Corrections of Original CFPREV Control in LCC-HVDC Links and Analysis of Its Inherent Plateau Effect

Dachuan Tian, and Xiaofu Xiong, *Member*, *IEEE*

***Abstract*—The most effective approach to suppressing the first commutation failure (CF) of the LCC-HVDC link at fault inception is to advance firings of the inverter, and the commutation failure prevention (CFPREV) control is the most commonly used method in practical engineering. However, it is discovered in this study that there exist a few serious defects in its original scheme, and thus targeted vital corrections were made. Furthermore, an interesting phenomenon termed the plateau effect, which states that an excessive advancement of firings will contrarily and inevitably lead to more commutation failures, is also revealed and analyzed. It turns out that the inherent commutation dents of the Graetz bridge should be primarily responsible, which bridges the knowledge gap and further enhances the cognition of the limitation of CFPREV control, and it may also be conducive to the design of related control parameters. Simulation results then validate the necessity of these presented corrections and confirm the existence of the plateau effect.**

***Index Terms*—Commutation failure, CFPREV, LCC-HVDC transmission, plateau effect.**

I. Introduction

THE most common malfunction of the inverters in the line-commutated converter-based high-voltage direct-current (LCC-HVDC) links is the commutation failure (CF), and it may result from the missing of a firing pulse, breakdown of a certain bridge arm, or most frequently, the insufficient commutation margin caused by the initiation of AC faults. The commutation failure prevention (CFPREV) control, first introduced in [1] by Zhang and Dofnas from ABB Utilities, noted, which is referred to as the original CFPREV control hereinafter, is a simple but effective measure adopted in engineering projects to suppress the first CF at fault inception.

As a rule, in order to successfully prevent the first CF caused by the AC fault, a rapid response of the control strategy and enough advancement of inverter firings are very crucial. In the original CFPREV control, the detection of the asymmetrical and symmetrical AC faults is respectively based on the zero-sequence component and $\alpha\beta$ transformation of the commutating bus voltages, and thus the response speed is closely related to the sensitivities of the above fault detection algorithms and the settings of their startup thresholds. Furthermore, the rationality of the adjustment value of inverter firings largely depends on the configuration of the gain coefficients corresponding to the detected characteristic fault components.

Yao *et al.* investigated the impact of the initial fault voltage angle on the performance of CFPREV control in [2] in cases of ideal AC voltage drop, and indicated that the sensitivity of zero-sequence voltage detection is susceptible to the fault initiation time, thus if a single-phase fault occurs near the zero-crossing point of the faulted phase voltage, it will significantly delay the startup of the CFPREV control. In addition, in order to address this issue, a "sin-cos" component detection method is utilized in [3] as a supplement to the original CFPREV control. However, it should be noted that the "sin-cos" method is equivalent to a *dq* transformation with a fixed angular velocity performed on each phase voltage, and since the quadrature signal generator used is based on the differential operation, it will be seriously affected by the noises existing in the measurement units. Likewise, in view of the fact that the $\alpha\beta$ transformation in the original CFPREV control is only able to reflect an overall drop of the three-phase voltage, and for the sake of speeding up the startup of control, the RMS value of each phase voltage at the inverter AC bus is calculated in [4] according to an algorithm based on the three-phase simultaneity sampling values. Nonetheless, the algorithm may be activated unexpectedly when the grid frequency is in real-time regulation or voltage harmonic exists, for the reason that it is premised on a perfect symmetry of three-phase voltage in normal state.

In terms of the startup threshold settings in the original CFPREV control, Wang *et al.* in [5] and Tang *et al.* in [6], respectively, proposed a global optimization method of startup thresholds in the multi-infeed HVDC systems, and their original intention was to regard the CFPREV control as a recovery strategy rather than an inhibition method of the first CF, and hence a lower startup threshold indicates that the LCC-HVDC link would resume in advance, yet at the expense of a higher reactive power consumption in the inverter due to the decrease of the firing angle. In their methods, however, to achieve

Manuscript received October 27, 2020; revised December 11, 2020; accepted February 18, 2021. Date of online publication September 10, 2021; date of current version October 12, 2021. This work was supported in part by the National Key Research and Development Program of China (2016YFB0900600), and in part by the Science and Technology Project of State Grid Corporation of China (52094017000W).

D. C. Tian (corresponding author, e-mail: shinic@sina.com; ORCID: https://orcid.org/0000-0001-5528-5064) is with the College of Automation, Chongqing University of Posts and Telecommunications, Chongqing 400065, China.

