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A Fuzzy Logic based Adaptive Source Current THD Controller for Thyristor-Controlled *LC*-Coupling Hybrid Active Power Filter

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Abstract— **Thyristor-controlled *LC*-coupling hybrid active power filter (TC*LC*-HAPF) is characterized with low DC-link voltage and wide operational range, which was recently developed for power quality conditioning in the medium-voltage-level system. This paper proposes a fuzzy logic based adaptive source current total harmonic distortion (THD) controller for the TC*LC*-HAPF. The proposed controller can adaptively change the hysteresis band (HB) according to the reference THD value, thereby possibly reduce the switching loss and keep the source current THD at an acceptable reference level. Simulation is conducted for verifying the proposed controller, in comparison with the fixed HB controller.**

Keywords—Thyristor-Controlled LC-Coupling Hybrid Active Power Filter (TCLC-HAPF), power quality, total harmonic distortion (THD), hysteresis control, fuzzy logic control

I. Introduction

In the modern power grid, the proliferation of motor loadings, power electronic devices (non-linear loads), and also a rapid increase in renewable energy generators and electric vehicles (EVs) are inevitable to cause the power quality (PQ) problems [1]. Low power factor and current harmonic distortion are considered as two of the major power quality problems in the three-phase distribution power grid.

Conventionally, passive power filters (PPFs) are widely used to compensate for the reactive power and eliminate the harmonic current [2]. However, PPFs suffers from fixed compensation capability and resonance problems. Active power filters (APFs) can overcome the aforementioned problems of PPFs [3], but the operational power loss and the initial cost of the APF are much higher because of its high DC-link voltage requirement. Thus, this slows down their largescale application in the power grid. To address this problem, a combination of active and passive power filters to form hybrid active power filters (HAPFs) are introduced, which can overcome the drawbacks of PPF and reduce the high initial and operational costs associated with the APF. The *LC*-coupling hybrid active power filter (*LC*-HAPF), thyristor-controlled *LC*-coupling hybrid active power filter (TC*LC*-HAPF) and *LCLC*-coupling hybrid active power filter (*LCLC*-HAPF) were proposed in succession for power quality conditioning in the recent two decades [4]-[5]. Although the *LC*-HAPF and *LCLC*-HAPF can reduce the DC-link voltage requirement, their compensation range are very narrow (not able to operate at capacitive loading situation), which lowers their practicability [5]. Fortunately, the TC*LC*-HAPF has distinct characteristics of low DC-link operating voltage and wide operation range (able to operate at both inductive and capacitive loading situations). Also, it can provide reactive, harmonic and unbalanced powers compensation simultaneously [6]. According to the advantages mentioned above, the TC*LC*-HAPF is more cost-effective than the conventional APF and HAPF in the medium-voltage system.

Because of the nonlinearity of the thyristor-controlled *LC* filter (TC*LC*) part of the TC*LC*-HAPF, it is difficult to design precise linear controllers such as proportional integral (PI), proportional resonant (PR) for the TC*LC*-HAPF to achieve accurate operating performances so far. Therefore, hysteresis band (HB) current control method, as one of the nonlinear controllers is the most popularly used because of its simplicity and fast controllability, was applied to control the TC*LC*-HAPF [6]. By applying HB current control, the nonlinear effects of the TC*LC* part can be neglected since the system model is not considered when designing the HB current controller. In principle, decreasing HB can increase inverter operation frequency and helps to get a better compensating performance with low total harmonics distortion (THD). However, small HB means higher switching frequency of the switching devices that yields higher switching loss.

In this paper, a new control strategy for the TC*LC*-HAPF is proposed to adaptively change the HB according to the desired source current THD value, so that the switching frequency and switching loss can be reduced, thus reducing the operational cost of the TC*LC*-HAPF system while keeping the system performance within an acceptable level. An approximated THD (ATHD) index is used to access the THD value instantaneously [7], [8] for the proposed control strategy. As the relationship between HB and source current THD is not easy to find in the TC*LC*-HAPF topology, a fuzzy logic [9], [10] based adaptive source current THD controller for the TC*LC*-HAPF is developed and proposed in this paper. Simulation results are presented to verify the proposed control method, in comparison with the fixed HB controller.

