Dual-Timescale Control for Power Electronic Zigzag Transformer

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(Invited)

Abstract—Power electronic zigzag transformer is an attractive solution for the flexible interconnection of smart distribution networks. It is constituted by slow-response and low-precision thyristor converters and fast-response and high-accuracy voltage source converters. This paper models its primary circuit and addresses its basic operation mechanism. Then a dual-timescale control scheme is investigated to realize the coordinated regulation of both types of converter. A simulation case is established in PSCAD containing interconnected mid-voltage distribution networks. Simulations with poor- and well-matched control timescales are both carried out. And accordingly, the power flow controllability under these conditions is compared. When the shorter control timescale is no more than tenth of the longer one, the power electronic zigzag transformer will operate with satisfying performances.

Index Terms—Power electronic transformer, thyristor converter, voltage source converter, dual-timescale control, flexible interconnection

I. INTRODUCTION

The flexibility of mid-voltage distribution networks becomes a more and more attractive topic, especially for the urban power grids with large amount of distributed generation, electric vehicles, energy storage systems and sensitive loads. Once bidirectional control of power flows are allowed between interconnected distribution networks, some cutting-edge technologies, such as advanced planning [1], refined reconfiguration [2], fast load transfer [3] and demand response [4]-[5], will be more practically feasible and make the networks smarter. So far, researchers have proposed kinds of power electronic solutions to realize the controllable interconnection, which can be classified into two categories. One is based on voltage-source-converter (VSC), and the other is based on thyristor converter. They have different circuit topologies and control performances.

Back-to-back voltage-source converter (BTB-VSC) has been approved worldwide in the operation of high-voltage direct-current (HVDC) transmission systems and low-voltage equipment. By the virtue of its full controllability and fast response, it was utilized in [6]-[8] as so-called soft normally-open points (SNOP) for mid-voltage distribution networks to take the place of mechanical interconnection switch. Although the potential benefits of SNOP was demonstrated, its cost, footprint and efficiency were always huge barriers in front of the real applications, because large amount of passive components were required in its modular multilevel converters (MMC) [9].

Comparatively, thyristor converter has competitiveness on expense, volume and power loss. It is well-accepted that thyristor-based HVDC systems are much more compact, inexpensive and efficient than MMC-based ones [10]. For mid-voltage power grid applications, a kind of thyristor-controlled voltage regulator (TCVR) was proposed in [11]-[12] to control the exchanged power between two ac lines, which was a technical extension of static phase shifter and Sen transformer [13]-[14]. TCVR is an ac-to-ac converter that contains only single-stage conversion avoiding the usage of dc capacitors and linkage reactors. However, thyristor-converter-based solutions are often confronted with the query about their regulating rate and precision.

Speaking of the control performances of two categories of converters, we can take the timescale as a focus here. VSCs are generally controlled in an instantaneous manner based on differential equation models [15]-[16]. Their control periods are usually less than a hundred microseconds and their response dynamics range from several to ten milliseconds. However, the regulating rate and precision of thyristor converters are inherently capped by their device characteristics. Hence, thyristor converters are described by phasor equations and their control periods are always dependent on the system frequency [11], [17]. The regulating transient periods of thyristor converters are commonly beyond hundreds of milliseconds, which is disparate from those of VSCs.

It is a fact that an appropriate flexible interconnecting solution for mid-voltage distribution networks is still under study. The combination of different types of converter is reckoned as a potential path which has not been extensively explored yet. This paper proposes a power electronic zigzag transformer (PEZT) that thyristor converters and VSCs are both involved in. Its primary circuit provides the possibility that the comprehensive cost-performance might exceed that of TCVR and BTB-VSC. Naturally, it is required a united regulating method by which the thyristor converters with slow response and VSCs with fast response can coordinate their behavior. So, this paper presents a dual-timescale control for PEZT.
section II, the circuit schematic and basic operating mechanism of PEZT are addressed. Section III details the dual-timescale control scheme by diagrams and gives the advice on the timescale matching. Simulations under different control timescales are carried out in Section IV and the results demonstrate the control performances. Section V concludes this paper and highlights the features of PEZT.

