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Current decoupling control strategy of cascaded STATCOM in d-q-0 coordinates

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ABSTRACT

As one of effective regulation methods, static synchronous compensator (STATCOM) has been widespread used to regulate dynamic reactive power and solve dynamic voltage stability problems into power-grid. Through the analysis of mathematical model, cascaded STATCOM, which is constructed by several cascaded H-bridges, is a nonlinear, multivariable, strongly coupled system. It will make difficulties in the design and practical application of controller. In this paper, mathematical models of cascaded STATCOM in a -b- c and d-q coordinates are deduced. Based on the theory of internal model control and PI control strategy, the internal decoupling control algorithm is introduced to realize independent control of active current and reactive current. At the same time, decoupling control algorithms are designed and decoupling control models are given and simulated. Both in a-b-c coordinates and d-q-0 coordinates, experiment and simulation results show that three-phase current of STATCOM has good tracking performance and control precision, which show the regulator design method and parameters setting are feasible and effective.

KEYWORDS

Static synchronous compensator (STATCOM); Cascaded H-Bridge; Internal model decoupling; *a -b- c* and *d-q co*ordinate.

INTRODUCTION

As one of latest technologies in the field of reactive compensation, static synchronous compensator is an important part of Flexible AC Transmission System (FACTS). STATCOM is connected to power-grid in the form of parallel. So, it can be used as controllable reactive current source. Its reactive current can quickly follow the changes of the load reactive current. According to the reactive power needed in power-grid system, it can automatic realize the dynamic reactive power compensation. Conventional reactive power compensation devices, such as parallel capacitor, do not have fast track, continuous compensation and other characteristics. Due to the poor dynamic regulation performance, the dynamic compensation cannot conform to the requirements of the system. At present, as one of important reactive power compensation devices, Static Var Compensator (SVC) has more application. However, if output current reaches the maximum capacity value, the reactive power output will drop down and the compensation effect will not be ideal. As an effective method for regulating the power quality for the distribution system, the medium voltage cascaded STATCOM becomes the research focus in recent years[1-2]. Relative to the traditional transformer multiple, cascaded STATCOM with H-bridge structure has obvious advantages, such as no multiple transformers, high efficiency, scalability, modular design[4].

Each phase of cascaded STATCOM is composed of multiple power units called H-Bridges. Based on LCL filter, the output current of STATCOM is optimized controlled into the grid. Through the analysis of mathematical model, cascaded STATCOM, which is constructed by several cascaded H-bridge, is a nonlinear, multivariable, strongly coupled system. It will make difficulties in the design and practical application of controller. Although the D-STATCOM mathematical model in the paper of modeling of cascaded STATCOM[5] is set up, but output current of STATCOM is used as state control. In the process of applications, complex control, slow dynamic response, poor stability will be shown. In the literature[8], the method of by changing output voltage amplitude and phase of STATCOM to control reactive current indirectly is used for STATCOM reactive current control. But in the real application, poor control characteristics of slow dynamic response, low control precision will be displayed Through equivalent conversion and simplification, mathematical models, which use *d*-axis and *q*-axis current of system as state control variables, are deduced in *a -b- c* and *d-q co*ordinates. In the process of analysis, active current component of load current is not included in system current. Based on the theory of internal model control and PI control strategies, the internal decoupling control algorithm is introduced to realize independent control of the active current and reactive current. At the same time, decoupling control algorithms are designed and decoupling control models are given and simulated. Then, the design of current controller for active and reactive is achieved to realize the decoupling control of active current and reactive current in the dynamic reactive power compensation device (STATCOM).

Finally, based on the development background of medium voltage cascaded STATCOM, the MATLAB simulation models and experimental devices, which are used to verify the rationality of system structure and control strategies, are established. Dynamic performance and steady-state performance are analyzed in the simulation and experiment. Simulation and experiment results show that the mathematical models and strategies in this paper are feasible and effective. The reactive current control has also rapid dynamic response, good stability characteristics.

