module is independent of each other.
Fig. 2 Equivalent circuit of the Proposal Fast Modeling Method

Since the calculation of each module is independent, if the expression of $u$, and for the JTH module is used, then the voltage at each node of the converter chain can be solved without the whole network inverse. For a single module, the computational complexity of the above 5 expressions is $O(5)$, and the computational complexity of $N$ modules is $O(5N)$. Therefore, when the number of power modules is large, the fast model can realize simulation acceleration.

The iterative formula of the capacitor voltage is

$$u_j(t) = \frac{\Delta T}{2C_0} i_j(t) + \left[ \frac{\Delta T}{2C_0} i_j(t - \Delta T) + u_j(t - \Delta T) \right]$$

$$= R_i i_j(t) + u_{eq}(t - \Delta T) \quad (2)$$

Among them

$$u_{eq}(t) = \frac{\Delta T}{2C_0} i_j(t - \Delta T) + u_j(t - \Delta T) \quad (3)$$

Therefore the circuit can be equivalent to Figure 3, and the operating status of CASCADED STATCOM is shown in table 1.

(a) PRELIMINARY SIMPLIFICATION OF THE MODEL
Here,\

$$u_{m-j}(t) = R_{m-eq}i_{ab}(t) + R_{kj}u_{eq}(t - \Delta T) \quad (4)$$

Among them

$$R_{m-eq} = \frac{R_R(R_R + R_1 + R_2) + R_R R_{R1}}{(R_R + R_1)(R_R + R_2) + R_R R_{R1} + R_2 R_R} + \frac{R_{R1}(R_1 + R_2) + R_{R1} R_R}{(R_1 + R_2)(R_1 + R_3) + R_2 R_R + R_3 R_1}$$

$$R_{kj} = \frac{R_R - R_1 R_2}{(R_1 + R_2)(R_1 + R_3) + R_2 R_R + R_3 R_1}$$

$$i_{ab}(t) = \frac{(R_3 R_4 - R_2 R_1) \cdot i_{ab}(t) - \sum_{i=1}^{3} R_i \cdot u_{eq}(t - \Delta T)}{(R_1 + R_2)(R_1 + R_3) + R_2 R_R + R_3 R_1}$$

According to literature \cite{13}, the control block diagram of high-power chain STATCOM is shown in FIG. 4. The current instruction of the converter chain is $i_{abq}, i_{bcq}, i_{caq}$, and the dc voltage instruction of the converter chain is $u_{dc}, u_{uc}, u_{uc}$, $u_{ucc}$ is the average value of each power module of the three-phase converter chain. $m_i (i = 1, 2, \cdots, 3N)$ is the modulation wave of each module calculated by the controller.
3. THE SIMULATION VERIFICATION

Compare with Simulink simulation. The basic parameters of the device in this paper are shown in Table 2, which is the appendix for the simulation model.

| Parameters                  | Sign | Value/Unit |
|-----------------------------|------|------------|
| Simulation Time             | $T$  | 0.5s       |
| Module Number               | $N$  | 40         |
| Inductance                  | $L$  | 7mH        |
| Angle Frequency             | $\omega$ | $100\pi$ |
| Rated Voltage(RMS)          | $V_{rate}$ | 35000V     |
| Rated Capacity              | $S$  | 100MVar    |
| Rated Current               | $I_{rate}$ | 952A      |
| Rated DC Voltage            | $V_{dc}$ | 1900V     |
| Capacitor                   | $C_0$ | 10000uF    |
| Carrier Wave Frequency      | $f_c$ | 250Hz      |

The results are shown in Fig5. Fig.5 (a) and fig.5 (b) are the dc capacitance voltage of the power module of the accurate model and the equivalent model. It can be seen that the error is approximately within 2.2v, and the relative error is 0.11%. In fig.5 (c) and fig.5 (d), the current waveform and its error of the two models of commutation chain are within 11A, and the relative error is 1.15%. Figure 5(e) and figure 5(f) are respectively the waveform and error of power. The error of active power is about 500kW, and the error of reactive power is 600kVar, respectively. Therefore, the total error of the model is less than 1.2%.
Fig. 5 Simulation results of the Accurate Model and Equivalent Model

The simulation execution time pairs for the three models are shown in Table 3.

| Simulation Step | Original Model/s | Equivalent Model/s |
|-----------------|------------------|--------------------|
| $10^{-4}$ s     | 183              | 38                 |
| $10^{-5}$ s     | 1598             | 331                |
| $10^{-6}$ s     | 15567            | 3452               |

Comparing the simulation execution time with simulation steps of $10^{-4}$ s, $10^{-5}$ s and $10^{-6}$ s in three different cases, it can be seen that the equivalent model is reduced by about 80% of execution time.

4. CONCLUSION

In order to solve the problem of slow off-line simulation speed of high-power chain STATCOM electromagnetic transient, this paper USES the circuit characteristics of h-bridge power module to
model the equivalent converter chain and improve the simulation speed. In this paper, the simulation comparison of 35kV high pressure chain STATCOM is carried out. The results show that the simulation error of the proposed equivalent model is less than 1.2%, and the simulation execution time is reduced by 80%.

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