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Balancing and filtering of currents from an unbalanced voltage source using an active filter with the Zero Direct Power command method

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Abstract **–** Balancing the unbalanced currents from the source is important to avoid the risks of overvoltage and damage to the various electrical devices. Non-linear loads absorb currents rich in harmonics, which affect the source current and make it distorted. The risks become more serious when those of the imbalance and those of the harmonics are added. The subject of this conference is the study of a dual-function energy system, which improves the quality of electrical energy by balancing the unbalanced currents from the source and compensating for the undesirable harmonics that distort the signal of the source current, using an active power filter whose command is "Zero Direct Power command (ZDPC)". This method uses a conventional PI controller to regulate the voltage of the DC bus and a highly selective filter to separate the harmonics from the fundamental. By eliminating the undesirable harmonics, the source currents become almost sinusoidal with a harmonic distortion rate close to 1%, an imbalance rate below 1% and the reactive power decreases. This system is simulated using MATLAB/Simulink software. The results prove the robustness and feasibility of the ZDPC command which simultaneously guarantees the compensation of harmonic currents, the correction of the power factor and the balancing of source currents.

Keywords –Active Power Filter, ZDPC, Photovoltaic Array. Fuzzy Logic MPPT Controller, Harmonic.

I. Introduction

No modern environment can escape this pollution originating from equipment such as computers, servers, air conditioners, variable-speed drives, etc. All these loads are called "non-linear." These devices produce harmonic currents that result in reactive power consumption and a degradation of the power factor of the electrical network [1],[2]. The quality of the current and voltage in the network is seriously affected [3]-[6]. The Parallel Active Power Filter (SAPF) injects a current that opposes the harmonic current emitted by the non-linear load to mitigate the effects of harmonic currents and reactive power. Thus, the current supplied by the power source remains sinusoidal. Researchers Noguchi et al. (1998) developed the Direct Power Control (DPC) method based on Direct Torque Control (DTC) for electric machine drives [3],[7]. DPC essentially involved eliminating both the PWM modulator and internal control loops, replacing them with a predetermined switching table [3]. This switching table, based on active and reactive power correction and indicating the sector angle of the source voltage vector position, allows for the selection of converter switching states [8].

Standard DPC requires a zero reactive power reference, while the active power reference is calculated from the output of the DC bus regulator [3],[9]. This article introduces a ZDPC technique, which, unlike the standard implementation, requires zero references for active and reactive power disturbances to reject all disturbances caused by harmonics. That is why we call it ZDPC (Zero Direct Power Command). This article is organized as follows: Section 2 presents the model to study, Section 3 discusses the detailed operating principle of the proposed ZDPC method. In Section 4, simulation results are presented to illustrate the proper behavior of the proposed system. Finally, we conclude our article

II. DESCRIPTION OF THE STUDIED MODEL:

The model depicted in Figure 1 consists of an electrical network supplying a nonlinear load, composed of a PD3 rectifier bridge with the load being a series combination of a resistor and an inductance, a voltage inverter, and a control system.

The control algorithm of the voltage inverter is designed to simultaneously ensure harmonic pollution compensation and reactive power control. To achieve this, real and imaginary powers of the network are calculated, taking into account the sector in which the voltage vector resides and the error values of active and reactive powers. This information is then used to determine the control vector for the inverter, and we will present the details of this process in the following sections.

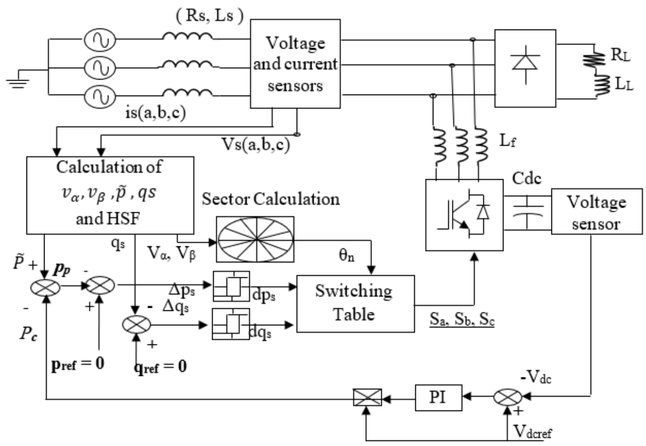

Fig. 1 Studied Model

III. THE PROPOSED ZDPC PRINCIPLE

Fig. 2 shows the structure of the proposed ZDPC. In this control strategy, the active and reactive power disturbance references are set to zero. We note that in this structure the PLL is not necessary [3]. The filter HSF (High Selective Filter) is used to separate the fundamental and harmonic components of the of the line currents and voltages in order to perform power compensation [3], [10].