X. F. Xiong is with the School of Electrical Engineering, Chongqing University, Chongqing 400044, China.

DOI: 10.17775/CSEEJPES.2020.05700

a preset objective function, the startup thresholds of each CFPREV control in those distributed LCC-HVDC links are required to be instantly reconfigured all together. Obviously, that assumption is unrealistic in practice. Note that the same is true for the proposed method in [7], even if it is, alternatively, implemented by dynamically modifying the gain coefficients of each CFPREV control. In addition, it is worth mentioning that Ouyang *et al.* in [8] attempted to substitute the startup thresholds and final output of the original CFPREV control in various fault conditions with related values calculated by the quasi-steady state equation in the premise of a mere three-phase fault. Unfortunately, an obvious fact ignored is that the equivalent RMS value of three-phase voltage in those derived formulas, especially the one that is used to obtain the final adjustment of inverter firings, must rely on a real-time detection. As a result, since the detected RMS value can never catch up with the decline of the actual one due to the lagging effect of the detection algorithm, the eventually calculated electrical angle for ignition in advance will always be insufficient.

Moreover, it should be highlighted that even if there are still a great many other studies focusing on the improvement of the original CFPREV control (e.g., [9]) or just claiming that they have used the original as a contrast (e.g., [10]), there exists no study to date that can provide a more in-depth discussion about the fact whether the original control scheme functions properly; and the investigation of characteristics of the original CFPREV control, in particular the variation specifics of the intermediate quantities, is also absent.

As pointed out by [11], it has been widely recognized that the performance of the CFPREV control might be limited by a rapid rise of the reactive power consumption in the inverter, for the reason that the depression of commutating bus voltages would be further aggravated under the grid fault in a relatively weak receiving-end AC system. In addition, it is also remarkable that [12] finds that an advancement of firings with a value surpassing 0.476 rad after the occurrence of an AC fault will contrarily lead to more CFs; whereas in that study, it is merely ascribed to an increase of DC current following the reduction of the inverter DC voltage. In fact, another reason for the counterproductive behavior of the CFPREV control essentially lies in the nature of valve commutation in the Graetz bridge, and here it is termed the plateau effect by referring to the terminology of the Miller plateau of MOSFET in the field of electronics due to the existence of some similarities. Namely, the existing platform or red line cannot be promptly crossed, or else side effects may come into being.

In this paper, the main contributions can be summarized from the following two aspects:

1) Uncover the truth, which has been hidden for a long time, that serious defects do exist in the original CFPREV control shown in [1], and then develop a few proper modifications to provide a correct scheme for future research.

2) Bridge the knowledge gap and issue a reminder that a relevant criterion should be satisfied in the off-line parameter design or real-time operations to avoid the adverse impact of the plateau effect of the CFPREV control.

The rest of this paper is organized as follows. In Section II, the defects existing in the original CFPREV control are discussed and thereby addressed, and the analysis of its inherent plateau effect is also conducted. In Section III, related simulation tests are carried out based on the CIGRE LCC-HVDC benchmark model to validate the effectiveness of the proposed corrections and existence of the plateau effect. Section IV provides the conclusion.

II. CFPREV Control and Its Plateau Effect

A. Corrections of the Original CFPREV Control

As mentioned earlier, even though the original scheme of the CFPREV control has been given in [1] and adopted for years in many studies, such as the textbook [13], the output characteristics, especially for the intermediate quantities, are rarely shown. In fact, when looking into the details, it can be found that there exist several serious defects in the original scheme. That is to say, the output characteristics displayed in [1] actually contradict its presented schematic diagram.

As shown in Fig. 1, the parts marked by the magenta color are merely owned by the original CFPREV control; whereas the parts identified by the red and blue colors are respectively the proposed crucial corrections and beneficial improvements. The distinctions between the original and corrected CFPREV controls are as follows.

1) Startup Criterions

In order to alleviate the influence of some unexpected transients, such as the sudden drops or frequent periodic changes in the intermediate outputs (i.e., ΔAB_{Inter} and ΔZ_{Inter}) resulting from the fluctuations in the detected characteristic components of the AC fault, which is most notable for the detection of zero-sequence voltage, the preset startup thresholds U_{ABth} and U_{Zth} should be compared with the outputs of the MAXHOLD modules, rather than their inputs.

2) Output Rate Limiter

Considering that after the clearance of AC fault, the CFPREV control is surely going to exit, its output, i.e., retained adjustment value of inverter firings, should be reduced to zero in a relatively slow way, which is not only to mitigate the overshoot of AC voltage due to overcompensation of reactive power if the inverter-side AC system is a bit strong, but also to prevent the onset of subsequent CFs in the post-fault recovery process in case the resumption of the commutating voltage in a weak AC system may somewhat lag behind.

3) Fast Initialization

The low pass filters (LPFs) in Fig. 1 are all implemented by the first-order transfer function. It should be noted that LPF1 has a large time constant. In addition, only after the output of LPF1 (i.e., $U_{\alpha\beta f}$) has caught up with its input $U_{\alpha\beta}$ will the CFPREV control be ready to come into operation. Thus, a fast initialization of LPF1 will remarkably accelerate the startup of the entire simulation model, and here it is achieved by assigning the input of the filter to its output in real time through the reset function.