TOPOLOGICAL STRUCTURE AND MODEL ANALYSIS OF MEDIUM VOLTAGE CASCADED STATCOM

Main Circuit Structure of Cascaded STATCOM

As shown in Figure 1, main circuit model of medium voltage cascaded STATCOM, which uses Y- connection topology structure, is established. This paper introduces the filter reactor designed by LCL structure in order to realize optimal control for output current.

u_{sa},u_{sb},u_{sc}–Three-phase voltage of system side; i_{sa},i_{sb},i_{sc}–Three-phase current of system side; i_{La},i_{Lb},i_{Lc}–Three-phase current of load; i_{2a}, i_{2b}, i_{2c}–Three-phase filter current of system side; L_2–Filter inductance of system side; R_2–Filter equivalent loss resistance of system side; i_{1a}, i_{1b}, i_{1c}–Three-phase filter current of the inverter; L_1–Filter inductance of the inverter; R_1–Filter equivalent loss resistance of the inverter; u_a, u_b, u_c–Three-phase output voltage of inverter; C–Filtering capacitor of LCL filter; R_d–Resistance of capacitance branch.

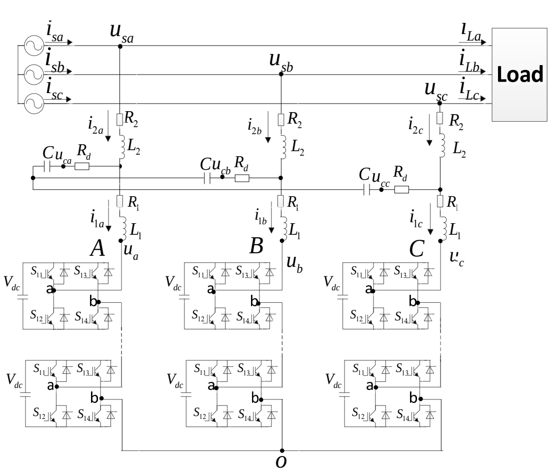


Figure 1 : Main circuit model of medium voltage cascade STATCOM

Based on H-bridges, the cascaded structure of medium voltage cascaded STATCOM is designed. Each phase consists of 12 H-Bridge cells in cascaded H-Bridges structure. The DC-side capacitors are used as energy storage. According to the DC bus voltage synthesis strategy, the desired output voltage is obtained. The three-phase cascaded STATCOM, which uses Y- connection and coupling inductances, is connected to the power grid. By changing the size and phase of output voltage, the power exchange between grids and STATCOM is realized. The measured voltage and current signals are accessed in STATCOM controller to generate trigger control signals.

Mathematical Mode of Cascaded STATCOM in *a-b-c* coordinates

As shown in Figure 1, three-phase of STATCOM is not only independent, and also is symmetrical each other. Three-phase voltage of system can be represented as the following form:

$$\begin{cases} u_{sa} = U_m \cos(\omega t) \\ u_{sb} = U_m \cos(\omega t - 2\pi/3) \\ u_{sc} = U_m \cos(\omega t + 2\pi/3) \end{cases} \quad (1)$$

Cascaded STATCOM, which uses LCL filters as filter device, is a nonlinear, multivariable, strongly coupled system. So, there is certain difficulty to control. The main design purpose of LCL filters is to filter out harmonic components; so, the system analysis can simplify the structure of LCL filters to the form of L filters. The variable symbols L_s and R_s are defined as the smoothing reactors and its losses. Three-phase of STATCOM is independent and symmetrical of each other. So, it is typical to choosing A-phase current of system as the research object. The established single-phase equivalent circuit model is shown in Figure 2. The symbol variables of $i_{saq}, i_{sap}, i_{Laq}, i_{Lap}$ are used to represent system reactive current, system active current, load reactive current, load active current of A-phase variables, respectively. System current and load current can be express as the following form: $i_{sa} = i_{saq} + i_{sap}$, $i_{La} = i_{Laq} + i_{Lap}$. Single-phase equivalent circuit model of A-Phase will decompose into two respective circuits; the specific model is shown in Figure 3. In the circuits, active current and reactive current could be controlled independently. Compensation device's aim is to provide reactive component and guarantee the value of reactive component in the system is zero. Before the compensation device starting,

$$\begin{cases} i_{sa} = i_{La} \\ i_{sap} = i_{Lap} \\ i_{saq} = i_{Laq} \end{cases} \quad (2)$$

After the compensation device starting, it will provide reactive current for load current,

$$\begin{cases} i_{2a} = i_{Laq} \\ i_{sap} = i_{Lap} \\ i_{saq} = 0 \end{cases} \quad (3)$$