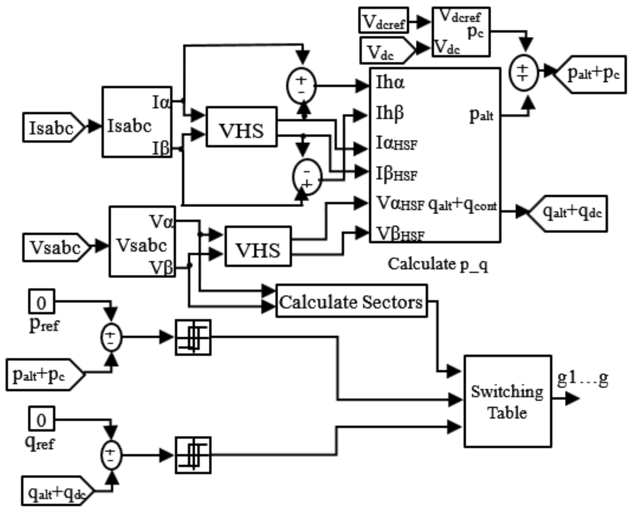

Fig. 2 Synoptic of the ZDPC

A. The transformation from ABC to αβ

The Concordia transform is a mathematical tool used in electrical engineering, particularly in vector control, to model a three-phase system using a two-phase model. It involves a change of reference frame. The two primary axes in the new basis are traditionally named α and β. The transformed quantities typically include currents, voltages, or fluxes.

The Concordia transform is unitary, which means that the powers calculated after transformation remain the same as in the original system. Therefore, the active and reactive powers calculated in the new system have the same values as in the original system.

The Concordia matrix is given by:

$$i_{\alpha\beta 0}(t) = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_a(t) \\ i_b(t) \\ i_c(t) \end{bmatrix} \quad (1)$$

The inverse Concordia matrix is equal to the transpose of the Concordia matrix

$$i_{abc}(t) = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 & \frac{\sqrt{2}}{2} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & \frac{\sqrt{2}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & \frac{\sqrt{2}}{2} \end{bmatrix} \begin{bmatrix} i_\alpha(t) \\ i_\beta(t) \\ i_0(t) \end{bmatrix} \quad (2)$$

B. Highly Selective Filter (HSF)

To improve the performance of the classical instantaneous power method, HSF has been implemented, to extract the fundamental component of current and voltage in the synchronous frame without any phase shift nor amplitude errors. The functional diagram of HSF is shown in Fig. 3 the transfer function can be expressed as follows [11]

$$H(s) = \frac{\hat{x}_{\alpha\beta}(s)}{x_{\alpha\beta}} = k\,\frac{(s+k)+j\omega_c}{(s+k)^2+\omega_c^2} \qquad (3)$$

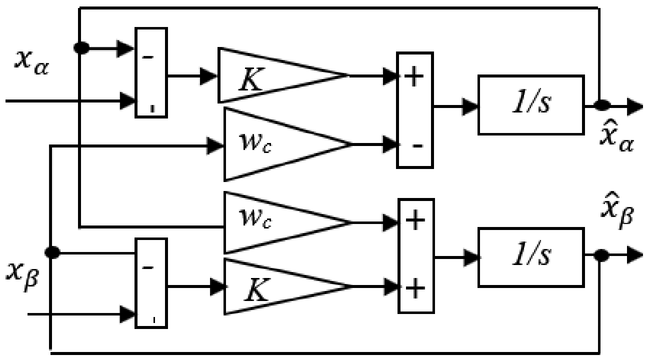

Fig. 3 Block diagram of HSF filter

from the transfer function 3, we obtain

$$\hat{x}_\alpha(s) = \frac{K}{s}[x_\alpha(s) - \hat{x}_\alpha(s)] - \frac{\omega_c}{s}\hat{x}_\beta(s) \qquad (4)$$