4) Output Transformation

Guided by [14], since the voltages at the inverter commutating bus are all specified in per-unit values, and if the

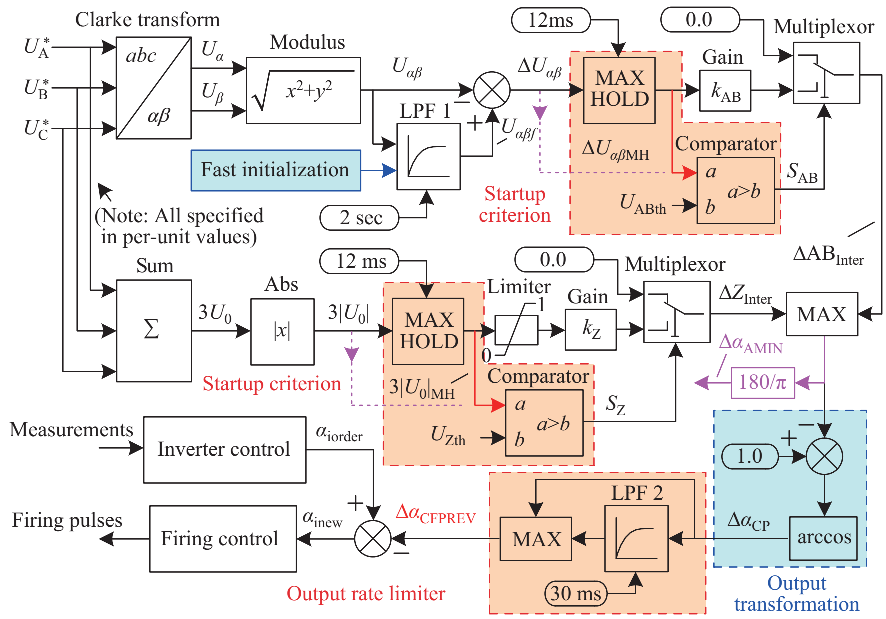

Fig. 1. Block diagram of the original and corrected CFPREV controls.

gain coefficients for the detection of the three-phase voltage depression and zero-sequence voltage amplitude are both set to the values less than 1, the inverse trigonometric function can be utilized to easily convert the maximum of the intermediate outputs to its corresponding electrical angle. Moreover, it is worth noting that the '$y = \arccos(1 - x)$' function in Fig. 1 can also be regarded as a lookup table with a series of variable slopes in the whole range of the input. Hence, if compared with the originally used fixed-slope linear function (i.e., "$y = x$"), it will have a much higher ramp up rate of output under the slight AC faults, and also a larger final output value in all cases.

It should be highlighted that the first two corrections are, of necessity, most vital to the proper functioning of the CFPREV control, and the salient features as well as the technical merits will be demonstrated in the simulation tests in Section III-A. In addition, it is noted that in accordance with the original scheme in [1], the output of the corrected CFPREV control, $\Delta\alpha_{\mathrm{CFPREV}}$, is directly deducted from the firing angle order calculated by the inverter core control (i.e., α_{iorder}) to obtain a final ordered value α_{inew} for the use of firing pulse generation.

B. Analysis of the Inherent Plateau Effect

Apart from the common factors, e.g., undue consumption of the inverter reactive power or increase of the DC current, that could limit the commutation failure suppressing capacity of the CFPREV controls given in Fig. 1, as referred to in the literature review, special attention should also be paid to an inherent plateau effect. Considering that the plateau effect of the CFPREV control can only be observed in a few specific cases, there is a need to first introduce the background in which it takes place. Referring to Fig. 2(a), the Graetz bridge shown is commonly employed to compose the 12-pulse inverter in the LCC-HVDC links, and there will be 2 or 3 valves conducting simultaneously during its normal operation. Moreover, in view of the fact that the phase-locked loop (PLL) works like a Kalman filter and is able to track the phase of the grid voltages under a balanced operating condition, hence according to the quasi-steady state analysis of a commutation process [15], the extinction angle of an outgoing valve can be expressed as

$$\gamma = \pi - \alpha_{\mathrm{iorder}} - \mu = \arccos\left[\frac{\sqrt{2}\omega L_{\mathrm{c}} I_{\mathrm{di}}}{U_{\mathrm{LL}}} - \cos\alpha_{\mathrm{iorder}}\right] \tag{1}$$

where γ is the actual extinction angle and it generally represents the commutation margin ζ, as shown in Fig. 2(b), α_{iorder} is the nominal value of the firing angle order during steady state, μ is the angle of commutation overlap, I_{di} is the inverter DC current, L_{c} is the commutation inductance, ω is the rated angular frequency of the AC system, U_{LL} is the RMS value of the valve-side line-to-line voltage. It is noted that in the specific scenario analyzed hereafter, the actual firing angle is identical to its ordered value.