II. POWER ELECTRONIC ZIGZAG TRANSFORMER

A. Primary Circuit Topology

Fig. 1 shows the primary circuit of PEZT. The primary side of PEZT includes conventional three-phase windings which are coupled with feeder 1. The secondary side contains a set of hybrid converters combined by nine thyristor converter modules and a BTB- VSC. The thyristor converter modules, Aa, Ba and Ca are series connected with the arm a’ of VSC1, which constitutes the phase a of PEZT. Similarly, Ab, Bb, Cb and arm b’ constitutes the phase b, and Ac, Bc, Cc and arm c’ constitutes the phase c. All the modules have the identical circuit topology, as shown in Fig. 2. Inside a module, there are \( n \) pairs of winding and thyristor full bridge. Let the turns ratio of the windings be a geometric sequence with a common ratio of three. So the voltage rating of thyristor converter 1 is \( 1/3^{(n-1)} \) of that of thyristor converter \( n \). Besides, the BTB-VSC is a typical two-level converter and its voltage rating is designed as a half of that of thyristor converter 1. The three arms of VSC2, u, v and w, are connected respectively with windings Au, Bv and Cw.

In PEZT, the strength of thyristor converters is the capability of carrying high power, and that of VSCs is the rapidity and accuracy of response.

B. Dual-Timescale Modelling

Because thyristor converters and VSCs have different switching characteristics, they are modelled with different timescales.

Thyristor converters have low switching frequency and are suitable to be described by phasors. The output voltage phasors of thyristor converter modules are denoted as \( \tilde{U}_{a_1}, \tilde{U}_{b_1}, \tilde{U}_{c_1}, \tilde{U}_{a_2}, \tilde{U}_{b_2}, \tilde{U}_{c_2}, \tilde{U}_{a_3}, \tilde{U}_{b_3}, \tilde{U}_{c_3} \). They are dependent on the transformer ratio, \( k_T \), and the switching state combination of converters. Here, regarding the switching state combinations as voltage coefficients and writing them into a matrix, we can describe the voltages as following

\[
\begin{bmatrix}
\tilde{U}_{a_1} \\
\tilde{U}_{b_1} \\
\tilde{U}_{c_1}
\end{bmatrix}
= \begin{bmatrix}
\rho_{a_1} & \rho_{b_1} & \rho_{c_1} \\
\rho_{a_2} & \rho_{b_2} & \rho_{c_2} \\
\rho_{a_3} & \rho_{b_3} & \rho_{c_3}
\end{bmatrix}
\begin{bmatrix}
k_T \tilde{U}_{1,a} \\
k_T \tilde{U}_{1,b} \\
k_T \tilde{U}_{1,c}
\end{bmatrix}
\]

(1)

where \( \rho_{a_1}, \rho_{b_1}, \rho_{c_1}, \rho_{a_2}, \rho_{b_2}, \rho_{c_2}, \rho_{a_3}, \rho_{b_3}, \rho_{c_3} \) are the voltage coefficients of each thyristor converter module, and \( \tilde{U}_{1,a}, \tilde{U}_{1,b} \) and \( \tilde{U}_{1,c} \) are the voltage phasors of the primary side of PEZT. Since the primary voltages are given by upstream power system, the voltages of thyristor converter modules are actually determined by the voltage coefficients in the above equation.

Fig. 1. Primary circuit of PEZT

Fig. 2. Circuit schematic of a thyristor module.

Based on (1), the output voltages of PEZT can be written as

\[
\begin{align*}
\tilde{U}_{ao} &= \frac{U_{ao} + U_{bo} + U_{co}}{3} + \omega L_{o1} I_a \\
\tilde{U}_{bo} &= \frac{U_{bo} + U_{bc} + U_{co}}{3} + \omega L_{o2} I_b \\
\tilde{U}_{co} &= \frac{U_{co} + U_{bc} + U_{oa}}{3} + \omega L_{o3} I_c
\end{align*}
\]

