Three-Phase Flexible Transformer Based on Bipolar Direct AC/AC Chopper and Its Control Strategy

YIBO WANG, (Member, IEEE), GUO-WEI CAI, (Member, IEEE), CHUANG LIU, (Member, IEEE), BINGDA ZHU, DONGBO GUO, AND HANWEN ZHANG
Northeast Electric Power University, Jilin 132012, China

Corresponding authors: Yibo Wang (469682939@qq.com) and Chuang Liu (victorliuchuang@163.com)

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ABSTRACT Dynamic states (e.g., voltage sags and swells) in the power grid can cause faults and defects in sensitive loads and in consequence financial losses. This paper deals with a flexible transformer based on bipolar direct AC/AC chopper (BD-AC). It is a combination of BD-AC and traditional power frequency transformer, and it can realize the flexible regulation of voltage amplitude and phase angle respectively according to voltage requirements. Firstly, the topology and modulation strategy of the selected BD-AC are analyzed. On this basis, the flexible transformer system topology based on BD-AC and transformer is proposed. Then, based on the structure of flexible transformer system, its working principle is analyzed in detail, and the regulation range of voltage amplitude and phase angle are quantitatively studied. Furthermore, considering the principle of voltage regulation, a triangle angle theory based control strategy is proposed. Finally, the correctness and effectiveness of the theoretical analysis of the proposed flexible transformer system are carried out by detailed computer simulation.

INDEX TERMS Flexible transformer, flexible ratio, voltage amplitude control, voltage phase angle control, bipolar direct AC-AC chopper (BD-AC).

I. INTRODUCTION

With the rapid development of social economy, the electrification of daily life is growing and the demand for power quality of the end-users is also increasing [1], [2]. The improvement of power quality can not only reduce the adverse impact on sensitive load, ensure the normal quality of industrial products and scientific experiments, but also play an important role in the safe and economic operation of power grid and reduce energy losses [3], [4]. Voltage quality is one of the basic indicators for power quality [5]–[7] and it has a great influence on the normal operation of electrical equipment, e.g., the voltage sags will increase the winding current of the motor, reduce the efficiency and service life of the motor, and make sensitive electronic equipment unable to work normally, etc., and the voltage swells will accelerate the aging of the insulation of electrical equipment, increase the loss of electric energy and the cost of electricity. Therefore, the parameters of voltage, its quality, are very important from both the viewpoint of the power grid and end-users [8]–[10].

At present, the reasons affecting the voltage quality are various, and the factors caused are more complicated, e.g., dynamic loads, switching effects, uncontrolled power flow, faults/accidents and adverse weather conditions. In order to mitigate the adverse effects of the above reasons on the voltage quality, there are two paths leading to the protection of sensitive loads against voltage perturbation and the reduction of energy losses [11], i.e., to improve the ride-through capability of electrical devices during voltage perturbation and install voltage stabilizers to reduce voltage fluctuation. Both of the means should be developed simultaneously and independently. For the latter, the ac voltage stabilizers based on mechanical or solid-state on-load tap-changers (OLTC) is of such kind of equipment [12], [13]. The OLTC realizes the voltage regulation of the power grid through mechanical or solid-state tap in static conditions. Besides, with the development of power electronic technology in recent years, there are various types of hybrid AC compensators used in modern
AC network to alleviate voltage disturbance. And a common design method of such devices is to combine the characteristics of traditional transformer and power electronic converter. The advantages of this design are that the transformer has the superiority of electromagnetic coupling - galvanic separation, and the power electronic converter has good dynamic performance and can realize the dynamic regulation of voltage.