Given that the voltage of phase A drops near the end of the commutation from valve T_6 to valve T_2 due to fault initiation, whereas the voltages of phase B and C remain unchanged, and if considering a temporary suppression effect of the smoothing reactor on the inverter DC current as well as a presumptively unchanged commutating voltage U'_{BC}, the duration of that ongoing commutation may turn out to be basically the same as normal. However, the succeeding commutation (i.e., valve T_1 to valve T_3) will be confronted with a great risk of failure owing to the depression of its commutation voltage U'_{BA} and an increase of DC current, as reflected by (1).

Through implementation of the AC fault fast detection, the CFPREV control may be able to prevent the CF by advancing firings with a value $\Delta\alpha_{\mathrm{CFPREV}}$, which is calculated based on the preset parameters. In addition, since the time left to the control system to take action after the fault initiation is extremely short, and if disregarding a circumstance of insuf-

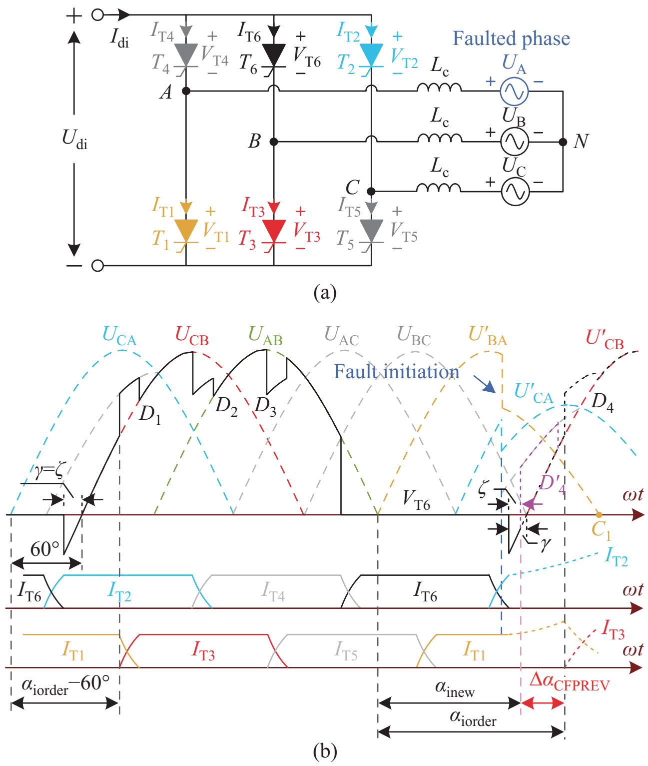

Fig. 2. Analysis of the plateau effect in the CFPREV control relating to the nature of valve commutation. (a) Topology of a Graetz bridge in the inverter operation mode. (b) Interaction between the control system and commutation process under a specified fault condition.

ficient reserve of the reactive power, advancing the firings as much as possible may provide a guarantee of extinction angle margin. However, it can be observed from the potential across valve T_6 (i.e., V_{T6}) in Fig. 2(b) that firing in advance will cause the commutation dent D_4 to move forward. Therefore, if the sudden adjustment of the inverter firing angle has surpassed a critical value, it may even result in the encroachment of the commutation margin ζ and make it smaller than the extinction angle γ. Note that this is the case in which the plateau effect of the CFPREV control emerges, and it will adversely lead to the reignition of the extinguished valve owing to an unsatisfied demand of the deionization time. In other words, the commutation dents inherently existing in the Graetz bridge should be responsible for the plateau effect and counterproductive consequence of an excessive advancement of firings by the CFPREV control. Likewise, other suppressing methods against the first CF by means of advancing inverter firings will also be affected by this plateau effect, whereas it has been ignored by the vast majority of researchers and scholars. In general, to avoid an adverse impact of the foregoing inherent plateau effect, the abrupt adjustment of the inverter firing angle order by the CFPREV control after fault initiation should satisfy:

$$\Delta\alpha_{\text{CFPREV}} < \alpha_{\text{iorder}} - 120^\circ + (\gamma_{\text{iref}} - \gamma_0) \tag{2}$$

where γ_{iref} is the reference and nominal value of the extinction angle, and γ_0 is the critical value corresponding to the minimum turn-off time of the thyristor valves. It can be found in (2) that a sudden change of the inverter firing angle order must be under the restrictions of a previous operating state of inverter, which means that the capacity of the CFPREV control is still limited, even without considering the factors such as the fault initiation time and inverter reactive power consumption.

There is, in addition, one further point to make. Because the aforementioned plateau effect is rooted in the topology of the line-commutated converter, it is almost impossible to be eliminated based solely on modification of the existing control strategies. That is to say, the corrected CFPREV control in Fig. 1 should also obey the restrictions imposed by that effect, and therefore the parameters in particular the gain coefficients k_Z and k_{AB} are required to be properly designed to avoid adversely triggering the plateau effect.