The operational principle and circuit configuration of the TC*LC*-HAPF will be given in Section II. Then, the proposed

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fuzzy logic based adaptive source current THD controller will be presented in Section III. Section IV provides the simulation results, whereas the conclusions will be drawn in Section V.

II. Operational Principle and Circuit Configuration of TC*LC*-HAPF

The TC*LC*-HAPF aims to compensate the reactive power, current harmonics, and unbalanced power. It can be divided into two parts: the *TCLC* part and the active inverter part. Fig. 1 shows a three-phase three-wire TC*LC*-HAPF circuit configuration, where the subscript '*x*' represents phase *a*, *b*, *c*. v_x represents the load voltage, i_{sx}, i_{cx}, i_{Lx} represent the source, compensating and load currents, respectively.

A. The TCLC Part

The TC*LC* part is constructed by a thyristor-controlled reactor L_{PF} parallel with a fixed value capacitor C_{PF}, and a ripple filtering inductor L_c. By controlling the firing angle $\alpha_x \in$ [90°, 180°] of two thyristors, it can provide a continuous and wide reactive power compensating range between capacitive and inductive loading. With this control, the TC*LC* part can perform unbalance reactive power compensation. The equivalent fundamental reactance of the TC*LC* is given as (1).

$$X_{TCLC}(\alpha_x)=\frac{\pi X_{L_{PF}}X_{C_{PF}}}{X_{C_{PF}}(2\pi-2\alpha_x+\sin 2\alpha_x)-\pi X_{L_{PF}}}+X_{L_c} \quad (1)$$

where X_{LPF}, X_{CPF} and X_{Lc} are the fundamental reactances of L_{PF}, C_{PF} and L_c respectively. The compensating fundamental reactive power Q_{cxf} provided by the TC*LC* part can be expressed as (2), in which $Q_{cxf\,(\alpha=90°)} \geq Q_{cxf} \geq Q_{cxf\,(\alpha=180°)}$.

$$\begin{aligned}Q_{cxf(\alpha=90°)}&=\frac{V_{sx}^2}{\frac{X_{L_{PF}}X_{C_{PF}}}{X_{C_{PF}}-X_{L_{PF}}}+X_{L_c}}\geq\\ Q_{cxf}&=\frac{V_{sx}^2}{X_{TCLC}(\alpha_x)}\\ &\geq-\frac{V_{sx}^2}{X_{C_{PF}}-X_{L_c}}=Q_{cxf(\alpha=180°)}\end{aligned} \quad (2)$$

B. The Active Inverter Part

The active inverter part is composed of a DC/AC voltage source inverter (VSI), a DC-link capacitor C_{DC} and a DC-link voltage source V_{DC}. The active inverter part aims to compensate the current harmonics and enhance the reactive power and dynamic compensating characteristics of the TC*LC* part.

In this paper, the instantaneous *p-q* theory is applied to calculate the current reference [11]. First of all, Clark transformation is applied in (3) and (4) to transform the source voltage v_x and load current i_{Lx} from *a-b-c* coordinates into *α-β* coordinates. Then the three-phase instantaneous active and reactive power can be deduced in (5).

$$\begin{bmatrix}v_\alpha\\ v_\beta\end{bmatrix}=\begin{bmatrix}1 & -1/2 & -1/2\\ 0 & \sqrt{3}/2 & -\sqrt{3}/2\end{bmatrix}\cdot\begin{bmatrix}v_a\\ v_b\\ v_c\end{bmatrix} \quad (3)$$

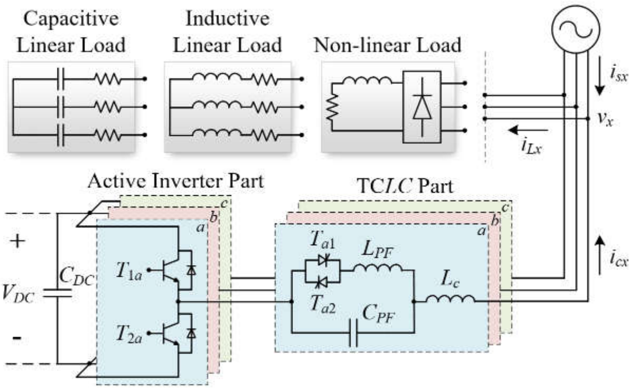

Fig. 1. Circuit configuration of a three-phase three-wire TC*LC*-HAPF for power quality conditioning.

