A review on voltage control using on-load voltage transformer for the power grid

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Abstract. Voltage control is an important method for regulating the feeder voltages in power systems. Various voltage control methods are used by distribution Grid-operators in order to maintain the voltages to be within an acceptable voltage level. Traditional OLTC (on-load tap-changer) and improved OLTC are most applied. However the traditional voltage control techniques are no longer leading in technically because of the long arcing time and the high investment. Combining power electronics and OLTC is the future. The use of a thyristor for controlling the current can achieve arc-free operation in power electronic switch OLTC with unparalleled advantages in terms of safety and invest control.

1. Introduction

Electrical power systems are normally operated at multiple voltage level. Since the invention was invented at the end of the 19th century, the transformer has laid an important foundation for the development of modern long-distance power supply systems. Today, the Grid power transformers are still extremely important equipment in the power system which is more complicated, and related research has never stopped.

On the transmission side, with the introduction of the concept of smart grid and the development of smart grids with UHV (Ultra High Voltage) grids as the backbone and coordinated development of power grids at all levels, power quality has attracted more and more attention. One of the important indicators for measuring power quality is the stability of the voltage. Since power generation and consumption cannot be balanced, loads and currents are volatile, and voltage fluctuations are inevitable, especially in radiated networks. In order to stabilize the grid voltage, connect the grid, and regulate the load flow, it is necessary to adjust the voltage.

The OLTC (on-load tap-changer) is a device for adjusting the amplitude of the in-phase voltage. Compared with the no-load voltage regulating transformer, the OLTC has the characteristics of large voltage regulation range and no power-off during the voltage regulation process, which has irreplaceable advantages in improving power quality and ensuring economic operation of the power system. At present, mechanical on-load tapping devices, ie mechanical on-load tap-changers, have been widely used in engineering, but there are still some inevitable defects in this traditional on-load tapping method, such as complex mechanisms, arc, slow response, etc [1].
In order to improve the structure and working performance of the OLTC transformer and adapt to the new requirements of power grid development, using the rapidly developing power electronics technology to construct the tap changer of the distribution transformer and improving the performance of traditional tap-changers is an inevitable trend in the future. This article describes several common OLTC technology routes and analyzes trends and prospects.

2. Basic principle of voltage regulation

2.1. Theoretical of transformer voltage regulation technology

As an important quality indicator of power, voltage fluctuation range and size will directly affect the performance, efficiency, and life of electrical equipment. The electrical equipment is designed and manufactured according to the rated voltage under which the effect is the optimization. The excessive voltage offset is not only negative for the normal operation of the user, but also is not conducive to the safe and economic operation of the power system. Too low a voltage will increase the network loss and may even damage the stable operation of the system. If the voltage is too high, it will damage the insulation level of the electrical equipment, and increase the corona loss generated in the high-voltage network. Voltages in the power network are in compliance with the prescribed standards, and voltage regulation strategies are needed to adjust the voltage [2].

The voltage adjustment principle is shown in Figure 1. The electric energy produced by the generator G is sent to the user through the step-up change, the transmission line and the step-down. Assume that the transmission line capacitance, network loss, and transformer excitation power are neglected. The transformer parameters have been reduced to the high voltage side. The ratios of step-up and step-down are respectively chemicalized. The total resistance of the transformer and the line is for the people. The total reactance is X. The voltage at the available load node is:

\[ U_n = \frac{U_Gn_b - \Delta U}{n_2} \approx \frac{U_Gn_1}{n_2} \frac{(PR + QX)/U}{n_2} \]

Formula (1) shows that to change the load node voltage, it is possible to change the terminal voltage of the generator, the line parameters \( R \) and \( X \), the active \( P \) and reactive power \( Q \) of the line, the step-up ratio \( n_1 \) and the step-down ratio \( n_2 \) to achieve.