III. Simulation and Discussion

The CIGRE LCC-HVDC benchmark model shipped with the PSCAD/EMTDC software [16] is used to verify the presented corrected CFPREV control and its plateau effect, and Table I shows the control parameters adopted in the simulations. Note that the parameters in case 1 are recommended by [14], and in order to be able to observe the plateau effect, the minimum turn-off time of the thyristor valves should be set to a non-zero value. Here, it is typically chosen as 400 μs, which corresponds to an electrical angle $\gamma_0 = 7.2^\circ$ in the 50 Hz AC system.

TABLE I
Parameters of the CFPREV Control Scheme

Specific items of the parameters	Case 1	Case 2	Case 3
Startup threshold for detection of the symmetrical AC fault (i.e., U_{ABth})	0.2 p.u.	0.1 p.u.	0.1 p.u.
Gain coefficient for three-phase voltage depression (i.e., k_{AB})	0.15 p.u.	0.34 p.u.	0.35 p.u.
Startup threshold for detection of the asymmetrical AC fault (i.e., U_{Zth})	0.3 p.u.	0.2 p.u.	0.2 p.u.
Gain coefficient for zero-sequence voltage component (i.e., k_Z)	0.15 p.u.	0.34 p.u.	0.35 p.u.

A. Verification of the Proposed Vital Corrections

On condition that the faults are applied at the inverter AC bus at $t = 8.974$ s with a duration of 0.2 s, and the fault inductance under the three-phase (TP) and the single-line-to-ground (SLG) faults are 0.3 and 0.05 H, respectively, Fig. 3 shows the output characteristics of the original and corrected CFPREV controls when using the parameters in case 1. It is important to note that the an actual CIGRE benchmark model is adopted to conduct the following investigation.

As shown in Fig. 3(i), when no fault is applied, the low pass filter LPF1 without a fast initialization in the original CFPREV control will take a long time of nearly 9 s to get into position and be ready. However, if it is fast initialized through the reset function, the LPF1 and entire CFPREV control will rapidly be able to be in full operation shortly after $t = 0.8$ s. In addition, it can be seen from Fig. 3(b) and (c) that the MAXHOLD modules implemented by the Fortran programming language are functioning correctly. In Fig. 3(ii), due to the fact that no significant zero-sequence voltage is detected under the symmetrical AC fault, the final output of the CFPREV control is merely determined by the intermediate