There are numerous different solutions and topologies of voltage stabilizers, also called hybrid AC voltage compensators. The research of hybrid AC voltage compensators is mainly focused on installations that replace transformer in distribution network, i.e., shaping flexible transformer. In [14], a smart distribution transformer based on bidirectional power electronic switches is proposed, and it has a step-wise characteristics and narrow control range. A hybrid transformer based on matrix converter is presented in [15]–[17], and its structure of the proposed solutions needs a more advanced control system, which increases complexity and costs and decreases reliability. Moreover, because of the untypical transformer voltage ratio, the hybrid transformer cannot operate after system fault occurs [15], and the voltage control range is limited to ±20% [16]. Additionally, in [18], the voltage regulation range can be increased to ±50%, however as, the proposed solution cannot operate after a fault in the power electronic unit, either. Furthermore, the gain of the solution proposed in [18] has non-linear characteristic and dependent on matching conditions. Besides, solid state transformer (SST) is another strongly developed group of hybrid AC voltage compensators [19]–[21], which is constituted by AC/DC, DC/DC, DC/AC converters and medium frequency transformer. However, as with [15], [17] and [18], SST cannot operate with power electronic module damaged, thus, the reliability of SST is reduced. And even if the reliability is improved by increasing system redundancy, the complexity of the whole system will be improved [22], [23]. Additionally, because of the electric energy from the power supply to the power load is transferred through the power electronic unit, the rated power of converters must be equal to the power of the load, and in view of the structural characteristics of SST, energy transfer is multi-level, which increases the energy cost of the whole system [22].

A solution based on bipolar direct AC/AC choppers (BD-AC) is proposed to build a flexible transformer in this paper, which can improve voltage parameters in the AC distribution system. The presented flexible transformer is a combination of BD-AC and transformer, and it can realize the flexible regulation of voltage amplitude and phase angle respectively according to voltage requirements. Furthermore, with the three-phase topology, voltage of each phase can be flexibly adjusted by means of other two phases voltage. Thus, yielding the possibility to control the RMS value and phase shift of output voltages. Moreover, unlike the solutions presented above, the proposed flexible transformer can operate after a fault in the electronic unit. In addition, it has a simple control strategy, a wider range and a continuously variable voltage control character. On the other hand, one point needs to be emphasized that the power in distribution network has the magnitude of MW and the BD-AC for medium voltage and high power scenarios is difficult to realize in engineering with the present state of the IGBT art. The main purpose of this paper is not considered matching the power rating of the proposed solution with the transmission line parameters in large-scale power systems. Instead, this article is a demonstration of a forward-looking solution.

This paper is organized as follows: in section II, the topology and PWM modulation principle of the BD-AC is described; the structure, operation principle and control strategy of the BD-AC based flexible transformer system are proposed in section III; in section IV and section V, some simulation results are presented; finally, in section VI, conclusions are provided.

II. TOPOLOGY AND PWM MODULATION PRINCIPLE OF THE BD-AC

Non-differential AC/AC chopper (ND-AC) shown in Fig. 1 (a) is currently used, and it consists of four insulated gate bipolar transistors (IGBTs) and a capacitor (C) used to absorb the energy stored in the stray inductance of the line [24]. Fig. 2 (a) and (c) are the modulation principles and switching signals corresponding to the ND-AC. It can be seen that the control of the ND-AC is similar to the one used for a DC/DC buck converter with the main difference that it takes into account the sign of the input voltage ($v_{in}$). Thus, if $v_{in}$ is positive, the $S_1$ and $S_{1C}$ power devices follow a complementary PWM pattern, while the others are turned on. Similarly, if $v_{in}$ is negative, the $S_2$ and $S_{2C}$ power devices follow a complementary PWM pattern, while the others are turned on. The advantage of this control is that the current path is always available regardless of the direction of inductance current. Since each IGBT has only half a cycle of PWM control, the total switching loss is reduced. On the other hand, according to the working principle of ND-AC, the polarity of $v_{in}$ is the same as that of the output voltage ($v_{out}$), i.e., the ND-AC has unipolar output characteristics. Then, in order to obtain voltage bipolar output, the BD-AC is proposed in [25], and the bipolar means that the $v_{out}$ of the AC/AC chopper could be ‘in-phase’ or ‘anti-phase’ in relation to the $v_{in}$. The topology and principle of PWM modulation of the BD-AC are shown in Fig. 1 (b) and Fig. 2.

