Muti-level voltage synthetic voltage direct power flow controller

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Abstract: Aiming at the defects of DC energy storage elements, complex structure and large volume of unified power flow controller (UPFC), the paper combines flying capacitor multilevel technology and voltage vector synthesis technology with unified direct power flow controller. A three-level direct power flow controller (3L-DPFC) and a new control strategy are proposed. By obtaining the power parameters of the receiving end and substituting them into the derived calculation formula, the compensation voltage can be deduced to adjust the phase and amplitude, and the change relationship between the compensation voltage and the power parameters of the receiving end can be calculated through multiple groups of data, so as to adjust the active power flow and reactive power flow in the power grid. Compared with the unified direct power flow controller, it has the advantages of no DC energy storage element, small volume, simple structure, and the voltage stress of each switch is reduced by half, which reduces the failure rate and economic cost of the controller. In the paper, the topology and control strategy of three-level synthetic DPFC are described in detail, and its buck AC conversion theoretical analysis is verified by simulation.

1. Introduction
Because the electric energy plays an increasingly important role in industrial production and daily life in modern society, the power generation and power supply industry must make profound changes to meet the needs of society. Therefore, compared with the previous power system, the power transmission capacity of the power grid must be improved. However, the previous power system facilities are difficult to meet the requirements of the current power grid due to the lack of infrastructure and long service time. Therefore, how to improve the power transmission capacity of the power grid and the stability of the system is of great significance to the economy, energy conservation and social life\(^{1-3}\).

The appearance of flexible alternating current transmission system (FACTS)\(^4\) and its development and application in recent decades have correspondingly solved the problems of insufficient power transmission capacity and system stability.

Unified power flow controller UPFC\(^5\) is the most perfect FACTS controller at present. A single-stage phase and amplitude controllable AC/AC converter ACCPA without DC energy storage link is proposed in literature [6], this converter is an excellent and simple structure of two-stage circuit \(\pi\)-type ACCPA\(^7\) and cascaded ACCPA\(^8\), with only a single-stage power conversion and no DC energy storage element, which not only has the functions of boosting and reducing voltage, and can lead and lag the phase of the regulated voltage.

On the basis of single-stage ACCPA, the orthogonal Direct power flow controller, DPFC) was proposed and studied in literature [9]. However, the orthogonal direct power flow controller has the
problem of the third harmonic. Literature [10] puts forward a two-level composite direct power flow controller, but it will be limited by the voltage stress of the switch tube in high-voltage applications such as actual power grid. Based on the basic topology and control strategy of synthetic DPFC, this paper proposes a multi-level voltage synthetic direct power flow controller and a new power flow control strategy with three levels as an example. The three-level synthesized DPFC has only one-level power conversion and does not contain DC energy storage elements, the voltage stress of the switch tube is reduced by half, and its input voltage is connected in parallel with the power grid. The output voltage is connected in series with the power grid to form a compensation voltage for adjusting the power grid voltage. Three-level synthesis DPFC can effectively adjust the active power flow and reactive power flow in the power grid by controlling the compensation voltage, and the phase of the compensation voltage can be adjusted within 360.

2 Two-level synthesis direct power flow controller

2.1 Topological structure

![Fig. 1 Topology structure of three-level synthesis direct power flow controller.](image)

Fig. 1 shows the main circuit topology of the three-level synthetic direct power flow controller. Considering the negative influence of the third harmonic, the primary and secondary sides of the input transformer are connected with \( \Delta |Y \), and the output transformer is connected with the same connection to avoid the third harmonic pollution of the power grid. The input transformer of the power flow controller is connected in parallel with the power grid, and the output transformer is connected in series with the power grid. In addition, it contains no DC energy storage element and an auxiliary transformer with the ratio of primary to secondary turns of 2:1 to ensure that the voltage of the self-following flying capacitor \( C_y \) can automatically and stably follow \( U_i/2 \) (\( U_i/2 \) is the input voltage). A three-level synthesis direct power flow controller has six Buck AC conversion units U1, U2, V1, V2, W1 and W2 and three output LC filters. Each phase conversion unit has four pairs of switch tubes, and each switch tube is
connected with a diode in reverse, so that the AC conversion unit can work in four quadrants, and the power factor is improved.

In practical application, the voltage withstand value of switching components has been paid close attention to due to the working requirements in high-voltage and high-power occasions. Therefore, it is of great significance to use the self-following flying capacitor multilevel synthetic direct power flow controller to reduce the voltage stress requirements of switching tubes by half, reduce the failure rate of the system and reduce the economic cost.