$$\begin{bmatrix}i_\alpha\\ i_\beta\end{bmatrix}=\begin{bmatrix}1 & -1/2 & -1/2\\ 0 & \sqrt{3}/2 & -\sqrt{3}/2\end{bmatrix}\cdot\begin{bmatrix}i_{La}\\ i_{Lb}\\ i_{Lc}\end{bmatrix} \quad (4)$$

$$\begin{bmatrix}p_{\alpha\beta}\\ q_{\alpha\beta}\end{bmatrix}=\begin{bmatrix}v_\alpha & v_\beta\\ -v_\beta & v_\alpha\end{bmatrix}\cdot\begin{bmatrix}i_\alpha\\ i_\beta\end{bmatrix}=\begin{bmatrix}\bar{p}_{\alpha\beta}+\tilde{p}_{\alpha\beta}\\ \bar{q}_{\alpha\beta}+\tilde{q}_{\alpha\beta}\end{bmatrix} \quad (5)$$

where $\bar{p}_{\alpha\beta}$, $\tilde{p}_{\alpha\beta}$, $\bar{q}_{\alpha\beta}$ and $\tilde{q}_{\alpha\beta}$ are the DC and AC components of the instantaneous active power $p_{\alpha\beta}$ and reactive power $q_{\alpha\beta}$, respectively. Finally, the reference compensating current for the active inverter part is given in (6).

$$\begin{bmatrix}i_{ca}^*\\ i_{cb}^*\\ i_{cc}^*\end{bmatrix}=\sqrt{\frac{2}{3}}\cdot\frac{1}{v_\alpha^2+v_\beta^2}\begin{bmatrix}1 & 0\\ -1/2 & \sqrt{3}/2\\ -1/2 & -\sqrt{3}/2\end{bmatrix}\cdot\begin{bmatrix}v_\alpha & -v_\beta\\ v_\beta & v_\alpha\end{bmatrix}\cdot\begin{bmatrix}\tilde{p}_{\alpha\beta}\\ q_{\alpha\beta}\end{bmatrix} \quad (6)$$

III. Fuzzy Logic Based Adaptive Source Current THD Controller

With reference to the IEEE standard 519-2014 [12], the source current THD should be limited within an acceptable range. A narrow HB can provide a good compensating performance with high switching frequency and low current THD, and vice versa. If the switching frequency is high, the switching loss would be increased, thus increasing the operational cost of the TC*LC*-HAPF system. It is a trade-off between the operational cost and the system performance when using the HB current controller. Therefore, the proposed fuzzy logic controller can be applied for controlling the HB value to reduce the switching frequency of the TC*LC*-HAPF while maintaining the source current THD at the acceptable reference value.

For the implementation of the proposed controller, the source current THD value must be calculated. An approximated THD (ATHD) index is adopted in this paper to instantaneously obtain the THD value, which is expressed as (7) [7], [8].

$$\text{ATHD}=\frac{\text{HB}}{\sqrt{2}\cdot I_{S,1}}\times 100\% \quad (7)$$

$I_{S,1}$ is the fundamental source current value which can be calculated as:

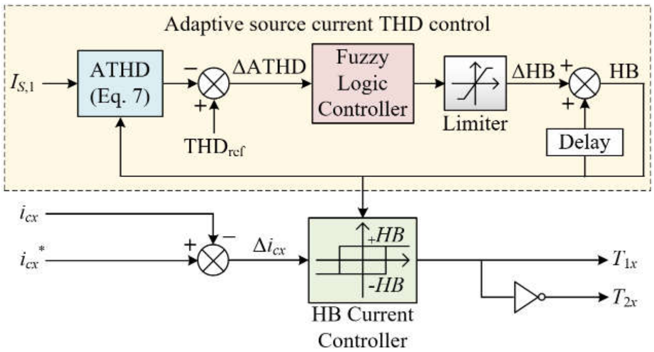

Fig. 2. Single-phase control block diagram of fuzzy logic based adaptive source current THD controller.