As can be seen from Fig. 1 (b), the BD-AC consists of two ND-AC parallel connection, thus forming H bridge structure. For convenience of description, the two ND-AC used are defined as P-Leg (Positive Leg) and N-Leg (Negative Leg) respectively. With the connection type, the common ground between the input and output ports of the two legs are retained. Moreover, the BD-AC achieves the output of continuously controllable bipolar voltage. In addition, due to the common sharing ground of the input and output, the feature that output can reverse or maintain phase angle with input is supported well.

According to the principle of PWM modulation shown in Fig. 2, the relationship between $v_{out}$ and $v_{in}$ is shown in
equation (1).

\[ v_{\text{out}} = (d_1 - d_2) \cdot v_{\text{in}} = D \cdot v_{\text{in}} \quad (1) \]

where \( d_1 \) and \( d_2 \) are defined as the time interval when switches are turned on during one switching period of P-Leg and N-Leg, respectively. Obviously, the range of values of \( d_1 \) and \( d_2 \) is \([0, 1]\). \( D \) is defined as modulation ratio of BD-AC, and its value is within the range of \([-1, 1]\).

III. BD-AC BASED FLEXIBLE TRANSFORMER SYSTEM

A. TOPOLOGY OF THE FLEXIBLE TRANSFORMER SYSTEM

Considering the characteristics of BD-AC, the topology of flexible transformer system based on BD-AC is proposed, which is shown in Fig. 3.

As can be seen from Fig. 3, the topology of the proposed flexible transformer system is composed of transformer, BD-AC modules (AC/AC-A, AC/AC-B, AC/AC-C) and its control system. The primary side of transformer consists of three windings: \( W_A \), \( W_B \) and \( W_C \). The secondary side consists of two parts: main winding (\( W_{a1} \), \( W_{b1} \) and \( W_{c1} \)) and auxiliary winding (\( W_{a2} \), \( W_{b2} \) and \( W_{c2} \)). Need to be pointed out that the three-phase auxiliary windings (\( W_{a2} \), \( W_{b2} \) and \( W_{c2} \)) in Fig. 3 are redrawn for ease of representation. From the connection relation of the electric power devices, the main parts of the presented flexible transformer system are BD-AC modules operating in each phase. The AC/AC-A is operating on A-phase, however, it is supplied from two other phases (B-phase and C-phase). Analogously, B-phase and C-phase have the same structure. Each BD-AC module consists of two BD-AC, and the outputs of BD-AC are connected to the main winding (\( W_{a1} \), \( W_{b1} \) and \( W_{c1} \)) respectively. That means A-phase, B-phase and C-phase have mutual support ability. Overall, the secondary main windings (\( W_a \), \( W_b \), \( W_c \)) of transformer and the BD-AC modules constitute a series system. Furthermore, in order to improve the reliability of the whole system, bypass switches (\( S_{bp1} \), \( S_{bp2} \), \( S_{bp3} \) and \( S_{bp-a} \), \( S_{bp-b} \), \( S_{bp-c} \)) are installed at the input and output ports of the BD-AC modules respectively. Similar to other high power and high voltage applications of bypass switches, in normal working condition, \( S_{bp1} \), \( S_{bp2} \), \( S_{bp3} \) are in closed state, \( S_{bp-a} \), \( S_{bp-b} \), \( S_{bp-c} \) are in open state. On the contrary, in overhaul/fault state, \( S_{bp1} \), \( S_{bp2} \), \( S_{bp3} \) are in open state, on the contrary, \( S_{bp-a} \), \( S_{bp-b} \), \( S_{bp-c} \) are in closed state.
B. OPERATION PRINCIPLE OF THE FLEXIBLE TRANSFORMER SYSTEM

Based on the analysis of flexible transformer topology, the operation principle of flexible transformer system is analyzed as follows. From the structure of flexible transformer system, it can be seen that the output voltage of flexible transformer system \( (\dot{v}_{La}, \dot{v}_{Lb}, \dot{v}_{Lc}) \) is equal to the sum of the main winding voltage of transformer \( (\dot{v}_{Ta}, \dot{v}_{Tb}, \dot{v}_{Tc}) \) and the output voltage of BD-AC modules \( (\Delta \dot{v}_{bc}, \Delta \dot{v}_{ca}, \Delta \dot{v}_{ab}) \). And the relationship can be described in equation (2).