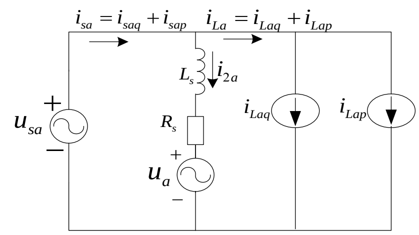


Figure 2 : Single phase equivalent circuit

As shown in Figure 3, A-phase equivalent model of cascaded STATCOM can be express as the following form,

$$u_{sa}(t) = L_s \frac{d(i_{saq}(t) - i_{Laq}(t))}{dt} + R_s(i_{saq}(t) - i_{Laq}(t)) + u_a(t) \quad (4)$$

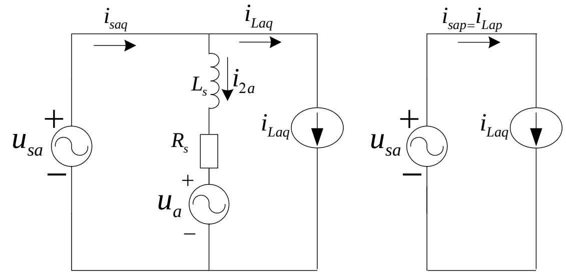


Figure 3 : The equivalent models of active and reactive power compensation

i.e.

$$\frac{di_{saq}(t)}{dt} = \frac{di_{Laq}(t)}{dt} - \frac{R_s i_{saq}(t)}{L_s} + \frac{R_s i_{Laq}(t)}{L_s} + \frac{u_{sa}(t)}{L_s} - \frac{u_a(t)}{L_s} \quad (5)$$

Similarly, the equivalent mathematical model of B-phase and C-phase can be built:

$$\frac{di_{sbq}(t)}{dt} = \frac{di_{Lbq}(t)}{dt} - \frac{R_s i_{sbq}(t)}{L_s} + \frac{R_s i_{Lbq}(t)}{L_s} + \frac{u_{sb}(t)}{L_s} - \frac{u_b(t)}{L_s} \quad (6)$$

$$\frac{di_{scq}(t)}{dt} = \frac{di_{Lcq}(t)}{dt} - \frac{R_s i_{scq}(t)}{L_s} + \frac{R_s i_{Lcq}(t)}{L_s} + \frac{u_{sc}(t)}{L_s} - \frac{u_c(t)}{L_s} \quad (7)$$

Formula 5, 6 and7 are the mathematical models of cascaded STATCOM in *a-b-c* coordinate.

If $i_{sabcq} = \langle i_{saq}, i_{sbq}, i_{scq} \rangle$, $u_{sabc} = \langle u_{sa}, u_{sb}, u_{sc} \rangle$, $i_{Labcq} = \langle i_{Laq}, i_{Lbq}, i_{Lcq} \rangle$, $u_{abc} = \langle u_a, u_b, u_c \rangle$, formula 5, 6 and7 can be simplified to the following form,

$$\frac{di_{sabcq}(t)}{dt} = \frac{di_{Labcq}(t)}{dt} - \frac{R_s i_{sabcq}(t)}{L_s} + \frac{R_s i_{Labcq}(t)}{L_s} + \frac{u_{sabc}(t)}{L_s} - \frac{u_{abc}(t)}{L_s} \quad (8)$$

Mathematical Mode of Cascaded STATCOM in *d-q* coordinates

Through the analysis of the above formulas, mathematical models of cascaded STATCOM in *a-b-c* coordinates in this paper which have time-variable coefficients are differential equation. It will make difficulties in theoretical analysis.

The application of coordinate rotating transition method is used to simplify the dynamic model of STATCOM. Three-phase coordinate transformation matrix (Park transform) between *a-b-c* coordinates and *d-q* coordinates is shown below.

$$T = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin \omega t & \sin(\omega t - \frac{2}{3}\pi) & \sin(\omega t + \frac{2}{3}\pi) \\ \cos \omega t & \cos(\omega t - \frac{2}{3}\pi) & \cos(\omega t + \frac{2}{3}\pi) \end{bmatrix} \quad (9)$$

In the above formula, symbol $\omega = 2\pi f$ is angular frequency of fundamental current. Three-phase coordinate transformation matrix and the coordinate inverse transformation between *a-b-c* and *d-q* coordinates is shown below.

$$\begin{cases} x_{dq0} = Tx_{abc} \\ x_{abc} = T^{-1}x_{dq0} \end{cases} \quad (10)$$