$$I_{S,1} = \frac{\overline{p}_{\alpha\beta}}{\sqrt{3}\cdot\|v_L\|} \tag{8}$$

where

$$\|v_L\| = \sqrt{v_a^2 + v_b^2 + v_c^2} \tag{9}$$

in which $\|v_L\|$ is the norm or magnitude of the load voltage and $\overline{p}_{\alpha\beta}$ can be obtained from (5) by passing the $p_{\alpha\beta}$ through a low-pass filter [5].

The input and output variables of the proposed controller can be set as the error of source current ATHD (ΔATHD) and the change of HB (ΔHB), respectively. Fig. 2 shows the single-phase control block diagram of the proposed fuzzy logic based adaptive source current THD controller, where i_{cx}^* is the reference compensating current obtained from (6). From Fig. 2, the source current ATHD is firstly calculated by using (7)-(9) and then compare it with a reference value $\mathrm{THD_{ref}}$, which is determined based on the international standard [12] and the users' demand. If the ATHD value is higher than the reference one, that means the HB is not small enough; On the contrary, if the ATHD value is lower than the reference value, the HB needs to be increased. Then the HB signal will be sent to the HB current controller to generate the trigger signals T_{1x} and T_{2x} for the active inverter part of the TC*LC*-HAPF. This control loop will be continuously executed for calculating the optimal HB. Finally, the switching devices of the active inverter are controlled to generate the compensating currents, which will make the source current THD tracks as its reference value.

However, since the relationship between HB and source current THD cannot be easily found in TC*LC*-HAPF, a fuzzy logic controller can be applied to deal with their relationship as shown in Fig. 2. The control concept of the fuzzy logic controller is to analyze the fuzzified input, and get the output by converting the linguistic output that is determined by the use of the preset linguistic rules. In the proposed controller, the following seven fuzzy levels or sets are chosen as [13]: NL (negative large), NM (negative medium), NS (negative small), Z (zero), PS (positive small), PM (positive medium), and PL (positive large). The corresponding control rule can be established as shown in Table I based on the intuitive feeling and experience of the process. The fuzzy system chosen in this paper is Mamdani system and its membership function graphs are shown in Fig. 3. The fuzzy controller is characterized as follows [13]:

TABLE I. FUZZY RULES OF FUZZY LOGIC CONTROLLER

ΔTHD	**NL**	**NM**	**NS**	**Z**	**PS**	**PM**	**PL**
ΔHB	NL	NM	NS	Z	PS	PM	PL

TABLE II. SYSTEM PARAMETERS OF SIMULATION

System Parameters	**Value**
Grid voltage v_{sx} and frequency f	110 Vrms, 50Hz
Filtering inductor L_c	5mH
Thyristor-controlled reactor L_{PF}	30mH
Capacitor C_{PF}	160μF
Firing angle α_x of TC*LC*	132.3°
DC-link voltage	80V
Three-phase full wave diode rectifier loads	100Ω, 30mH
Linear loads	15Ω, 30mH
Simulation time step	2μs

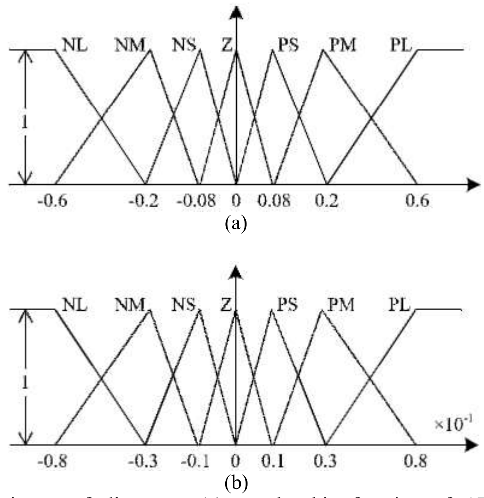

Fig. 3. Universe of discourse: (a) membership function of ΔTHD; (b) membership function of ΔHB.