$$\hat{x}_\beta(s) = \frac{K}{s}\left[x_\beta(s) - \hat{x}_\beta(s)\right] + \frac{\omega_c}{s}\hat{x}_\alpha(s) \qquad (5)$$

where the quantities $\hat{x}_{\beta\alpha}$ and $x_{\alpha\beta}$ represent respectively the output and the input of the filter. They can be Vαß or Iαß. We note that for the pulsation ω = ωc, the phase shift introduced by the filter is zero and the gain is equal to 1. We also observe that the decrease in the value K improves the selectivity of the HSF.

From the HSF output, the AC component of the instantaneous active power can be obtained [3]

With ihα and ihβ given respectively by the equations (6) and (7)

$$i_{h\alpha} = (i_{\alpha d} - \hat{\imath}_{\alpha d}) + (i_{\alpha inv} - \hat{\imath}_{\alpha inv}) \qquad (6)$$

$$i_{h\beta} = \left(i_{\beta d} - \hat{\imath}_{\beta d}\right) + \left(i_{\beta inv} - \hat{\imath}_{\beta inv}\right) \qquad (7)$$

where the terms ihα and ihß are the harmonic components in the axis αß, whereas the instantaneous reactive power is defined by equation (8):

$$q_s = \hat{v}_\beta \hat{\imath}_\alpha - \hat{v}_\alpha \hat{\imath}_\beta \qquad (8)$$

Fig. 4 shows the calculation of the disturbing powers $\tilde{p}$ and q_s

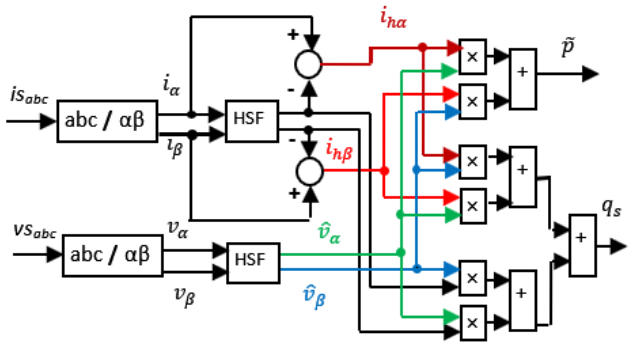

Fig. 4 Computation of vα, vβ, p and qs with HSF

C. Hysteresis controller

The main idea of the ZDPC method is to keep the instantaneous active and reactive power within a desired band. This command is based on two comparators with hysteresis whose input is the error between the reference values and the estimate of the active and reactive power [10], [11], given respectively by equations (9) and (10).

$$\Delta p_s = p_{ref} - p_s. \qquad (9)$$

$$\Delta q_s = q_{ref} - q_s. \qquad (10)$$

The hysteresis comparators are used to provide two logic outputs dps and dqs. State "1" corresponds to an increase in the controlled variable (ps and qs), whereas "0" corresponds to a decrease according to equations (11) and (12)

$$if\ \Delta p_s \geq h_p\ d_{p_s} = 1;\ if\ \Delta p_s \leq -h_p\ d_{p_s} = 0 \ (11)$$

$$if\ \Delta q_s \geq h_q\ d_{q_s} = 1;\ if\ \ \Delta q_s \leq -h_q\ d_{q_s} = 0 \ (12)$$

D. Calculate Sectors

The digitised variable dps, dpq and the position of the network voltage vector (θ), equation (13), from a digital word, allowing access to the address of the switch table to select the appropriate voltage vector.