\[
\begin{bmatrix}
\dot{v}_{La} \\
\dot{v}_{Lb} \\
\dot{v}_{Lc}
\end{bmatrix} =
\begin{bmatrix}
\dot{v}_{Ta} \\
\dot{v}_{Tb} \\
\dot{v}_{Tc}
\end{bmatrix} +
\begin{bmatrix}
\Delta \dot{v}_{bc} \\
\Delta \dot{v}_{ca} \\
\Delta \dot{v}_{ab}
\end{bmatrix}
\]  

(2)

The main winding voltage of transformer \( (\dot{v}_{Ta}, \dot{v}_{Tb}, \dot{v}_{Tc}) \) depends on the turn ratio of the primary winding to the secondary main winding \( (n_{Ta1} = n_{Tb1} = n_{Tc1} = n_{T1}) \). The output voltage of the BD-AC module \( (\Delta \dot{v}_{bc}, \Delta \dot{v}_{ca}, \Delta \dot{v}_{ab}) \) depends on the turns ratio of the primary winding to the secondary auxiliary winding of the transformer \( (n_{Ta2} = n_{Tb2} = n_{Tc2} = n_{T2}) \) and the duty cycle of the converter. That is, the flexible transformer system satisfies the following equation (3) and (4).

\[
\begin{bmatrix}
\dot{v}_{Sa} \\
\dot{v}_{Sb} \\
\dot{v}_{Sc}
\end{bmatrix} =
\begin{bmatrix}
n_{Ta1} & 0 & 0 \\
0 & n_{Tb1} & 0 \\
0 & 0 & n_{Tc1}
\end{bmatrix}
\begin{bmatrix}
\dot{v}_{Ta} \\
\dot{v}_{Tb} \\
\dot{v}_{Tc}
\end{bmatrix} +
\begin{bmatrix}
\Delta \dot{v}_{bc} \\
\Delta \dot{v}_{ca} \\
\Delta \dot{v}_{ab}
\end{bmatrix}
\]  

(3)

\[
\begin{bmatrix}
\Delta \dot{v}_{bc} \\
\Delta \dot{v}_{ca} \\
\Delta \dot{v}_{ab}
\end{bmatrix} =
\begin{bmatrix}
D_{A1} & D_{A2} \\
D_{B1} & D_{B2} \\
D_{C1} & D_{C2}
\end{bmatrix}
\begin{bmatrix}
\dot{v}_{Ca} \\
\dot{v}_{Cb} \\
\dot{v}_{Cc}
\end{bmatrix}
\]  

(4)

where \( (\dot{v}_{Sa}, \dot{v}_{Sb}, \dot{v}_{Sc}) \) are the input voltage of flexible transformer system, i.e., the primary side voltage of transformer. \( (\dot{v}_{Ca}, \dot{v}_{Cb}, \dot{v}_{Cc}) \) stand for auxiliary winding voltage of the transformer, and can be expressed as (4). \( (D_{A1}, D_{A2}, D_{B1}, D_{B2}, D_{C1}, D_{C2}) \) are the duty cycle of BD-AC installed in A-phase, B-phase and C-phase respectively, their values satisfy the equation (5) and (6).

\[
\begin{bmatrix}
\dot{v}_{Ca} \\
\dot{v}_{Cb} \\
\dot{v}_{Cc}
\end{bmatrix} =
\begin{bmatrix}
1/n_{Ta2} & 0 & 0 \\
0 & 1/n_{Tb2} & 0 \\
0 & 0 & 1/n_{Tc2}
\end{bmatrix}
\begin{bmatrix}
\dot{v}_{Sa} \\
\dot{v}_{Sb} \\
\dot{v}_{Sc}
\end{bmatrix}
\]  

(5)

\[
\begin{bmatrix}
D_{A1} \\
D_{B1} \\
D_{C1}
\end{bmatrix} =
\begin{bmatrix}
d_{A1b1} & d_{A2b1} \\
d_{A1b2} & d_{A2b2} \\
d_{A1c1} & d_{A2c1}
\end{bmatrix}
\]  