![Figure 1. Voltage adjustment schematic.](image)

Transformer voltage regulation essentially changes the ratio \( n \), which is divided into stepless voltage regulation and step voltage regulation. The former is generally used in places with low voltage levels and small capacity. Step voltage regulation is by changing the winding taps of the transformer. Change the number of turns, and then change the ratio to stabilize the voltage output from the secondary winding. Transformer step-by-step voltage regulation includes: OPTC (Off-Power Tap Changer) and OLTC. The former is to change the voltage ratio of the transformer in the case of power failure (the primary side is disconnected from the grid), and then adjust the voltage of the secondary winding. It is only suitable for occasions that can be short-time power-off and does not need frequent voltage regulation, and is gradually replaced by on-load voltage regulation. On-load step-by-step voltage regulation means that the transformer is equipped with a tap on a certain winding, and the tap
change is completed when the secondary side is connected to the load. When the tap change is performed, a part of the winding is removed or connected to change the number of winding turns. The ratio has also changed, eventually changing the output voltage and achieving voltage regulation.

2.2. OLTC Transformer in the power system
OLTC is a very important transmission and distribution equipment in power system substations. It is often equipped with OLTC for high-voltage transmission and distribution of important loads. The transformer equipped with OLTC can change the number of turns of the coil through the switching action when the load is loaded, thereby changing the ratio to adjust the node voltage and improve the power quality; and can adjust the load flow of the power system, reduce the cost of the reactive power compensation device and save Electrical energy: In the power system, it also plays a role in connecting the power grid and stabilizing the load. In a power grid with sufficient reactive power supply, on-load voltage regulation is a convenient, effective and economical method for controlling voltage quality. It has a large adjustment range, can be adjusted at any time, is flexible in operation, and has a small investment. In addition, it can also reduce the power grid. Circulation, prevent unintended reactive power exchange, reduce the loss of parallel operation lines, make power supply more reliable, and make power grid scheduling more flexible. The combination of reactor, capacitor and on-load tap changer can also form flexible and reliable transmission components.

3. Basic principle of voltage regulation
As early as 1920, Japan, the United States, and many countries in Europe began to use on-load tap-changers. It can be divided into two types of reactance and resistance. As the switching capacity continues to increase, in addition to the use of current-limiting reactance in the United States, other countries have chosen to use lower-cost resistive switches. The key to achieving on-load tuning is that the load current can continue to flow while switching. Switching at high currents is often accomplished using parallel multi-contacts, series multi-contacts, or sequential switching of multiple current-limiting resistor shunts. Until 1960, people began to develop on-load tap-changers using vacuum as the arc-extinguishing medium. The switch has the advantages of long electrical life, good arc-extinguishing performance, no pollution to the medium and simple maintenance of the contacts, and can be used in places where large currents are switched. After another 20 years, with the rapid development of power electronics technology, many researchers began to improve on the basis of the traditional switching scheme. The on-load tap-changer solution combining high-power power electronic devices such as thyristors has gradually emerged. In the meantime, Japan has compared the new switch with the traditional switch, and concluded that the traditional mechanical switch has higher reliability. In the 1990s, the UK developed an on-load tap-changer that uses thyristor-assisted shunting, and has been developing and improving on this basis.

3.1. Mechanical On-load Voltage Regulation Technology
The classic reactance on-load tap-changer is shown in Figure 2 [3]. This switch has two independent selector switches and diverters. The reactive on-load tap-changer with the transition reactor as the current limiting device needs to cut off the current, which not only increases the volume, but also increases the amount of transformer oil. With the advent of vacuum switches, the re-arrangement of the reactance windings makes the vacuum switch appear on the reactive on-load tap-changer. The typical wiring of a reactive on-load tap-changer with a vacuum switch is shown in Figure 3 [4].
The vacuum switch can suppress the generation of the arc. The vacuum environment is suitable for the switching of large currents, and the contacts are basically maintenance-free. However, due to some limitations of vacuum switch operation, this solution has not been widely applied in engineering practice.

3.2. Resistive On-load Tap-changer.
Since Dr. Jansen proposed the famous high-speed resistance transition theory in 1927, the principle of resistive transition has been widely used in the development and improvement of switch structures. Resistive OLTC usually adopts a structure of buried type, transformer oil switching, and resistance transition. The breaking current of each contact of the transition circuit is in phase with the recovery voltage between the contact fractures, which is favourable for arc extinction. Moreover, the power factor of the circulating current is one, and the electrical life of the switching switch arc contact is much longer than that of the reactance type [5]. Due to the short transition time, the yellowing of the fast mechanism is generally driven by the motor-driven mechanism to make the switching work more reliable and rapid. At present, most of the applications in engineering practice are resistive on-load tap-changers.