The symbol variables of x_{abc} and x_{dq0} are used to represent the corresponding vector in *a*-*b*-*c* coordinates and *d*-*q* coordinates, respectively. If $i_{sabcq} = \langle i_{sqd}, i_{sqq} \rangle, u_{sabc} = \langle u_{sd}, u_{sq} \rangle, i_{Labcq} = \langle i_{Lqd}, i_{Lqq} \rangle, u_{abc} = \langle u_d, u_q \rangle$, the mathematical model of cascaded STATCOM in *d*-*q* coordinates can be simplified to the following form,

$$\begin{bmatrix} \frac{di_{sqd}}{dt} \\ \frac{di_{sqq}}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_s}i_{sqd} + \omega i_{sqq} + \frac{1}{L_s}u_{sd} + \frac{di_{Lqd}}{dt} + \frac{R_s}{L_s}i_{Lqd} - \omega i_{Lqq} - \frac{1}{L_s}u_d \\ -\frac{R_s}{L_s}i_{sqq} - \omega i_{sqd} + \frac{1}{L_s}u_{sq} + \frac{di_{Lqq}}{dt} + \frac{R_s}{L_s}i_{Lqq} + \omega i_{Lqd} - \frac{1}{L_s}u_q \end{bmatrix} \quad (11)$$

In the above formula, the output variable symbol u_d and u_q of STATCOM are input variables in the mathematical model and the variables of i_{sqd} and i_{sqq} are system control quantities. In this model, there's also coupling relationship between reactive current and active current. Decoupling control algorithm is required to realize independent control of active current and reactive current.

CURRENT DECOUPLING DESIGNS OF CASCADED STATCOM BASED ON INTERNAL MODEL CONTROL

Principle of internal model control

The principle diagram of internal model control is shown in Figure 4.

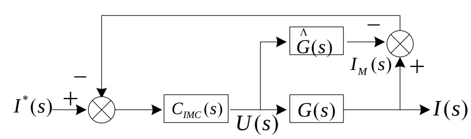


Figure 4 : Principle block diagram of internal model control (IMC)

$\hat{G}(s)$ - Internal control model; $G(s)$ -Controlled objects; $G_{IMC}(s)$ - Internal model controller

The equivalent feedback control principle diagram of internal model control is shown in Figure 5. The equivalent controller can be expressed as the following form.

$$G_F(s) = \left[I - C_{IMC}(s)\hat{G}(s) \right]^{-1} C_{IMC}(s) \circ$$

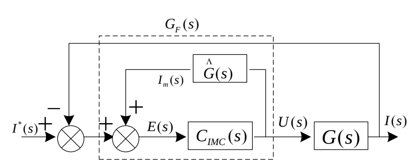


Figure 5 : The equivalent feedback control principle diagram of internal model control

Decoupling control strategy of internal model

The state equations of formula 11 are given by using Laplace transform. The specific formula is shown in the formula 12.

$$\begin{bmatrix} u_d - u_{sd} - sL_s i_{Lqd} - R_s i_{Lqd} + L_s \omega i_{Lqq} \\ u_q - u_{sq} - sL_s i_{Lqq} - R_s i_{Lqq} + L_s \omega i_{Lqd} \end{bmatrix} = \begin{bmatrix} sL_s + R_s & -L_s\omega \\ L_s\omega & sL_s + R_s \end{bmatrix} \begin{bmatrix} i_{sqd} \\ i_{sqq} \end{bmatrix} \quad (12)$$

If $v_d = u_d - u_{sd} - sL_s i_{Lqd} - R_s i_{Lqd} + L_s \omega i_{Lqq}$; $v_q = u_q - u_{sq} - sL_s i_{Lqq} - R_s i_{Lqq} + L_s \omega i_{Lqd}$, the formula 12 can be simplified to the following form.