(2)

where \( \tilde{U}_{ao}, \tilde{U}_{bo} \) and \( \tilde{U}_{co} \) are the voltage phasors of the PEZT outputs, \( \tilde{U}_{a_1}, \tilde{U}_{b_1}, \) and \( \tilde{U}_{c_1} \) are the voltage phasors of VSC1, \( I_a, I_b \) and \( I_c \) are the current phasors of the secondary side of PEZT, \( L_{o1} \) is the zigzag transformer leakage reactance for the thyristor part, and \( \omega \) is the system angular frequency. Because the thyristor converter modules are series connected into strings, (2) can be simplified as

\[
\begin{align*}
\tilde{U}_{ao} &= \frac{U_{ao} + U_{bo} + U_{co}}{3} + \omega L_{o1} I_a \\
\tilde{U}_{bo} &= \frac{U_{bo} + U_{bc} + U_{co}}{3} + \omega L_{o2} I_b \\
\tilde{U}_{co} &= \frac{U_{co} + U_{bc} + U_{oa}}{3} + \omega L_{o3} I_c
\end{align*}
\]

(3)

where \( \tilde{U}_{ao}, \tilde{U}_{bo}, \) and \( \tilde{U}_{co} \) are the voltage phasors of the
thyristor converter strings in each phase.

Although the contribution by VSC is represented in phasor forms in (2) and (3), the behavior of VSC itself should be described by dynamics as following

\[
\frac{d}{dt}\begin{bmatrix}
L_{a1}i_a \\
L_{a1}i_b \\
L_{a1}i_c
\end{bmatrix} = \begin{bmatrix}
u_{ua} - u_{ua}' \\
u_{ub} - u_{ub}' \\
u_{uc} - u_{uc}'
\end{bmatrix} - \begin{bmatrix}
u_{ua} - u_{ua}' \\
u_{ub} - u_{ub}' \\
u_{uc} - u_{uc}'
\end{bmatrix} - \begin{bmatrix}
S_i u_{dc} \\
S_i u_{dc} \\
S_i u_{dc}
\end{bmatrix}
\]  \quad (4)

and

\[
\frac{d}{dt}\begin{bmatrix}
L_{a2}i_a \\
L_{a2}i_b \\
L_{a2}i_c
\end{bmatrix} = \begin{bmatrix}
u_{ua} \\
u_{wb} \\
u_{uc}
\end{bmatrix} - \begin{bmatrix}
u_{ua} \\
u_{wb} \\
u_{uc}
\end{bmatrix} - \begin{bmatrix}
S_i u_{dc} \\
S_i u_{dc} \\
S_i u_{dc}
\end{bmatrix}
\]  \quad (5)

where \(i_a, i_b\) and \(i_c\) are the instantaneous currents of phase a, b and c, the same with those of arm a′, b′ and c′. Besides, \(i_a, i_b\) and \(i_c\) are the instantaneous currents of arm u, v and w. \(u_{ua}, u_{ub}, u_{uc}, u_{ua}', u_{ub}', u_{uc}', u_{vb}, u_{wb}, u_{vc}\) and \(u_{v0}\) are the instantaneous values of \(\hat{U}_{ua}, \hat{U}_{vb}, \hat{U}_{wc}, \hat{U}_{ua}', \hat{U}_{vb}', \hat{U}_{wc}', \hat{U}_{v0}, \hat{U}_{v0}\) and \(u_{v0}\). \(u_{ua}, u_{ub}\) and \(u_{uc}\) are the instantaneous voltages of windings Au, Bv and Cw. \(L_{a2}\) is the zigzag transformer leakage reactance for VSC2. \(S_a, S_b, S_c, S_u, S_v\) and \(S_w\) are the switching functions of arm a, b, c, u, v and w. And, \(u_{dc}\) is the dc-link voltage.

Thus, the dual-timescale mathematical model of PEZT is established and the timescale of (1) to (3) is on a millisecond level and that of (4) to (6) is on a microsecond level. And specifically, this model implies that the two parts on different timescale levels be coupled through the voltage phasors and their instantaneous values.

C. Basic Operation Mechanism

PEZT can be utilized as a power router for the interconnection of smart distribution networks, as depicted in Fig. 3. In this scenario, distribution zone 1 and 2 are linked by a PEZT installed in zone 1. The impedance of tie-line is represented by a concentrated parameter, \(Z_{Tie}\). The bus voltages of zone 1 and 2 are represented by \(\hat{U}_1\) and \(\hat{U}_2\), and the voltages before and after \(L_{a1}\) are represented by \(\hat{U}_{ref}\) and \(\hat{U}_{PEZT}\), respectively. Thus, the expected active and reactive power exchanged by the PEZT, \(P_{ref}\) and \(Q_{ref}\), can be written as