Transition resistance is an important part of resistive OLTC. Traditional resistive OLTC typically use single, double, and four resistors current limiting. The cycle of contact between contacts includes flag cycle, symmetric flag loop and asymmetric flag loop. The single-resistance asymmetric flag-flag transition mode is only used as a selection switch, and is suitable for use in low-voltage and small-capacity applications of 10KV and below. In the double resistance flag cycle transition mode, the number of contact between the moving contact and the fixed contact follows the 1-2-1-2-1 cycle mode. And the degree of transformation is 1-2-1, which is the most widely used transition form. When the capacity of the double-resistance switch cannot be satisfied, a four-resistor transition form with a large switching capacity can be adopted, and the contact number is performed in a cycle of 2-3-2-3-2. The degree of transformation is 2-3-2. The typically four resistors current limiting OLTC are the T-type of MR company and UCL type of ABB.

The characteristic of single resistance OLTC is that the transition circuit is asymmetrical, and the one-arm connection is adopted; the output voltage changes twice; the contact switching task is relatively light, and the service life is long. When the power factor of the load is zero, the heaviest is reached; the main contact is switched. The capacity will increase by four times due to the change in the direction of the load current. The structure of the dual resistance current limiting is relatively simple and low in cost, and is suitable for PMSL on small and medium capacity transformers. The power system still mainly adopts the star-neutral point and dual-resistor current limiting CM type OLTC.
In the switch using the four-resistance transition principle, the T-type OLTC of the German MR factory is a typical example, using the contact change program "2-3-2", see Figure 4. Its transition circuit has a symmetrical structure with 6 contacts, 4 current limiting resistors, and the output voltage changes a total of six times. The contact switching capacity is lower than the double resistance, so the life can be increased by 50%. The contact recovery voltage is low, the arc is not easy to re-ignite, and is generally applied to high-voltage, large-capacity power transformers. In addition, the contact switching task is not affected by the change of load flow direction, and can be used for voltage regulation on the contact transformer. However, the four-resistor switch also has the disadvantages of complicated structure, large power loss, large occupancy, and relatively expensive.

Figure 4. Four resistance OLTC structure.

After the efforts of researchers and engineers, the performance of mechanical resistance tap-changer has been greatly improved. For example, the four-resistance switch is often changed to a "series double-break" structure on the transition circuit, so that the recovery voltage between the contact fractures can be reduced, the arc is not easily re-ignited, and the switching capacity of the OLTC can be improved. However, whether it is a reactive or resistive on-load tap-changer, there are some inevitable defects and problems. First, switching transmission is complicated, and the cost will be much higher than that of transformers without load regulation. Therefore, most of the on-load tap-changers are large-capacity, and are rarely used in distribution networks with medium voltage and below voltage levels. Second, the arc generated during the switching process will erode the surface of the contact, affecting the life of the contact, and will also age the transformer oil and increase the workload of the transformer oil treatment. Third, the presence of an arc complicates the design of the structure, resulting in reduced reliability. Fourth, the voltage regulation response time is long and the maintenance amount is large.

3.3. Comparison of Resistive and Reactive OLTC
Resistive OLTC usually adopts a structure of buried type, transformer oil switching, and resistance transition. The breaking current of each contact of the transition circuit is in phase with the recovery voltage between the contact fractures, which is favorable for arc extinguishing, and the power factor of the circulating current is one. The electrical life of the switch arc contact is much longer than that of the reactance type. Due to the short transition time, the spring mechanism of the fast mechanism is generally driven by the motor-driven mechanism to make the switching work more reliable and rapid. The characteristic of reactive OLTC is simple structure, and the number of voltage regulation steps is doubled when the number of taps is constant. And even if the power supply of the motor-drive
mechanism fails at a certain position during the switching, it does not affect the normal operation of the device. The disadvantage is that the power factor of the circulating current is low, the phase is delayed by 90 degrees, and the electrical life of the switch contacts is relatively short. The transformer with the reactance switch is large and expensive, and now only the United States is still adopting.