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} sL_s + R_s & -L_s\omega \\ L_s\omega & sL_s + R_s \end{bmatrix} \begin{bmatrix} i_{sqd} \\ i_{sqq} \end{bmatrix} \quad (13)$$

The construction of $\hat{G}^{-1}(s)$ and $L(s)$:

$$\hat{G}^{-1}(s) = \begin{bmatrix} sL_s + R_s & -L_s\omega \\ L_s\omega & sL_s + R_s \end{bmatrix},$$

$$L(s) = \begin{bmatrix} \lambda/(s+\lambda) & 0 \\ 0 & \lambda/(s+\lambda) \end{bmatrix}, \text{ then}$$

$$C_{IMC}(s) = \hat{G}^{-1} \cdot L(s) = \begin{bmatrix} sL_s + R_s & -L_s\omega \\ L_s\omega & sL_s + R_s \end{bmatrix} \begin{bmatrix} \lambda/(s+\lambda) & 0 \\ 0 & \lambda/(s+\lambda) \end{bmatrix} = \lambda \begin{bmatrix} \frac{sL_s + R_s}{s+\lambda} & \frac{-L_s\omega}{s+\lambda} \\ \frac{L_s\omega}{s+\lambda} & \frac{sL_s + R_s}{s+\lambda} \end{bmatrix} \quad (14)$$

When the parameter of $\lambda = 1/T$ is increased, the response speed and oscillation increased, while inertia decreased; on the contrary, the effect is the opposite.

By using the equivalent feedback control principle diagram of internal model control, the input and output current transfer function can be deduced in the following form.

$$\frac{I(s)}{I^*(s)} = \frac{G_F(s)G(s)}{1 + G_F(s)G(s)} = \frac{C_{IMC}(s)G(s)}{1 + C_{IMC}(s)\left[G(s) - \hat{G}(s)\right]} \quad (15)$$

$$I(s) = \begin{bmatrix} i_{sqd} \\ i_{sqq} \end{bmatrix}, \quad I^*(s) = \begin{bmatrix} i^*{}_{sqd} \\ i^*{}_{sqq} \end{bmatrix}$$

$$G_F(s) = \left[I - C_{IMC}(s)\hat{G}(s)\right]^{-1} C_{IMC}(s) = \left[I - \frac{\lambda}{s+\lambda} I\right]^{-1} G^{-1}(s) \frac{\lambda}{s+\lambda} = \lambda \begin{bmatrix} \frac{sL_s + R_s}{s} & \frac{-L_s\omega}{s} \\ \frac{L_s\omega}{s} & \frac{sL_s + R_s}{s} \end{bmatrix} \quad (16)$$

When the condition of $G(s)=\hat{G}(s)$ is true, the formula 15 can be represented as the form of $\frac{I(s)}{I^*(s)}=L(s)$, At last, the decoupling control algorithm is realized in formula 17 using the parameters of $I(s)$ and $I^*(s)$.

$$\begin{bmatrix} i_{sqd} \\ i_{sqq} \end{bmatrix} = \begin{bmatrix} \lambda/_{s+\lambda} & 0 \\ 0 & \lambda/_{s+\lambda} \end{bmatrix} \begin{bmatrix} i^*_{sqd} \\ i^*_{sqq} \end{bmatrix} \quad (17)$$

The formula of $G(s)=\hat{G}(s)$ will be true, if the necessary parameters of L_s and R_s are designed accurately. On the contrary, by choosing a larger value for parameter λ, the equivalent response of I and I^* can be supposed to be inertial link. At last, in order to achieve ideal response effect, PI controller is also introduced into the control algorithm. According to the principle of decoupling control, first-order internal model control principle block diagram of STATCOM is shown in Figure 6.

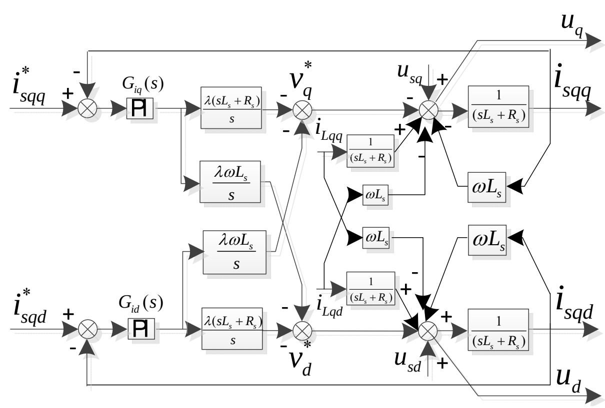


Figure 6 : The decoupling principle diagram of internal model control

SIMULATION AND EXPERIMENTAL

Simulation platform of system

As shown in Figure 7, the cascaded STATCOM actual simulation circuits, in order to verify the correctness of STATCOM mathematical model in *a-b-c* coordinates and *d-q-0* coordinates and the rationality of internal model decoupling control algorithm for decoupling control of active and reactive power, are built in MATLAB. Compared with the simulation model in *a-b-c* coordinates, control algorithm is made with an internal model control structure and coordinate transformation in *d-q-0* coordinates. The simulation model is shown in Figure 7. Inverter system adopts cascaded connecting mode, and the structure of H-bridge and star connection method is also presented. The simulation parameters of experiment device are shown in TABLE 1.