\[
\begin{aligned}
P_{ref} &= \frac{3U_{ref}U_{PEZT}}{\omega L_{a1}} \sin(\theta_{PEZT} - \theta_{ref}) \\
Q_{ref} &= \frac{3U_{ref}U_{PEZT}}{\omega L_{a1}} \cos(\theta_{PEZT} - \theta_{ref}) + \frac{3U_{ref}^2}{\omega L_{a1}}
\end{aligned}
\]  \quad (7)

where \(U_{ref}\) and \(\theta_{ref}\) are the amplitude and phase angle of the referenced value of \(\hat{U}_{ref}\). And \(U_{PEZT}\) and \(\theta_{PEZT}\) are the amplitude and phase of \(\hat{U}_{PEZT}\). From the above equations, \(U_{ref}\) and \(\theta_{ref}\) can be solved as following

\[
\begin{aligned}
P_{ref} &= \frac{3U_{ref}U_{PEZT}}{\omega L_{a1}} \sin(\theta_{PEZT} - \theta_{ref}) \\
Q_{ref} &= \frac{3U_{ref}U_{PEZT}}{\omega L_{a1}} \cos(\theta_{PEZT} - \theta_{ref}) + \frac{3U_{ref}^2}{\omega L_{a1}}
\end{aligned}
\]  \quad (8)

In essence, PEZT is a power electronic voltage regulator. Its thyristor and VSC parts can be unitedly controlled to make the output voltage phasor track the expected amplitudes and phases formulated in (8).

III. DUAL-TIMESCALE CONTROL OF PEZT

Based on the dual-timescale mathematic model presented above, PEZT is controlled by the coordination of two control strategies with different timescales. One of them is the thyristor converter control with a longer timescale, and the other is the VSC control with a shorter timescale, as depicted in Fig. 4.

A. Long-Timescale Control for Thyristor Converters

For an individual thyristor converter module, its output voltage is determined by its voltage coefficient which is a function of the switching patterns of entire converters involved in it. Taking module as an example, we can define the voltage coefficient as the following

\[
\text{TABLE I}
\]
\[ \rho_{Aa} = \sum_{i=1}^{n} 3^{-1} S_{Aa}(i) \]  

where \( n \) is the total converter number in a module, \( i \) is the converter pointer, and \( S_{Aa}(i) \) is the switching pattern of the \( i \)th converter of module Aa. The voltage coefficients of other modules in (1) can be defined similarly using the according switching pattern variables, \( S_{Ab}(i), S_{Ac}(i), S_{Ba}(i), S_{Bb}(i), S_{Bc}(i), S_{Ca}(i), S_{Cb}(i), S_{Cc}(i) \) and \( S_{Cc}(i) \). The definitions of switching pattern are listed in Table I.

From (1), the expected voltage coefficients can be solved as the following

\[
\begin{bmatrix}
\rho_{Aa} \\
\rho_{Ba} \\
\rho_{Ca} \\
\rho_{Ab} \\
\rho_{Bb} \\
\rho_{Cb} \\
\rho_{Ac} \\
\rho_{Bc} \\
\rho_{Cc} \\
\end{bmatrix}_{\text{ref}} = \begin{bmatrix}
k_1 \bar{U}_{1a} & \bar{U}_{1b} & \bar{U}_{1c} \\
k_2 \bar{U}_{2a} & \bar{U}_{2b} & \bar{U}_{2c} \\
k_3 \bar{U}_{3a} & \bar{U}_{3b} & \bar{U}_{3c} \\
\end{bmatrix}
\]

And further, the expected switching patterns can be determined by (9) and Table I. The updated values of \( S_{Aa}(i), S_{Ab}(i) \) and \( S_{Ac}(i) \) are allowed to be assigned only when the phase a current across zero, the updated values of \( S_{Ba}(i), S_{Bb}(i) \) and \( S_{Bc}(i) \) are allowed to be assigned only when the phase b current across zero, and the updated values of \( S_{Ca}(i), S_{Cb}(i) \) and \( S_{Cc}(i) \) are allowed to be assigned only when the phase c current across zero. Hence, in a 50Hz three-phase system, the control frequency of the thyristor part of PEZT is 150Hz that signifies a timescale of milliseconds.