The similarity between the two is that the selection tap is always completed under no-load conditions, the transfer of the load is performed by a special contactor or switcher, and the current limiting element only works during the switching process. The difference is that the reactor does not generate much heat, and the current limiting current limit can be switched slowly. The switching time is 5 to 6s. The resistance component consumes a large amount of power, and the heat is severe. It must be switched quickly. The switching time is about 40ms. Otherwise, the current carrying time of the resistor will be too long, the temperature rise will be too limited, and the loss will be large, and it will not be economical. Therefore, the resistance switch device must have a fast action mechanism. The switching current of the reactive switch is delayed by 90 degrees, the arc-extinguishing performance is poor, the contact life is short, the pollution of the transformer oil is more serious, and the maintenance work is cumbersome.

The resistive switching current is the same as the recovery voltage phase, the power factor of the circulating current is 1, the resistive arc is more easily suppressed, the contact life is long, and the maintenance and repair work is simple. Therefore, the resistive type is more suitable for occasions with higher voltage and larger capacity. From the perspective of manufacturing process, the transient reactance is designed according to the continuous rated load, which consumes more materials, takes up more volume, and is more expensive. The transition resistor is designed according to short-time load, small in size and low in cost. The structure of the resistive on-load tap-changer is more complicated but compact. If the process level is high, the resistive type will save material.

4. New technology of on-load voltage regulation

In view of the defects and problems of the traditional mechanical OLTC, the researchers have done a lot of research and proposed a variety of new on-load voltage regulators. According to the characteristics of the taps of these devices, they can be mainly divided into two types: mechanical improved type and power electronic switch type.

4.1. Mechanical improved OLTC

The mechanical improved OLTC refers to a tap changer made of a power electronic switch assisted mechanical switch. The purpose is to use the power electronic device as a transition device when switching the tap, using the power electronic switch as the turn-on and turn-off circuit, and the mechanical contact is not powered off or equipotential switching, thereby suppressing the arc in switching.

A typical arcless switching scheme is shown in Figure 5(a). The switching switch M and the tap selector can be combined to form a single-resistance on-load tap-changer capable of arc-free operation. Figure 5(b). In the figure, the numbers 3~6 represent a double switch, 7, 8 are thyristors, 9, 12 are trigger diodes, 10, 11 are transition resistors, and 1, 2 are M output terminals.
In 1990, Cook G.H et al. of the United Kingdom proposed an on-load voltage regulator using thyristor-assisted shunt based on the problem of scheme 1. The device uses a separate transition resistor and thyristor to suppress the arc generated during the switching process. A simple mechanical switch contact arrangement ensures that the thyristor used for arc suppression is only connected to the circuit for a short period of time, and that the failure of the thyristor does not cause damage to the tap selector or transformer [6], as shown in Figure 6. When the switch is actuated, the pulse transformer provides a trigger signal to both sets of thyristors regardless of the current direction of the action. There will always be a set of conduction, so that the load current will flow through the thyristor to complete the arc extinguishing. The advantage is that there is no arc during the switching process, the switch life is greatly extended, and thus the number of switching can be increased; the disadvantage is that the trigger of the thyristor is realized by the pulse transformer, and it is relatively difficult to design and manufacture the transformer, and the OLTC schematic diagram of the switch is adopted. See Figure 7.

Through the above scheme, it can be seen that the Mechanical improved OLTC has the following characteristics: the introduction of the thyristor switch in the switching circuit enables the mechanical switch to operate without power or equipotential, thereby achieving arc-free switching, and after the switching is finished, the thyristor is withdrawn, still using the mechanical The switch carries the load current; the switching speed is mainly determined by the operating time of the mechanical switch.
Therefore, the mechanically modified OLTC can basically solve the arcing problem of the mechanical switch during switching, but the structure is still complicated, the action cycle is long, and the response speed is relatively slow [7], and the voltage cannot be quickly adjusted.