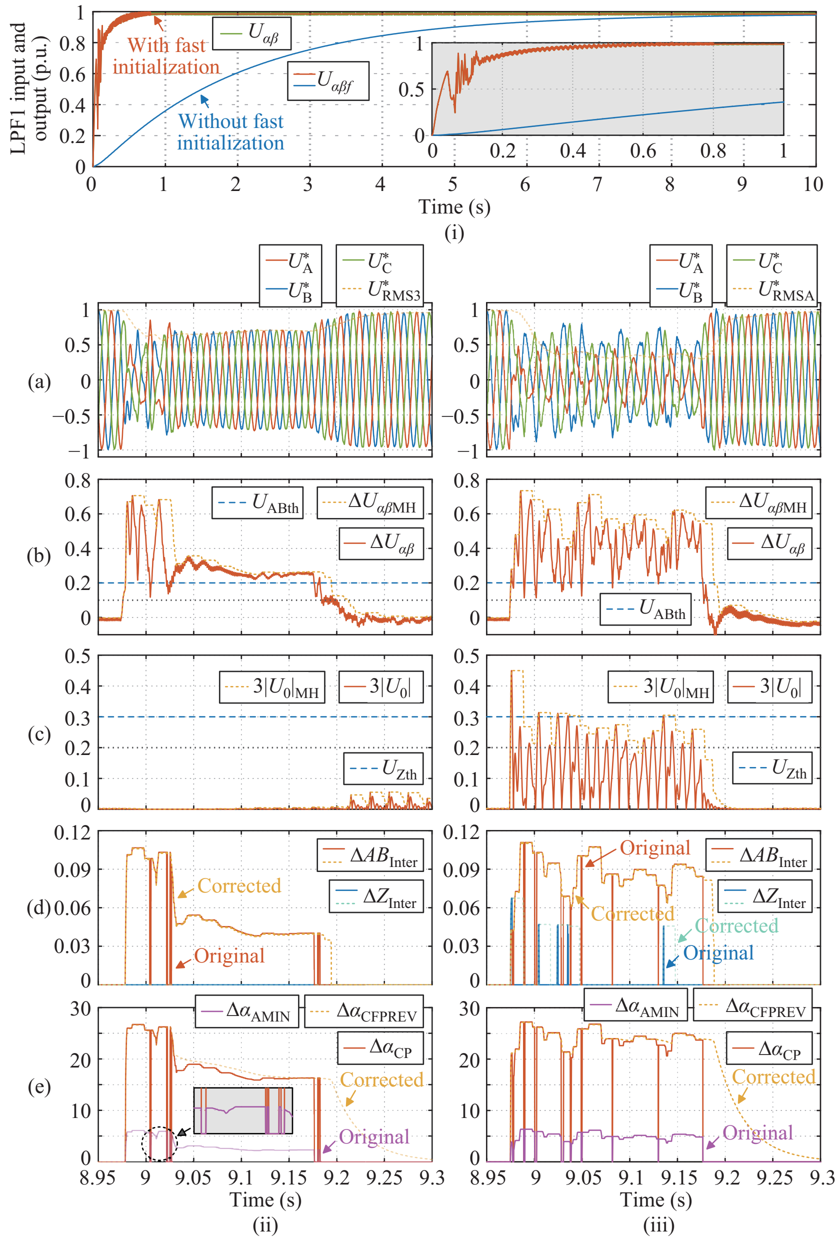

Fig. 3. Output characteristics of the original and corrected CFPREV controls with the parameters in case 1. (i) During simulation model startup process. (ii) Under the TP fault. (iii) Under the SLG fault. (a) Inverter commutating bus voltages [p.u.]. (b) Three-phase voltage depression detected by the Clarke transform and its preset startup threshold [p.u.]. (c) Absolute value of the zero-sequence voltage and its startup threshold [p.u.]. (d) Intermediate outputs [rad]. (e) Final outputs [deg].

quantity $\Delta AB_{\mathrm{Inter}}$, which is obtained by performing the Clarke transform. Nonetheless, drastic changes will appear in the final output of the original scheme during the fault-on period (see $\Delta\alpha_{\mathrm{AMIN}}$ in Fig. 3(e, ii)), for the reason that the uncertain fluctuations existing in characteristic fault component $\Delta U_{\alpha\beta}$ may result in a sudden drop below its startup threshold U_{ABth}. On the contrary, that issue could be effectively mitigated in the corrected CFPREV control. Furthermore, when taking a good look at the waveforms of the final outputs in Fig. 3(e) at the moment of algorithm startup, it can be found that the output of the corrected CFPREV control has a higher ramp up rate, which means that in contrast with the original scheme, it will take less time for the corrected output to reach an exact same value due to the variable-slope characteristics of the inverse trigonometric function used in Fig. 1, and it should be noted that the larger slope will speed up the output and is beneficial during the slight AC faults.

Referring to Fig. 3(iii), the alternating zero-sequence voltage arises under the asymmetrical AC fault and its absolute value, $3|U_0|$, will be reduced to zero periodically. In other words, its corresponding intermediate output (i.e., $\Delta Z_{\mathrm{Inter}}$) in the original CFPREV control would frequently vanish, and thus causing the $\Delta\alpha_{\mathrm{AMIN}}$ to diminish precipitously. In addition, considering that a steep descent of the CFPREV final output after fault clearance may also pose a threat to the safe operation of the inverter, it is reasonably necessary to limit the descending slope of the final output of CFPREV control in particular for the prevention of subsequent CFs in the LCC-HVDC links.

In view of the fact that the proposed scheme in Fig. 1 can be regarded as a corrected version of the original CF-PREV control, and also for the reason that the main working mechanism, e.g., the fault detection algorithms as well as their startup threshold settings, is in essence the same, the first CF suppressing capacity of the CFPREV control with the proposed corrections at fault inception may not be significantly enhanced. It can be seen in Fig. 3(e) that if the gain coefficients k_{Z} and k_{AB} are respectively set to the same values in both control schemes, the final output of the corrected CFPREV control is always larger than that of the original control due to usage of the "arccos" function. Therefore, from the standpoint of the univariate analysis, the comparability of the CF suppressing performance is limited, and thus this paper places special emphasis on the investigation of output behavior of the original CFPREV control during the fault-steady and post-fault periods so as to address the defects existing in the original scheme.

B. Confirmatory Test of the Presented Plateau Effect

In order to achieve consistency between the scenarios in the simulation test and theoretical analysis, a special technique is devised by referring to [1] and [2], i.e., first reduce the impedance of the AC tie-line (here it is set to 0.74 Ω) to strengthen the inverter AC system, then use a programmable infinite three-phase power supply to simulate a single-phase voltage drop. It is worth noting that such a type of modification on the inverter-side power circuit of the CIGRE benchmark model is essential to exclude a distraction of insufficient reactive power reserve, since the default inverter AC system is relatively weak with a short circuit ratio (SCR) of 2.5. Now assuming that an initiation of the AC fault at $t = 0.974$ s has caused a voltage drop on phase A with the remaining voltage to be 0.6 p.u., Fig. 4 illustrates the scenario in which the plateau effect of the CFPREV control emerges.

It can be seen from Figs. 4(c, ii) and (d, ii) that if the abrupt change of the CFPREV control output has exceeded a certain value between the electrical degrees 29.7° and 30.1°, then according to (2), the extinguished thyristor valve would re-conduct due to inadequate reverse bias time after the valve current (i.e., I_{T6}) has fallen to zero. Note that this phenomenon could also be observed in the D bridge. In the modified CIGRE benchmark model, the minimum extinction angle γ_0 and the gamma reference γ_{iref} are set to 7.2° and 15°, respectively.