(6)

\[
\begin{bmatrix}
D_{A2} \\
D_{B2} \\
D_{C2}
\end{bmatrix} =
\begin{bmatrix}
d_{A1c2} & d_{A2c2} \\
d_{A1b2} & d_{A2b2} \\
d_{A1c2} & d_{A2c2}
\end{bmatrix}
\]  

(7)

where \( (d_{A1b1}, d_{A2b1}, d_{A1b2}, d_{A2b2}, d_{B1c1}, d_{B2c2}, d_{C1b1}, d_{C2b2}) \) are the duty ratios of P-Leg and N-Leg in each BD-AC of A-phase, B-phase and C-phase respectively.

Based on the above analysis, the input-output relationship of flexible transformer system, i.e., the relationship between \( (\dot{v}_{La}, \dot{v}_{Lb}, \dot{v}_{Lc}) \) and \( (\dot{v}_{Sa}, \dot{v}_{Sb}, \dot{v}_{Sc}) \) can be expressed as equation (8).

\[
\begin{bmatrix}
N_{TA} \\
N_{TB} \\
N_{TC}
\end{bmatrix} =
\begin{bmatrix}
\dot{v}_{Ta} & 0 & 0 \\
0 & \dot{v}_{Lb} & 0 \\
0 & 0 & \dot{v}_{Lc}
\end{bmatrix}
\begin{bmatrix}
1 \\
\dot{v}_{Sa} \\
\dot{v}_{Sb} \\
\dot{v}_{Sc}
\end{bmatrix}
\]  

(8)

where \( (N_{TA}, N_{TB}, N_{TC}) \) represent the transformer ratio of flexible transformer system.

Furthermore, the primary voltage of flexible transformer system can be expressed as equation (9).

\[
\begin{bmatrix}
\dot{v}_{Sa} \\
\dot{v}_{Sb} \\
\dot{v}_{Sc}
\end{bmatrix} = V_S \begin{bmatrix}
\frac{e^{j\phi_0}}{\sqrt{2}} \\
\frac{e^{j\alpha_0}}{\sqrt{2}} \\
\frac{e^{j\beta_0}}{\sqrt{2}}
\end{bmatrix}
\]  

(9)

where \( V_S \) represents the primary voltage amplitude of flexible transformer system.

Then, formula (2), (3), (4) and (9) can be brought into formula (8), and it can be rewritten as follows.

\[
\begin{bmatrix}
N_{TA} \\
N_{TB} \\
N_{TC}
\end{bmatrix} =
\begin{bmatrix}
D_{A1} & D_{A2} \\
D_{B1} & D_{B2} \\
D_{C1} & D_{C2}
\end{bmatrix}
\begin{bmatrix}
\dot{v}_{La} \\
\dot{v}_{Lb} \\
\dot{v}_{Lc}
\end{bmatrix}
\]  

(10)

Thus,

\[
\begin{bmatrix}
\dot{v}_{La} \\
\dot{v}_{Lb} \\
\dot{v}_{Lc}
\end{bmatrix} =
\begin{bmatrix}
1/n_{T1} & 1/n_{T2} & 1/n_{T3}
\end{bmatrix}
\begin{bmatrix}
D_{A1} & D_{A2} \\
D_{B1} & D_{B2} \\
D_{C1} & D_{C2}
\end{bmatrix}
\begin{bmatrix}
\dot{v}_{Sa} \\
\dot{v}_{Sb} \\
\dot{v}_{Sc}
\end{bmatrix}
\]  

(11)

Furthermore, equation (12) can be obtained with taking (9) into (11).

\[
\begin{bmatrix}
\dot{v}_{La} \\
\dot{v}_{Lb} \\
\dot{v}_{Lc}
\end{bmatrix} = V_S \begin{bmatrix}
\frac{e^{j\phi_0}}{\sqrt{2}} \\
\frac{e^{j\alpha_0}}{\sqrt{2}} \\
\frac{e^{j\beta_0}}{\sqrt{2}}
\end{bmatrix}
\]  