TABLE 1 : The simulation parameters of experiment device

Parameters	value
Voltage class(V)	380
Number of power unit	3
DC-side capacitors(*uF*)	9
Equivalent resistance of DC-side capacitors (Ω)	0.0003
Inductance of filter(*mH*)	4.8
Equivalent resistance of filter(Ω)	0.03

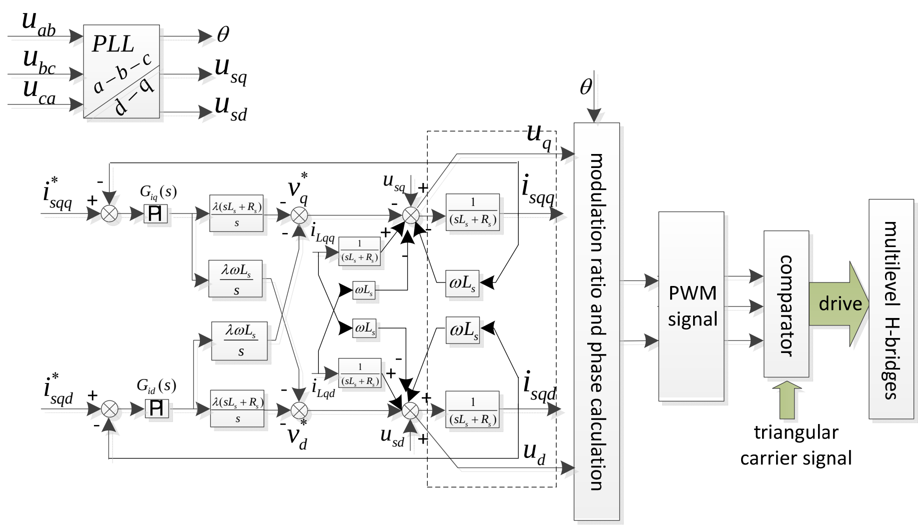


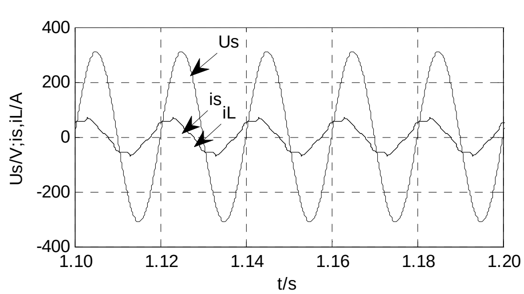
Figure 7 : System simulation model

The output variables u_d , u_q of STATCOM are input variables in the mathematical model. The variables of i_{sqd} and i_{sqq} are system control variables, which should satisfy the following conditions, $\begin{cases} i^*_{sqd} = 0 \\ i^*_{sqq} = 0 \end{cases}$. The reference voltage of v^*_q and v^*_d, using decoupling control method, are used to achieve the control of output current. Cascaded H-bridge modulation signals generate three-phase output voltage of u_a, u_b, u_c.

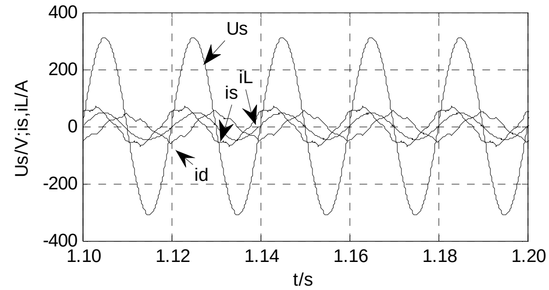
Simulation Verification of Cascaded STATCOM in MATLAB

In order to simulate the various conditions in engineering practice, a comparison of the two kinds of load in simulation system, that is, capacitive load and inductive load is made. Capacitive load is composed of resistor and capacitor in series, its specific values are 2Ω and $600\mu F$. Another condition is that resistance and inductance in series are used to simulate inductive load. Its specific values are 2Ω and $3mH$. The wire connection method of the two kinds of load adopts star connection method. In the process of simulation, the load consists of universal bridges, resistances and inductances which are controlled as a harmonic current source. Its value is 20Ω and $3mH$, respectively. The simulation results are shown below.