- Seven fuzzy sets for input and output;
- Triangular membership functions for simplicity;
- Fuzzification using continuous universe of discourse;
- Defuzzification using the centroid method.

IV. SIMULATION RESULTS

To verify the performance of the proposed controller for the three-phase three-wire TC*LC*-HAPF, simulation studies are carried out by using MATLAB/Simulink. Table II lists the simulated system parameters of the TC*LC*-HAPF, and its DC-link voltage is supported by a DC voltage source. With reference to the IEEE standard 519-2014 [12], the acceptable Total Demand Distortion (TDD) ≤ 15% with I_{SC}/I_L is in 100 < 1000 scale. The nominal rate current is assumed to be equal to the fundamental load current at the worst-case analysis, which results in THD = TDD ≤15%. Therefore, this paper evaluates the TC*LC*-HAPF current harmonics compensating performance by setting an acceptable THD ≤15%.

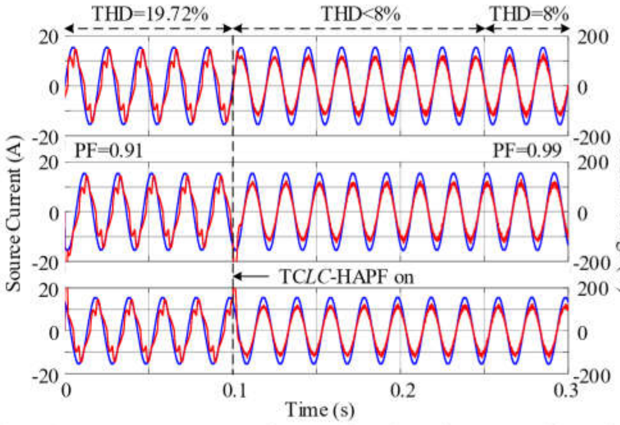

Fig. 4. Source current compensation waveforms by using proposed fuzzy logic based adaptive source current THD controller with reference $THD_{ref} = 8\%$.

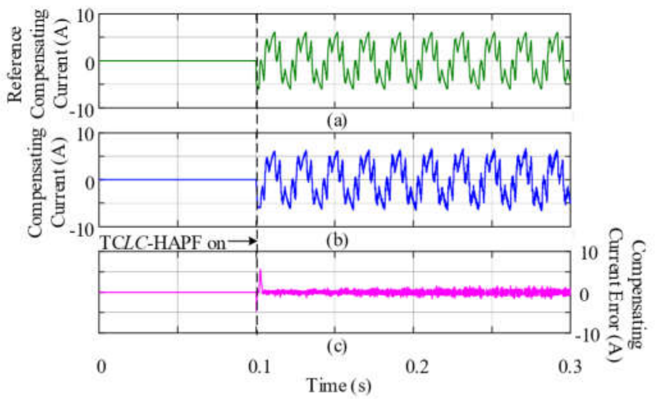

Fig. 5. Phase *a* current waveforms by using proposed fuzzy logic based adaptive source current THD controller with reference $THD_{ref} = 8\%$: (a) Reference compensating current; (b) Compensating current; (c) Compensating current error.

By using the proposed control method, the TC*LC*-HAPF has ability to compensate the source current THD tracks with the required reference THD value. The source current compensation waveforms with THD_{ref}=8% is illustrated in Fig. 4. At 0.1s, the TC*LC*-HAPF is switched on to perform the compensation with initial HB=0.1, the source current THD is lower than the reference value (THD<8%) and tracks with its reference value during 0.1s-0.25s. After 0.25s, the source current THD is controlled as its reference value (THD_{ref}=8%). Fig. 5 shows the waveforms of phase *a* reference compensating current i_{ca_ref}, compensating current i_{ca} and compensating current error i_{ca_err}. The i_{ca_err} is very small at around 0.1s. During the adaptive HB tracking process, the i_{ca_err} increases gradually along with the HB increases.