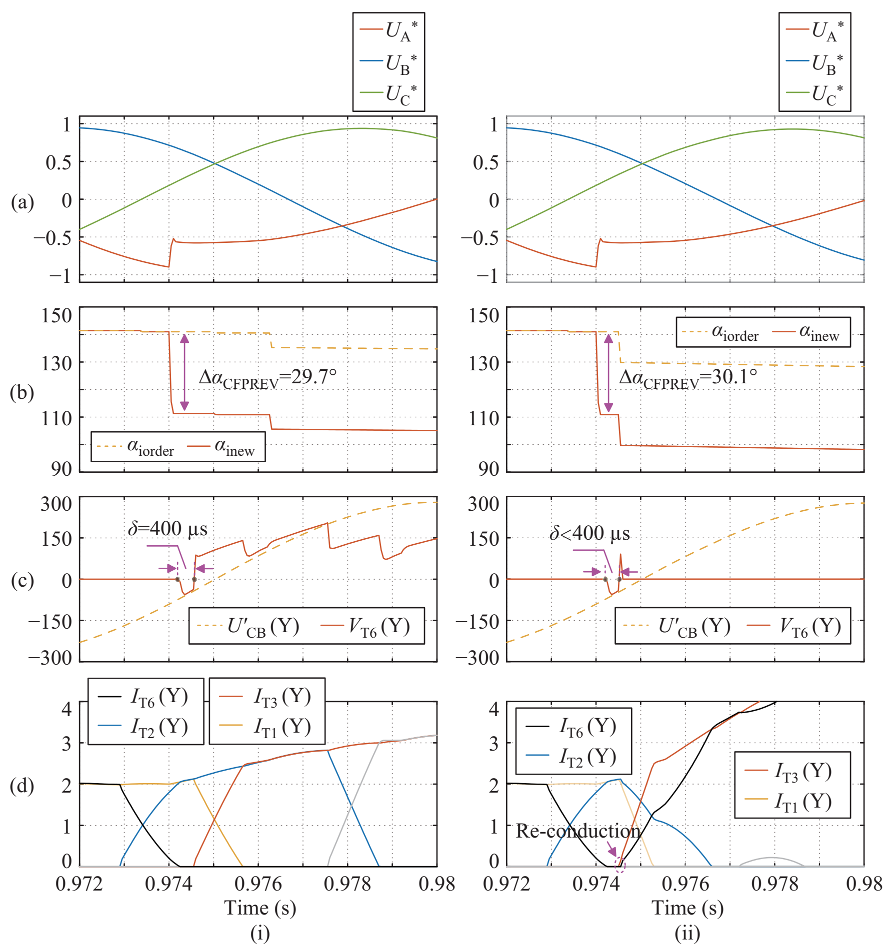

Fig. 4. Confirmation of the plateau effect in the CFPREV control on condition of single-phase voltage drop at inverter commutating bus. (i) Inverter system response with the control parameters in case 2. (ii) Inverter system response with the control parameters in case 3. (a) Commutating bus voltages [p.u.]. (b) Firing angle orders [deg]. (c) Valve voltage and corresponding commutating voltage [kV]. (d) Valve currents [kA].

Considering that the inverter firing angle order α_{iorder} is approximately 141° in the steady state, the critical value of the plateau effect calculated by (2) will then turn out to be 28.8°, and the tiny deviation between the theoretical and actual values may result from a small disturbance in the tracking frequency of the PLL used for electrical angle conversion. Furthermore, it is also worth mentioning that the theoretical critical value obtained by (2) tends to be conservative, and thus if (2) is applied as an output limit of the corrected CFPREV control in Fig. 1, it is apparent that this manipulation would be able to effectively prevent the undesired trigger of the plateau effect at fault inception.

IV. Conclusion

The significance that a correct scheme of CFPREV control should be presented to the public in the research field of LCC-HVDC transmission is self-evident. In this paper, the serious defects in the original CFPREV control are expounded, and the targeted corrections as well as beneficial improvements are put forward. To bridge the knowledge gap that the counterproductive result of an excessive advancement of inverter firings should not only be ascribed to the increase of DC current or reactive power consumption, an inherent plateau effect existing in the Graetz bridge which relates to the shift of commutation dent is also revealed and analyzed in this paper. It indicates that when suddenly changing the firing angle order of the inverter through the CFPREV control, the minimum turn-off time of a previously conducting valve should first be respected. Otherwise, the excessive advancement of firings will inevitably lead to more CFs. Thus, the plateau effect should be taken into account whether in the off-line parameter design or in real-time operation of the CFPREV control. Simulation results then show the technical merits of those corrections made to the defective original CFPREV control, and also confirm the existence of the presented plateau effect.

References

[1] L. D. Zhang and L. Dofnas, "A novel method to mitigate commutation failures in HVDC systems," in *Proceedings of the International Conference on Power System Technology*, 2002, pp. 51–56.