(12)

It can be seen from (10) to (12) that flexible transformer system can not only adjust the amplitude of output voltage,
but also has the ability of adjusting the phase angle. And
whether the three phases are balanced or not, the load voltage
is supported by corresponding phase and regulated by the
other two phases, so as to ensure the balance of three-phase
voltage. The amplitude and phase angle regulation range of
output voltage of flexible transformer system depend on the
transformer ratio ($N_{TA}$, $N_{TB}$, $N_{TC}$). Taking A-phase as an
example, the relation surface between the transformer ratio
of flexible transformer system and the duty cycle of BD-AC
under different transformer ratio of transformer can be drawn
in Fig. 4, based on this, the voltage regulation ability of the
flexible transformer system is analyzed.

![Figure 4](image)

**FIGURE 4.** Relation between ratio of flexible transformer system and duty
cycle of BD-AC.

As can be seen from Fig. 4, the voltage regulation range of
flexible transformer system is different with various ratio of
transformer. No matter in $N_{T1} = N_{T2}$ or $N_{T1} \neq N_{T2}$ scene,
the voltage regulation range of flexible transformer system is
smaller with the increase of transformer ratio, and vice versa.
On the other hand, when the demand of voltage regulation
is high, the pressure bearing demand of AC/AC chopper
increases, and vice versa. When ratio is designed, i.e., as a
constant, the relationship between duty cycle of BD-AC and
flexible transformer system ratio is a corresponding surface
in Fig. 4. The transformer ratio of transformer needs to be
optimized according to grid voltage and voltage demand of
the load. On the other hand, the regulation range of the voltage
phase is $[-\pi/3, \pi/3]$ with the range $[-1, 1]$ of duty cycle of
BD-AC installed in flexible transformer system.

In order to facilitate further analysis, the voltage regulation
range of flexible transformer system when transformer ratio
equals $N_{T1} = N_{T2} = 1$ is quantitatively analyzed, then,
equation (12) can be simplified to equation (13). Then, taking

A-phase as an example, the regulation range diagram of
equation (13) is given in Fig. 5.

$$
\begin{bmatrix}
\dot{v}_{La} \\
\dot{v}_{Lb} \\
\dot{v}_{Lc}
\end{bmatrix}
= V_S
\begin{bmatrix}
1 & D_{A1} & D_{A2} \\
D_{B2} & 1 & D_{B1} \\
D_{C1} & D_{C2} & 1
\end{bmatrix}
\begin{bmatrix}
e^{j0} \\
e^{j\pi/3} \\
e^{j2\pi/3}
\end{bmatrix} 
$$

(13)

When the duty cycle of the BD-AC satisfies the relation
$D_{A1} = D_{A2} \in [-1, 1]$, the output voltage $\dot{v}_{La}$ and the input
voltage $\dot{v}_{Sa}$ of the flexible transformer system are collinear,
that is to say, the flexible transformer system can only realize
the voltage amplitude regulation, and the regulation range is
$[0, 2]$; Moreover, when the duty cycle of the BD-AC satisfies
the relation $D_{A1} \neq D_{A2}$, the flexible transformer system has
the ability to adjust the amplitude and phase angle of voltage
at the same time, and the regulation range is $[0, 2]$ and $[-\pi/3,
\pi/3]$, respectively.

From another point of view, the transformation ratio
of transformer is optimized with the flexible transformer
installed in the power system. And if the input voltage of the
flexible transformer system fluctuates at this time, the flexible
transformer system has the function of maintaining the volt-
age stability at the output, i.e., realizing the voltage flexible
regulation.