2.2 switch mode.

Here, for convenience of explanation, the U1Buck AC converter in Phase A is taken as an example, and the other five Buck AC converters are analogized. In a voltage input cycle, because the flow direction of input voltage \( U_i \) and filter inductor current \( i_{Lf} \) changes, when input voltage \( U_i > 0 \) and \( U_i < 0 \) and filter inductor current \( i_{Lf} > 0 \) and \( i_{Lf} < 0 \), U1 Buck AC converter has four different working modes and four switching modes. When the input voltage \( U_i > 0 \), the switching tubes \( S_{1A1} \) and \( S_{7A1} \), \( S_{3A1} \) and \( S_{5A1} \) are complementarily switched on and off at high frequency, and the switching tubes \( S_{2A1}, S_{4A1}, S_{6A1} \) and \( S_{8A1} \) are kept in synchronization. When the input voltage \( u_i \) is less than 0, the switching tubes \( S_{4A1} \) and \( S_{6A1} \), \( S_{2A1} \) and \( S_{8A1} \) are complementarily switched on and off at high frequency, and the switching tubes \( S_{1A1}, S_{3A1}, S_{5A1} \) and \( S_{7A1} \) keep in constant synchronization. In which the duty ratio signals of switching tubes \( S_{1A1} \) and \( S_{3A1} \) and \( S_{5A1} \) and \( S_{7A1} \) are different by 1/2 of a single cycle of input AC voltage. Let's take \( U_i > 0 \) and \( i_{Lf} > 0 \) as examples. The four switching modes of U1Buck AC converter are shown in the following figure.

Fig. 2 Equivalent circuit diagrams of four switching modes.

As shown in fig. 2, in a switching cycle, the switching mode sequences involved are also different according to the duty cycle \( D < 0.5 \) or \( D > 0.5 \).
2.3 Adjustment area of compensation voltage.

As shown in fig. 5, taking phase a as an example, the output compensation line voltage $u_{abc}$ synthesized by the U1 Buck AC converter and the V2 Buck AC converter is vector synthesized with the grid primary line voltage $u_{iab}$ to obtain a new modulation line voltage $u_{ab}$, where The region I (O-F-H-J) represents the basic adjustment region of the compensation voltage when the input voltage of Buck AC conversion unit U1 is $u_{iab}$ and the input voltage of V2 is $u_{ibc}$.

According to the analysis of fig. 5, the amplitude and phase of the new modulation line voltage $u_{ab}$ of the power grid are related to those of the compensation voltage $u_{oab}$, and the amplitude and phase of the new modulation line voltage of the power grid can only be increased and the phase can only be adjusted in the interval of \([-90, 30]\) compared with the original line voltage of the power grid in region I. In order to realize buck and other phase modulation, other adjustment areas must be obtained. To realize the adjustment range of the compensation voltage of 360, we have connected two selector switches SW0 and SW1 in the topology shown in fig. 1, and the two selector switches SW0 and SW1 are connected to the primary sides of input transformers T1 and T2 respectively. The selector switch changes...
the input voltage of the Buck AC conversion unit by changing the connection sequence between the primary side of the input transformer and the power grid, thus obtaining different output voltages and obtaining three different regulation regions.

3. Control strategy

![Electric energy transmission system](image)

Fig. 6 Electric energy transmission system

The control strategy we usually use in power flow control analysis is shown in Figure 6. In the daily energy transmission process of the power grid, we can control the active power and reactive power of the power grid by adjusting one or several parameters. The specific relational expression is as follows:

\[
\begin{align*}
P &= \frac{U_s U_R \sin \theta}{2X} \\
Q &= \frac{U_s U_R \cos \theta - U_R^2}{2X}
\end{align*}
\]

(1)

The usual control strategy is to determine the receiving terminal voltage \(U_{RM}\) and the sending terminal voltage \(U_{SM}\), and then deduce the amplitude and phase angle of the compensation voltage \(U_B\) that the AC converter should provide. In actual power grid operation, the voltage at the receiving end is often affected by the power consumption of the load connected to the receiving end. For example, due to the heating demand in winter, the cooling demand in summer will inevitably lead to a significant increase in electricity consumption and a decrease in terminal voltage \(U_{RM}\).