$$\theta = arctg\left(\frac{v_\beta}{v_\alpha}\right) \qquad (13)$$

For this reason, the stationary coordinates are divided into 12 sectors, as shown in figure 3, and the sectors can be expressed numerically as shown in the equation (14): [3]

$$(n-2).\frac{\pi}{6} \leq \theta_n \leq (n-1).\frac{\pi}{6} \qquad (14)$$

with $n = 1,2, \ldots \ldots ,12.$

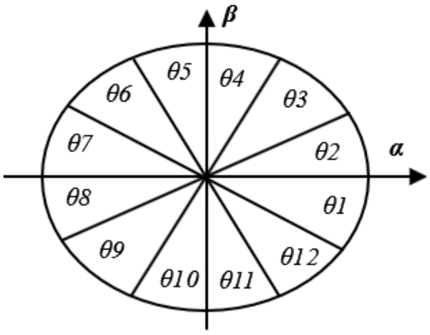

Fig. 5 (α, β) sectors

The digitized signal errors dps, dqs and voltage phase θn are the inputs of the switching table shown in Table 1, whereas the output represents the switching state of the inverter (Sa, Sb, Sc). By using this switching table, the optimal state of the inverter can be uniquely selected during each time interval depending on the combination of the table entries. The selection of the optimal switching state is made so that power errors can be reduced in the hysteresis bands.

Table 1. ZDPZ switching table

dp	dq	θ1	θ2	θ3	θ4	θ5	θ6	θ7	θ8	θ9	θ10	θ11	θ12
1	*0*	v_6	v_7	v_1	v_0	v_2	v_7	v_3	v_0	v_4	v_7	v_5	v_0
	1	v_7	v_7	v_0	v_0	v_7	v_7	v_0	v_0	v_7	v_7	v_0	v_0
0	*0*	v_6	v_1	v_1	v_2	v_2	v_3	v_3	v_4	v_4	v_5	v_5	v_6
	1	v_1	v_2	v_2	v_3	v_3	v_4	v_4	v_5	v_5	v_6	v_6	v_1
v_1(100), v_2(110), v_3(010), v_4(011), v_5(001), v_6(101), v_0(000), v_7(111).													

E. PI Controller

The ZDPC method must ensure DC bus regulation to maintain the capacitor voltage, around the voltage reference (Vdcref). For this porpus, a PI controller is usually used [10],[11]. Fig. 6 shows the controller simulation model.

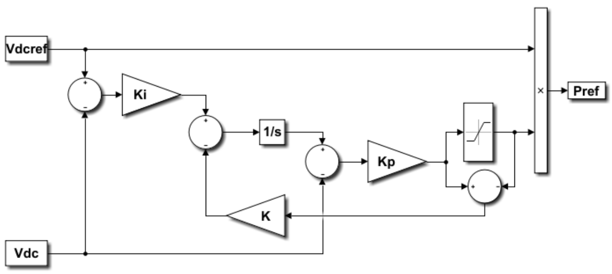

Fig. 6 Simulation model of IP controller

The values of proportional and integral gain, Kp and Ki, are given respectively by the equations (15) and (16)

$$K_i = \frac{\omega_n}{2.\xi} \tag{15}$$

$$K_p = 2.C.\xi.\omega_n \tag{16}$$

With ξ : damping coefficient (ξ=0.707)
ω_n: nominal pulse

F. Generation of control vector

By adding the alternating component ($\tilde{p}$) of the instantaneous active power which is linked to both current and voltage disturbances, to the active power p_c necessary for the regulation of the DC bus, we obtain the disturbing active power p_p which can be expressed by:

$$p_p = \tilde{p} + p_c \tag{17}$$

To compensate for active and reactive power disturbances (pp and qs), a comparison with their zero reference is carried out. The results of the comparison pass through a hysteresis block which generates dps and dqs. Depending on the sector selected (θn) and (dps, dqs), the appropriate command vector (Sa, Sb, Sc) is produced using the commutation table (Table 1).

IV. Simulation Results and Discussion

Various simulations were performed using MATLAB/Simulink Figure 1 to evaluate the proposed approaches. The parameters used for these tests are represented in Table 2.

Table 2. Simulation parameters

Parameters	Values with dimensions
Vs, Fs	100 V, 50 Hz
F switching (DC/AC APF converter)	20 KHz
Ls, Rs	0.1 mH, 0.1 Ω
Ll, Rl	0.566 mH, 0.01 Ω
Lf, Rf, Cdc	2.5 mH, 0.01Ω, 2200µF
L, R	10 mH, 40 Ω
DC bus voltage reference (Vcref)	282 V

The SAPF simulation results controlled by the ZDPC, equipped with conventional PI and fuzzy MPPT, operating under a balanced network, are shown in the following figs. Fig. 7 shows all simulated cases together during time (0 – 0.65).