[2] W. Yao, C. Liu, J. K. Fang, X. M. Ai, J. Y. Wen, and S. J. Cheng, "Probabilistic analysis of commutation failure in LCC-HVDC system considering the CFPREV and the initial fault voltage angle," *IEEE Transactions on Power Delivery*, vol. 35, no. 2, pp. 715–724, Apr. 2020.

[3] S. Y. Chen, X. N. Li, J. Yu, T. Li, P. F. Lü, and Y. H. Yin, "A method based on the sin-cos components detection mitigates commutation failure in HVDC," *Proceedings of the CSEE*, vol. 25, no. 14, pp. 1–6, Jul. 2005.

[4] X. H. Li, C. Z. Y. Zhang, W. Y. Cai, Z. P. Tan, Z. S. Chen, and Z. X. Cai, "Improvement of HVDC CFPREV based on a three phase simultaneity sampling values algorithm," *Power System Protection and Control*, vol. 48, no. 20, pp. 170–176, Oct. 2020.

[5] Y. Wang, Y. Q. Hou, F. S. Liu, L. Cao, W. Li, F. Xue, and Z. L. Huang, "Optimization method for startup threshold of commutation failure prediction control considering coordinated recovery of multi-infeed HVDC systems," *Automation of Electric Power Systems*, vol. 42, no. 22, pp. 85–90, Nov. 2018.

[6] Y. Tang, C. Y. Zheng, Y. Wang, and F. S. Liu, "Optimization method for commutation failure prevention control considering AC/DC reactive power interaction characteristics," *Automation of Electric Power Systems*, vol. 44, no. 21, pp. 50–57, Nov. 2020.

[7] C. H. Li, Y. C. Tan, Y. X. Xiong, J. Zhan, W. Yao, X. M. Ai, Y. F. Rao, and J. Y. Wen, "Coordinated control of UHVDC multi-infeed system for commutation failure prevention," *Power System Technology*, vol. 43, no. 10, pp. 3532–3542, Oct. 2019.

[8] J. X. Ouyang, Z. Zhang, and C. Xiao, "Improved prevention and control strategy of commutation failure in HVDC transmission system," *Automation of Electric Power Systems*, vol. 44, no. 22, pp. 14–21, Nov. 2020.

[9] Z. N. Wei, Y. Yuan, X. Lei, H. W. Wang, G. Q. Sun, and Y. H. Sun, "Direct-current predictive control strategy for inhibiting commutation failure in HVDC converter," *IEEE Transactions on Power Systems*, vol. 29, no. 5, pp. 2409–2417, Sept. 2014.

[10] L. Liu, S. Lin, K. Liao, P. Y. Sun, Y. J. Deng, X. P. Li, and Z. Y. He, "Extinction angle predictive control strategy for commutation failure mitigation in HVDC systems considering voltage distortion," *IET Generation, Transmission & Distribution*, vol. 13, no. 22, pp. 5171–5179, Nov. 2019.

[11] C. Zheng, J. M. Zhou, H. L. Li, L. Wan, and H. D. Sun, "Impact of commutation failure prediction control on voltage stability and its optimization measures," *Automation of Electric Power Systems*, vol. 40, no. 12, pp. 179–183, Jun. 2016.

[12] S. Mirsaeidi, X. Z. Dong, D. Tzelepis, D. M. Said, A. Dyśko, and C. Booth, "A predictive control strategy for mitigation of commutation failure in LCC-based HVDC systems," *IEEE Transactions on Power Electronics*, vol. 34, no. 1, pp. 160–172, Jan. 2019.

[13] Y. Tao, *Analysis and Application of DC Transmission Control and Protection Systems*, Beijing, China: China Electric Power Press, 2015.

[14] *Technical Specification of HVDC Control and Protection System*, Q/GDW 10548-2016, 2017.

[15] J. Arrillaga, *High Voltage Direct Current Transmission*, 2nd ed., London, UK. : Institution of Electrical Engineers, 1998.

[16] M. Szechtman, T. Wess, and C. V. Thio, "A benchmark model for HVDC system studies," in *Proceedings of the International Conference on AC and DC Power Transmission*, 1991, pp. 374–378.

Dachuan Tian received a B.S. degree in Automation, an M.S. degree in Control Science and Engineering from Nanjing University, Nanjing, China, in 2012 and 2015, respectively, and a Ph.D. degree in Electrical Engineering from Chongqing University, Chongqing, China, in 2021.

He is currently a Lecturer with the College of Automation, Chongqing University of Posts and Telecommunications. His research interests include the LCC-HVDC system control and protection, smart grid and applications.

Xiaofu Xiong (M'05) received B.E., M.E., and Ph.D. degrees in Electrical Engineering from Chongqing University, Chongqing, China, in 1982, 1986, and 2005, respectively.

He is currently a Professor with the School of Electrical Engineering, Chongqing University. His research interests include smart grid, power system risk assessment, and power system protection and control.