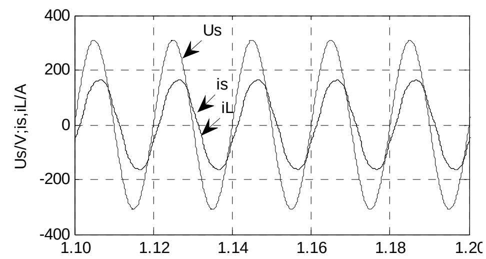
As shown in Figure 8, waveforms of system voltage, current, load current and device current with different steady-state loads before and after the compensation are analyzed. With the application of inductive load in 1.15 seconds, the dynamic waveforms of system voltage, current, load current and device current are shown in Figure 9. In the process of switching resistor-inductance load to capacitive load, the dynamic waveforms of system voltage, current, load current, device current, real-time and reference *q*-axis current are shown in Figure 10 and Figure 11, respectively.



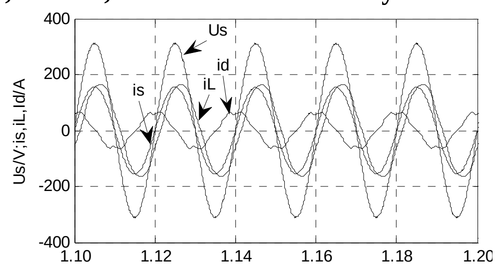
Waveforms of system voltage, current, load current with steady-state capacitive load before the compensation



Waveforms of system voltage, current, load current with steady-state capacitive load after the compensation



Waveforms of system voltage, current, load current with steady-state inductive load before the compensation



Waveforms of system voltage, current, load current with steady-state inductive load after the compensation

Figure 8 : Voltage and current waveform of capacitive load and inductive load

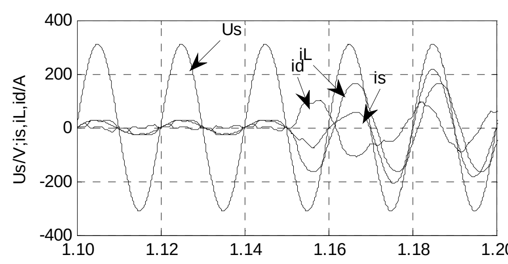


Figure 9 : Voltage and current waveform of putting inductive load

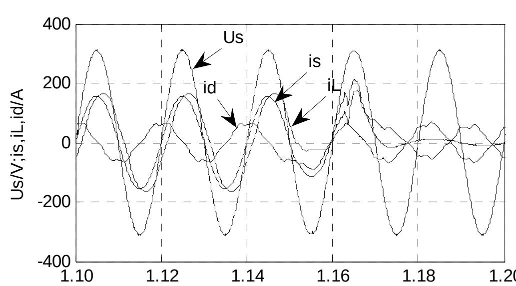


Figure 10 : Voltage and current waveform of switching between capacitive and inductive load

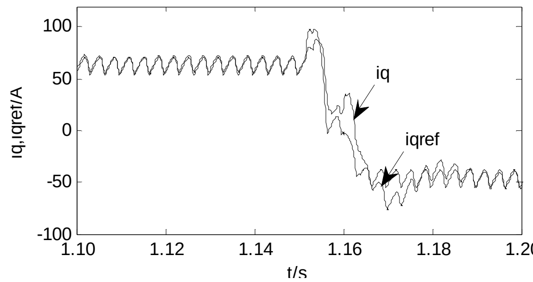


Figure 11 : Current tracing waveform of reference reactive power and real-time reactive power

Experiment verification

Dynamic reactive compensation experiment device (STATCOM) is mainly composed of control cabinet, power cabinets, starting cabinet, reactors, etc. Based on the structure of cascaded H-bridges, star connection method is adopted in the design of the wire connection method in three-phase system. Multiple FPGA control structure is introduced which consists of FPGA control board, A/D board, I/O board, optical fiber interface board and power board. The parameters of experiment device are shown in TABLE 2.

During the experiment, control system has two experimental devices of STATCOM, one is compensation device, and another is used to generate reactive current and harmonic current. The experimental structure is shown Figure 13.