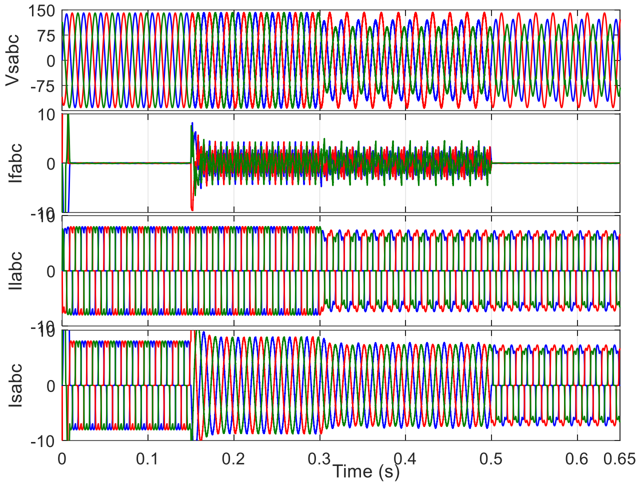

Fig. 7 Simulation signals in the different cases

A. 1^{st} case: the voltage source is balanced in the absence of the active filter

Fig. 8 zooms the signals in the time interval (0.1 – 0.12) where the filter is not activated and in balanced voltage source, in this case we notice the load current and the source current are identical with a THDi =27.72%.

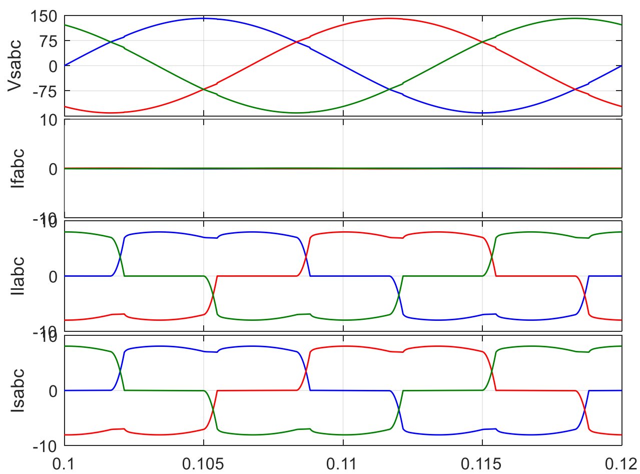

Fig. 8 Simulation signals in voltage source is balanced and in the absence of the APF

B. 2^{end} case: the voltage source is balanced with activation of the APF (0.15-0.3)

Fig. 9 represents the simulation signals during the time (0.2-0.22), we notice the source current signal has resumed its sinusoidal form with a THDi=0.91%.

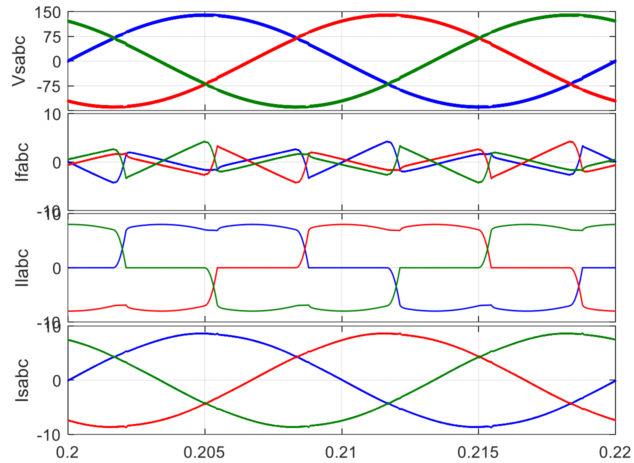

Fig. 9 Simulation signals in voltage source is balanced with activation of the APF