In the simulation, the switching loss of the TC*LC*-HAPF was obtained by measuring the collector-emitter voltage and current of each insulated gate bipolar transistor (IGBT). The total inverter switching loss of the TC*LC*-HAPF can be found with the following equation [8]:

$$P_{loss} = \sum_{n=0}^{6} P_{loss,n} = \sum_{n=0}^{6} \frac{1}{T_s} \int_0^{T_s} v_{ce,n}(t) \cdot i_{ce,n}(t) \mathrm{d}t \qquad (10)$$

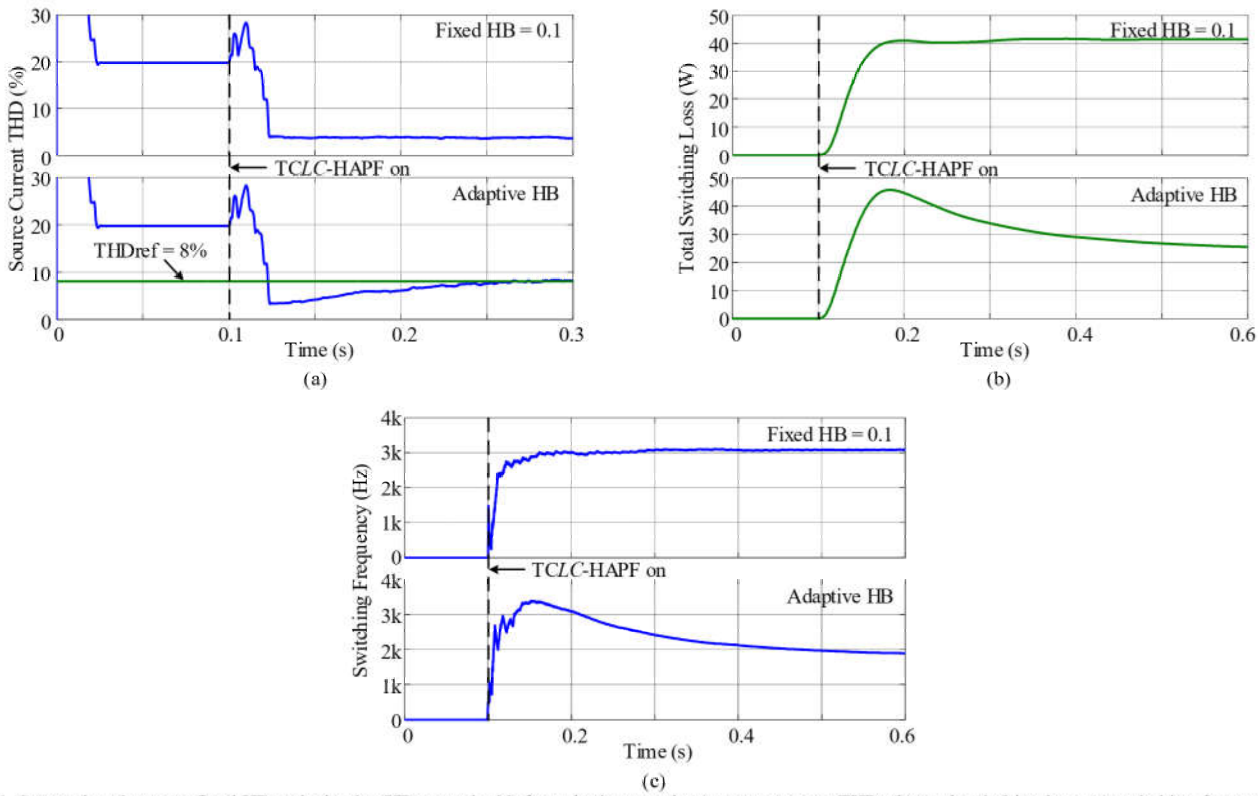

Fig. 6. Comparison between fixed HB and adaptive HB control with fuzzy logic control: (a) source current THD; (b) total switching loss; (c) switching frequency.