**C. CONTROL STRATEGY OF THE FLEXIBLE TRANSFORMER SYSTEM**

Based on the analysis of the operation principle of the pro-
posed flexible transformer system above, it can be known
that in order to meet the load demand for voltage, the real-
time sampling value of load voltage needs to be obtained.
Then, the control strategy based on voltage control signal is
generated by the control circuit and pulse drive of IGBT is
formed. Moreover, the regulating voltage is generated and
superimposed to the main winding voltage of transformer.
The protection control circuit starts the relevant equipment
to bypass the secondary side auxiliary winding of the trans-
former under the case of system failure, i.e., the BD-AC mod-
ular is bypassed until the system recovers. Thus, the control
strategy of flexible transformer system is constructed, and in
order to facilitate the elaboration, the A-phase voltage is taken as the control object for analysis and the details are as follows.

In the voltage regulation process of the flexible transformer system, the A-phase regulated voltage is constructed as the control object for analysis and the details are as follows.

As can be seen that the flexible transformer system can not only realize the regulation of the voltage amplitude, but also has the voltage phase angle regulation capability. Based on the analysis above, the control block of the flexible transformer system is shown in Fig. 7.

It can be seen from Fig. 7 that when the load voltage meets the requirements or the converter in the flexible transformer system fails, the bypass switch $S_P$ is turned on. When the sampling circuit detects that the voltage does not meet the requirements, the regulation capability of the flexible transformer system is activated, and voltage regulation is performed by comparing the voltage sample value with its target value until it is satisfied.

IV. SIMULATION RESULTS

Through the analysis of the working principle of flexible transformer system above, it can be known that the proposed flexible transformer system makes it possible to improve energy quality. When the duty cycle of BD-AC in each phase takes different values, the flexible transformer system has different voltage regulation capabilities, i.e., it is working in different modes. In this paper, two scenarios (voltage amplitude and phase angle regulation mode) are simulated and verified, respectively. And the main specification and components of the analyzed flexible transformer is shown in Table 1.

### TABLE 1. Simulation parameters.

| Parameters               | Value |
|--------------------------|-------|
| Inductance L/mH          | 0.3   |
| Capacitance $C_1$ and $C_2$/μF | 10    |
| Output capacitance $C_v$/μF | 10    |
| Switching frequency/kHz  | 10    |
| Rated load voltage/kV    | 10    |
| Transformer ratio        | 2     |

A. VOLTAGE AMPLITUDE REGULATION

Keeping the phase angle of the voltage as a constant, and setting symmetric scene (voltage amplitude symmetrical sags/swells 30%) and asymmetric scene (A-phase voltage amplitude sag 40%, B-phase voltage amplitude sag 30% and C-phase voltage amplitude swell 30%) to verify the voltage regulation capability of the flexible transformer system, respectively. And the simulation results are shown in Fig. 8-9.
In the above two scenarios, flexible transformer has a good compensation effect. In Fig. 8, the primary side voltage amplitude \(v_{Sa}, v_{Sb}, v_{Sc}\) sags 30% at 0.05s, and after 0.05s, a three-phase voltage amplitude \(v_{Sa}, v_{Sb}, v_{Sc}\) swells occurs (swells 30%). During this process, compensation voltage \(\Delta v_{bc}, \Delta v_{ca}, \Delta v_{ab}\) is provided and the target voltages of the output side of the flexible transformer \(v_{La}, v_{Lb}, v_{Lc}\) remain stable. Similarly, in order to maintain the voltage of the secondary side of flexible transformer, compensation voltage \(\Delta v_{bc}, \Delta v_{ca}, \Delta v_{ab}\) is provided with the asymmetric voltage sags/swells occurs, and the simulation results are shown in Fig. 9.

**B. VOLTAGE PHASE ANGLE REGULATION**

When the phase angle of the primary side voltage of flexible transformer changes and the amplitude is a constant, the simulation results are shown in Fig. 10.