TABLE 2 : The parameters of experiment device

Parameters	value
Voltage class	10kV
Capacity	±5M
Number of power unit	12
DC-side capacitors	10μF
Filter reactor	2mH 8.4mH
Filter capacitor	6.76μF
Filter resistance (Suppress resonance)	8.55Ω

The integral control principle diagram is shown in Figure 12.

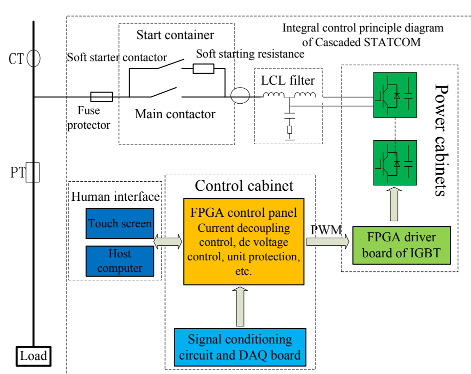


Figure 12 : Structure diagram of system controller

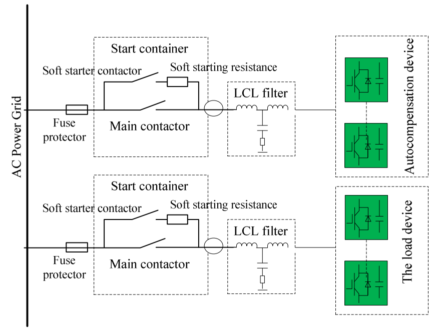


Figure 13 : Structure diagram of system experiment

The analysis of experiment waveforms is shown in the following figures. From Figure 14, in steady-state condition, the value of reactive current, which is generated by load cabinet, is 150A. But the actual data indicates that part of reactive current that should be compensated by compensation device is now being absorbed by LCL filters. The specific value is 25.4(A) and120.4 (A). Then, the value of system reactive current is 1.6(A). As can be seen from the above data, the compensation device can achieve dynamic compensation without the need of reactive current from the grid. As shown in Figure 15, in the process of load variations, dynamic reactive output current of STATCOM can track the reference current quickly. The value of changes is 150(A) and 50(A). The date in Figure 16 is the real-time value of DC-side capacitor voltage. Data in the Figure 16 shows that there is small deviation between units, indicating balance control DC-side capacitor voltage.

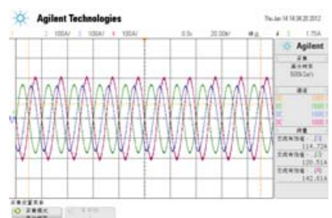
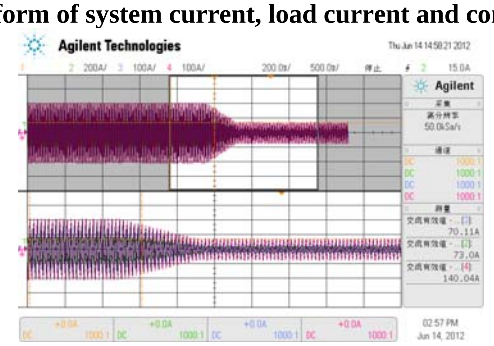
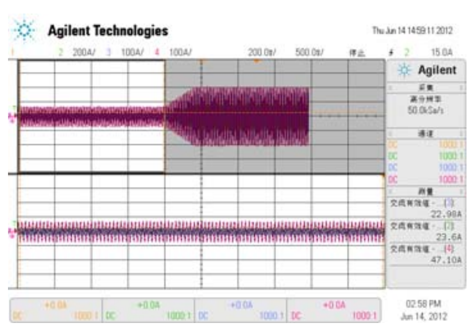


Figure 14 : Current waveform of system current, load current and compensation device current



Dynamic current waveform of Load change and its value changes from 150(A) to 50(A).



Dynamic current waveform of load change and its value changes from 50(A) to 150(A).

Figure 15 : Current tracing waveform of load variations

Figure 16 : The value of DC-capacitor voltage

CONCLUSIONS

According to the development background of the medium voltage cascaded STATCOM, mathematical models of cascaded STATCOM in *a -b- c* and *d-q co*ordinates has been established in this paper. Decoupled control structure, which consists of internal model decoupling control and PI method, is adopted in current control loop. The design of decoupling control is also realized between the active and reactive power. Simulation and experiment show that the established mathematical model and the decoupling control strategy can realize the dynamic decoupling current control.

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