B. Short-Timescale Control for VSCs

For the BTB-VSC, The control diagram is shown in Fig. 5 where \( u_{dc,ref} \) and \( u_{dc} \) are the referenced and measured values of dc-link voltage, \( i_a, i_b \) and \( i_c \) are the secondary-side currents of PEZT, \( k_1 \) and \( k_2 \) are proportional control coefficients, and \( f_s \) is the switching frequency of the VSCs. The target of the BTB-VSC is to generate voltages, \( u_{a,ref}, u_{b,ref} \) and \( u_{c,ref} \), with the exact instantaneous values that are equal to the differences between \( (\bar{U}_{ref,a}, \bar{U}_{ref,b}, \bar{U}_{ref,c}) \) and \( (\bar{U}_{a,ref}, \bar{U}_{b,ref}, \bar{U}_{c,ref}) \).

From (9) and (10), it tells that the values of \( \rho_{Aa} \) are a series of evenly discrete points ranging from \(-1\) to \(1\) with the step of \( \frac{1}{\sum_{i=1}^{n} 3^{-1}} \). In other words, the lower \( n \) is, the larger the step of thyristor converter voltages is and the faster the tracking speed of VSC voltages is required. Under the manufacturing limitation, \( n \) generally does not exceed four, or the voltage coefficient is no less than 1/40. Hence, it is required that \( f_s \) is sufficiently high in order to make the VSC voltages track such kind of voltage steps. Meanwhile, \( f_s \) is also expected to be as low as possible to reduce switching energy losses.

Besides, the choice of \( f_s \) is comprehensively influenced by primary circuit parameters and frequency characteristics of the control loops shown in Fig. 4 and Fig. 5. Generally speaking, due to the nonlinearly coupling features of hybrid converters, it is kind of difficult to obtain the values of \( f_s \) and a series of other parameters by certain calculations. Although, it is feasible to determine a reasonable \( f_s \) by simulations in a given scenario.

IV. SIMULATIONS

Based on the scenario shown in Fig. 3, the PEZT and its control strategy is modeled in PSCAD. The system voltage rating is 10kV. The winding number in a module is 4 and their turns ratio is 1:3:9:27. The parameters of simulation are listed in Table II where \( k_{P1} \) and \( k_{P2} \) and \( k_{P3} \) and \( k_{P4} \) are the parameters of PI1, PI2 and PI3, respectively.
Fig. 6. The amplitude and phase angle of PEZT voltage and their references

Fig. 7. BTB-VSC voltage and its reference.
The dual-timescale control strategy is an effective framework for PEZT based on which its thyristor and VSC parts realize mutual support. The control timescale of thyristor part is several milliseconds and that of VSC part is around tenth of it. Provided the two control timescales are well-matched, the PEZT output voltages will track their references accurately. As a consequence, the power flow exchanged through the PEZT exhibits a smooth curve and little steady state errors.

Further simulation with higher switching frequency are also conducted and their outcomes are similar to those of Fig. 6(e) and (f), Fig. 7(e) and (f), and Fig. 8(c). Therefore, it is reasonable to believe that a practical match between the thyristor converter control timescale and the BTB-VSC control timescale is that the latter stays equal to or shorter than tenth of the former. By this way, the power flow control performance will meet the system requirements and the power losses of BTB-VSC will be as low as possible.

V. CONCLUSION

The PEZT proposed in this paper is a kind of power electronic equipment used to interconnect mid-voltage distribution networks. Its primary circuit shows the advantages on cost, footprint and efficiency thanks to the combination of zigzag transformer, thyristor converters and a BTB-VSC.

By means of dual-timescale modeling, it is convenient to recognize the interactive relationships between the thyristor converters and the VSCs. On one hand, the thyristor converters behave in a manner of phasor, which provides a quasi-steady state for the VSCs. On the other hand, the operation of VSCs is liable for maintaining such a quasi-steady state for the commutation of thyristor converters by fast response and as short as possible transient process.

The dual-timescale control strategy is an effective framework for PEZT based on which its thyristor and VSC parts realize mutual support. The control timescale of thyristor part is several milliseconds and that of VSC part is around tenth of it. Provided the two control timescales are well-matched, the PEZT output voltages will track their references accurately. As a consequence, the power flow exchanged through the PEZT commendably meet the demands from smart distribution networks and benefits both the utility and consumers.

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