As can be seen, in Fig. 10, the A-phase primary side voltage \(v_{Sa}\) phase angle lags 45° at 0.05s, and after 0.05s, B-phase voltage \(v_{Sb}\) phase angle lags 30° occurs. During this process, in order to ensure that the voltage on the output side of the flexible transformer \(v_{La}, v_{Lb}, v_{Lc}\) are not affected, a compensation voltage is provided. Moreover, the simulation results of voltage fluctuations with phase angle jump are also given in Fig. 11. As can be seen from Fig. 11 that A-phase primary side voltage amplitude \(v_{Sa}\) sags 30% with phase angle lags 15° at 0.05s, and after 0.05s, the phase angle leads 15° and hold for 0.05s. In the above process, the use of flexible transformer makes it possible to improve energy quality. And with the regulation of power electronic equipment, the flexible transformer works well. Besides, owing to the adopted AC/AC chopper has the same buck/boost operation process for non-inverting and inverting modes [25], the proposed flexible transformer can realize bidirectional regulation of power. Thus, it is suitable for the active distribution network with bidirectional power regulation requirements with distributed power access.
Voltage fluctuation will affect the normal operation of the sensitive load, and even lead to its breakdown, resulting in unnecessary economic losses. To solve this problem, a flexible transformer based on bipolar direct AC/AC chopper for flexible regulation of supply voltage, and additionally operating as a power shifter transformer has been presented in this paper. Based on the analysis of topology and modulation strategy of bipolar direct AC/AC chopper, the structure and operation principle of flexible transformer system are analyzed in detail. Then, the voltage regulation range of the flexible transformer system is studied with voltage amplitude and phase angle as the analysis object. And the relationship between transformer ratio of the flexible transformer system and duty cycle of the BD-AC is acquired in different scenarios. Finally, in order to test and verify the operation and circuit described in this paper, the exemplary time waveforms of voltage are shown in the simulation investigation. And the obtained result validate that the proposed system is able to realize the flexible regulation of voltage.

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YIBO WANG (Member, IEEE) was born in Shandong, China, in 1989. He received the B.S. and M.S. degrees in electrical engineering from Northeast Electric Power University, Jilin, China, in 2010 and 2016, respectively, where he is currently pursuing the Ph.D. degree. His current research interests include renewable energy integration into power networks, power systems, and power quality.

GUO-WEI CAI was born in Jilin, China, in 1968. He received the B.S. and M.S. degrees in electrical engineering from Northeast Electric Power University, Jilin, in 1990 and 1993, respectively, and the Ph.D. degree in electrical engineering from the Harbin Institute of Technology, Harbin, China, in 1999. Since 2004, he has been a Professor with the School of Electrical Engineering, Northeast Electric Power University. His current research interests include power system transient stability analysis and smart grid with renewable power generation.

CHUANG LIU (Member, IEEE) received the M.S. degree in electrical engineering from Northeast Electric Power University, Jilin, China, in 2009, and the Ph.D. degree in electrical engineering from the Harbin Institute of Technology, Harbin, China, in 2013.

From 2010 to 2012, he was with the Future Energy Electronics Center, Virginia Polytechnic Institute, and State University, Blacksburg, VA, USA, as a Visiting Ph.D. Student, supported by the Chinese Scholarship Council. He was an Associate Professor with the School of Electrical Engineering, Northeast Electric Power University, in 2013, where he has been a Professor, since 2016. His research interests include power-electronics-based on ac and dc transformers for future hybrid ac–dc power grids, flexible operation and control of power grid based on ac–ac transformation, and power-electronics-based power system stability analysis and control.

BINGDA ZHU was born in Henan, China, in 1996. He received the B.S. degree from Northeast Electric Power University, Jilin, China, in 2018, where he is currently pursuing the M.S. and Ph.D. degrees in electrical engineering. His current research interests include direct PWM ac–ac converters, control strategy, power quality optimization in distribution networks, and the application of high-power electronic conversion technology in smart grid.

DONGBO GUO was born in Shandong, China, in 1990. He received the B.S. degree from Northeast Electric Power University, Jilin, China, in 2016, where he is currently pursuing the M.S. degree in electrical engineering. His current research interests include flexible operation and control of power grid based on ac–ac conversion, direct PWM ac–ac converters, and the application of high-power electronic conversion technology in smart grid.

HANWEN ZHANG was born in Jilin, China, in 1994. He received the B.S. degree from Northeast Electric Power University, Jilin, in 2017, where he is currently pursuing the M.S. degree in electrical engineering. His current research interests include power quality control in distribution networks, direct PWM ac–ac converters, and energy efficient integrated conversion technology.