The new control strategy proposed here is based on the derivation of the basic relational expression, taking \(U_{SM}\), \(x\), \(p\) and \(q\) as known quantities, and finding \(U_{RM}\) and \(\theta\). The specific relational expression is as follows:

\[
\begin{align*}
U_{RM} &= \sqrt{\frac{\left(U_s^2 - 4XQ\right) + \sqrt{-8XQU_s^2 + U_s^4 - 16X^2P^2}}{2}} \\
\theta &= \tan^{-1} \frac{2XP}{U_s^2 + \sqrt{-8XQU_s^2 + U_s^4 - 16X^2P^2}}
\end{align*}
\]

(2)

Set the specific \(U_{SM}\) and obtain \(U_{RM}\) and \(\theta\) by monitoring the receiving terminals \(p\) and \(q\). According to \(U_{SM}\), the relationship between \(U_R\), \(p\) and \(q\) can be deduced by measuring multiple sets of data on the premise of monitoring \(U_{SM}\). Adjust \(\theta\) to adjust active power, adjust \(U_{SM}\) to adjust reactive power, and combine with multilevel synthetic direct power flow controller, \(\theta\) and \(U_{SM}\) can be adjusted independently, so as to achieve the purpose of quickly adjusting power flow.

4. Simulation experimental results

We use the simulation software Saber Sketch to prove the correctness of the proposed theory, and always set the amplitude of the primary line voltage of the power grid as 538V during simulation. According to the three-phase symmetry of the input voltage, the new modulated phase voltages \(u_a\), \(u_b\), and \(u_c\) of the power grid synthesized by them are naturally sinusoidal symmetrical and have a positive sequence difference of 120 between phases.

Fig. 7 shows that the input voltage of the A-phase Buck AC converter unit and the voltage stress borne by the switching tubes \(S_{1a}\) and \(S_{3a}\) are always half of the input voltage of the A-phase Buck AC converter when the actual duty cycle \(D<0.5\) of the main circuit of the three-level synthetic direct power
flow controller, which obviously reduces the voltage stress borne by the switching tubes during operation.

When the duty cycle D1 of Buck AC conversion unit is 0.2 and D2 is 0.2, and the regulation area of compensation voltage is in area I, the waveforms of voltage $u_{ia}$, $u_{oa}$ and $u_a$ are shown in Fig. 8. After measurement, the amplitude of voltage $u_a$ is 406.6v, and the phase lag $u_{ia}$ is 7.07 °, which is close to the amplitude of voltage $u_a$ calculated by the formula is 406.7580v, and the phase lag is 7.0605 °.

Only change the connection form of the input transformer so that the compensation voltage is in area II. When the duty cycle of the buck AC conversion unit remains D1 = 0.2 and D2 = 0.2, FIG. 9 shows the waveforms of the voltages $u_{ia}$, $u_{oa}$ and $u_a$ at this time. At this time, the measured amplitude of the voltage $u_a$ is 328.12v and the phase advance $u_{ia}$ is 19.386 °, which is very close to the calculated value 328.14v and the phase advance 19.1417 °.

Fig. 10 shows the waveforms of voltages $u_{ia}$, $u_{oa}$ and $u_a$ when the compensation voltage $u_{oa}$ is located in region III. when the duty cycle of Buck AC conversion unit remains D1 = 0.2 and D2 = 0.2, the measured amplitude of voltage $u_a$ is 223.96v and phase lag $u_{ia}$ is 13.7268 °, which is very close to the calculated value 223.3909v and phase lag 13.9358°.
5. Conclusions

In order to effectively control the power flow in the power grid, this paper proposes a multi-level synthetic direct power flow controller and a new control strategy, taking three-level as an example. Similar to UPFC structure, they all contain input parallel transformers and output series transformers. However, the three-level voltage synthesis direct power flow controller does not contain DC energy storage components (DC energy storage components often lead to high failure rate of equipment). Set the specific $U_{SM}$ and obtain $U_{RM}$ and $\theta$ by monitoring the receiving terminals $p$ and $q$. According to $U_{SM}$, the relationship between $U_{B}$, $p$ and $q$ can be deduced by measuring multiple sets of data on the premise of monitoring $U_{SM}$. Adjust $\theta$ to adjust active power and $U_{SM}$ to adjust reactive power. Combined with the multilevel synthesis direct power flow controller, $\theta$ and $U_{SM}$ can be adjusted independently, so as to achieve the purpose of quickly adjusting the power flow of the power grid. The topology theory of the three-level voltage synthesis direct power flow controller is demonstrated by simulation.

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