4.2. Power electronic switch OLTC

Since the 1990s, scholars have begun to study the on-load tap-changer of power electronic switch type, which has improved the voltage-regulating response speed of on-load voltage regulation. Scholars mainly from the structure and circuit of power electronic on-load tap-changer. Topologies and types of power electronics have been studied. In 1999, Meyer proposed the application of power electronics as a tap changer in distribution systems [8] and made many feasibilities for the implement-tation of the scheme. Research has proposed new research ideas for improving the performance of distribution transformers, but he did not do more in-depth research and experimental verification of the program. In 2003, Faiz designed a topology of a solid-state on-load tap-changer [9], which implements a wide range of voltage regulation functions with fewer power electronic switches and overcomes mechanical divisions. Some defects in the switch. In 2003, Mailah proposed a scheme for non-contact automatic voltage regulation through microcomputer-controlled power electronic switches [10]. From this, the research on power electronic type non-contact tap-changers has taken a new direction. In 2010, Abbaszadeh proposed a new type of solid-state on-load tap-changer based on power electronic switch. The scheme uses a thyristor as a switching device and uses AVR microcontroller to control it by discrete-period modulation method [11].

Figure 8 is a schematic diagram of a contactless OLTC with a controllable switching circuit. In circuit I, K1-K6, K0 represents the thyristor switch, QF is the mechanical switch, and R0 and R are the transition resistors, which are used to avoid damage to the switch tube caused by the excitation surge current and to balance the voltage. The advantage of this scheme is that arc-free switching can be realized, switching loss is small, switching speed is fast, and switching can be frequently performed. The disadvantage is that the thyristor is also used to carry load current under normal conditions, and the working reliability is poor. The branch K22-K0 and K21 each carry a part current, the current per thyristor is reduced, making the circuit more reliable, but requires twice as many thyristors.

Figure 8. Schematic diagram of power electronic switch circuit I (left) and circuit II (right).

4.3. Comparison of characteristics in different OLTC

At present, most of the OLTC still use mechanical contact type, which has the following defects: arcing is easy to occur during switching, the action and response speed are slow, the switching action time cannot be accurately controlled, the error is easy, the fault rate is high, and the maintenance amount is large. The transient transition process during handover may be detrimental to the safe operation of the grid. The rapid development of power electronics disciplines has led researchers to improve the arc-extinguishing medium and began to study the switch structure and transition principle.
The new OLTC based on power electronics technology has become domestic and foreign due to its durability, economy and frequent adjustment. Areas of enthusiasm for research. The all-electronic OLTC usually connects the winding tap and the power electronic switch composed of the high-power thyristor anti-parallel, and realizes the voltage regulation by controlling the on-off of the switch tube. It has no mechanical moving parts, does not generate an arc when switching, and has a fast response speed. It has higher controllability, but the number of thyristors is large. Under normal conditions, it must withstand voltage and conduct current. When selecting the type, it needs to leave more margin, increase the cost, reduce the reliability, and also need to install the cooling device. And there are also Achilles heel: once the thyristor is damaged, the switch fails completely.

The mechanically improved OLTC has not changed much in structure. When the switch is switched, the thyristor is introduced to prevent the arc from being generated. After the switchover, the mechanical switch is still responsible for the flow, and the arc-free operation can be basically realized, which increases the reliability and the service life to a certain extent. However, the response speed has not improved much. At present, many people still tend to study the hybrid on-load tap-changer solution to avoid the reliability brought by the all-electronic solution and the heat dissipation problem of the controllable device. The characteristics of several different switching types OLTC introduced above are compared in Table 1 below.

| Type                        | Speed | Arc  | Impact after thyristor failure | System fault detection | Cost       |
|-----------------------------|-------|------|--------------------------------|------------------------|------------|
| Traditional mechanical     | Slow  | Large| Yes                            | No                     | No         |
| Mechanical improved        | Slow  | Smaller | Yes                          | No                     | No         |
| Power electronic switch    | Fast  | No   | A little                       | Serious                | Yes        |

5. Conclusion

This paper has reviewed the existing OLTC voltage controls scheme as well as the new voltage control techniques. The voltage control scheme for OLTC transformers both in traditional mechanical, mechanical improved and power electronic switched has been discussed. Although the traditional mechanical OLTC is widely used in the regulation of voltage in the power grid, its long arcing time and expensive cost limit its further development. With the development of power electronics technology, the cost advantages of electronic OLCT and good arcing characteristics are unmatched by other types. At present, the main problem of the electronic OLTC is that the reliability needs to be further improved, and the algorithm needs further optimization and improvement.

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