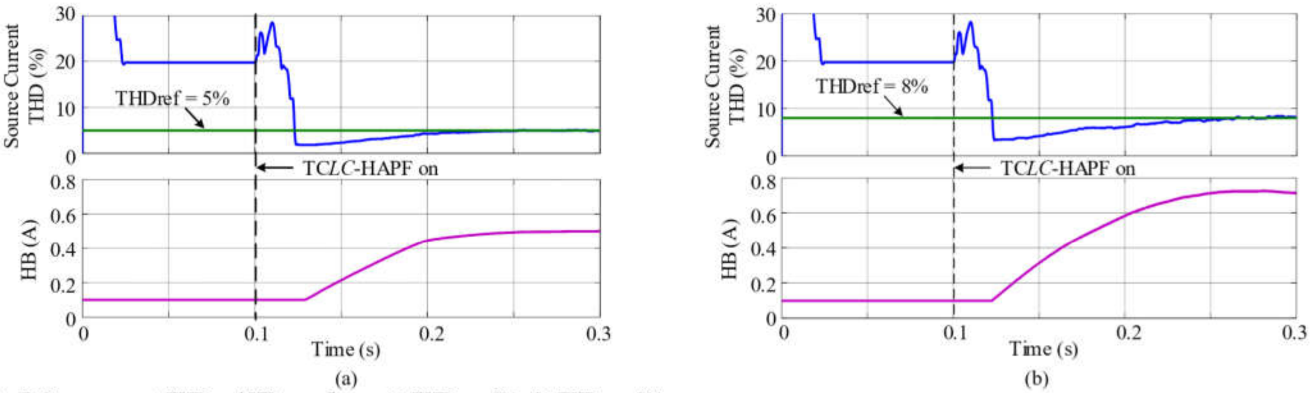

Fig. 7. Source current THD and HB waveforms: (a) THD_{ref} = 5%; (b) THD_{ref} = 8%.

TABLE III. SIMULATION RESULTS WITH DIFFERENT HB CONTROL

HB control	**Source current THD (%)**	**Avg. SW freq. (kHz)**	**Total SW loss (W)**
Fixed HB	3.7	3.1	40.9
Adaptive HB	8.0	1.9	25.4 (**↓38%**)

TABLE IV. SIMULATION RESULTS WITH DIFFERENT THDREF

THD_{ref} (%)	**Steady state error (%)**	**Settling time (s)**	**Avg. SW freq. (kHz)**	**Total SW loss (W)**
5	0.3	0.12	2.4	33.8
8	0.6	0.15	1.9	25.4

where $v_{ce,n}(t)$ and $i_{ce,n}(t)$ are the collector-emitter voltage and current of the IGBT, respectively. T_s is the fundamental period and n is the number of IGBTs. Also, the average switching frequency of the VSI is measured by the average switching frequency detection tool in the MATLAB/Simulink.

A. Fixed HB control versus Adaptive HB control

Fig. 6 shows the source current THD, total switching loss and switching frequency comparisons between the fixed HB and adaptive HB with fuzzy logic control. The simulation results show that even though the source current with a HB=0.1 has a better performance with THD=3.7%, its average switching frequency is 3.1kHz and the switching loss is higher than that of the adaptive HB control. When the proposed control method is applied, both switching frequency (average: 1.9kHz) and switching loss (reduced by 38%) are released with the desired source current THD (=8%). The corresponding simulation results are summarized in Table III.

B. Adaptive HB with different reference THD_{ref} value

In addition, the simulation results under different THD_{ref} values are shown in Fig. 7. It shows that the proposed controller can track with its THD_{ref} accurately with similar settling time and relatively small steady-state error. The corresponding simulation results are summarized in Table IV. The simulation results prove the accuracy and effectiveness of the proposed fuzzy logic based adaptive source current THD controller for the TC*LC*-HAPF.

V. CONCLUSION

In this paper, a three-phase three-wire TC*LC*-HAPF with fuzzy logic based adaptive source current THD controller is proposed and verified by simulation. The proposed controller can adaptively change the HB according to the reference THD value in order to reduce switching loss, thus reducing the operational cost of the TC*LC*-HAPF system while keeping the system performance within an acceptable reference level.

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