C. 3^{rd} case: the voltage source is unbalanced with activation of the APF (0.3-0.5)

Fig. 10 represents the simulation signals during the time (0.4-0.42), the voltage source is unbalanced with an unbalance rate Tunb = 35%, the filter played its role in compensating the harmonics and makes the source current sinusoidal with a THD = 1.69% with an unbalance rate (Tunb) = 0.48%

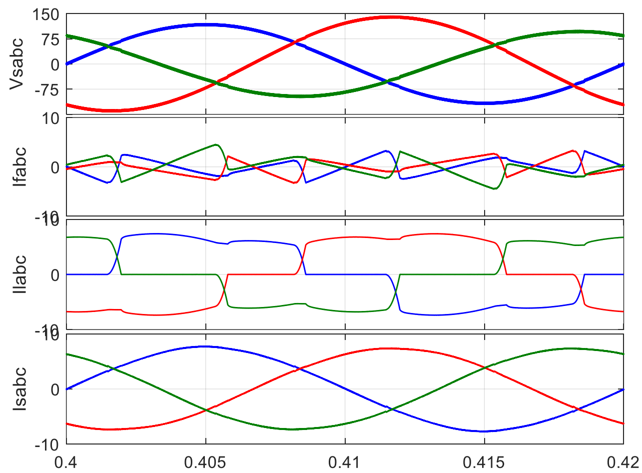

Fig. 10 Simulation signals in voltage source is unbalanced with activation of the APF

D. 4^{th} case: the voltage source is unbalanced with deactivation of the APF (0.5-0.65)

Fig. 11 represents the simulation signals during the time (0.6-0.62), the voltage source is unbalanced with an unbalance rate Tunb = 35%, the APF is deactivated, We notice the source current is distorted with a THD= 25.06% and an unbalance rate Tunb=8.57%.

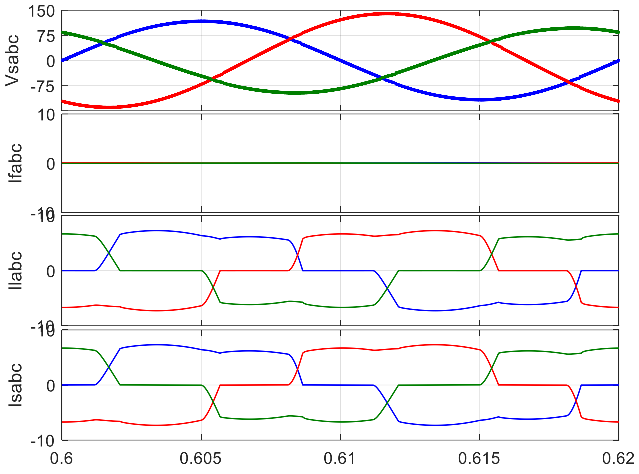

Fig. 11 Simulation signals in voltage source is unbalanced with deactivation of the APF

The different values of THD and unbalance rates in the four cases are presented in the following table

Table 3. Summary of different cases

		1st case Balanced voltage Without APF		
Vsabc	**Value**	140.8	140.8	140.8
	THDv	0.51%		
	Tunb	0		
Isabc	**value**	8.046	8.046	8.046
	THDi	27.72%		
	Tunb	0		
		2end case Unbalanced voltage with APF activated		
Vsabc	**value**	142.2	142.2	142.1
	THDv	2.15%		
	Tunb	0		
Isabc	**value**	8.625	8.683	8.694
	THDi	0.91%		
	Tunb	0.8%		
		3rd case Unbalanced voltage with APF activated		
Vsabc	**value**	120	142.4	99.82
	THDv	2.68%		
	Tunb	35%		
Isabc	**value**	7.733	7.419	7.383
	THDi	1.69%		
	Tunb	0.48%		
		4th case Unbalanced voltage Without APF		
Vsabc	**value**	120	142.4	99.82
	THDv	2.68%		
	Tunb	35%		
Isabc	**value**	7.322	7.321	6.712
	THDi	25.06%		
	Tunb	8.57%		

V. CONCLUSION

In this paper, the modified DPC (ZDPC) technique was proposed to ensure the compensation of harmonics, reactive power and source current balance. HSF filters are used to separate harmonic currents and voltages causing degradation of network power quality. The simulation shows the good performance of the proposed approach by reducing the THD and the Tunb.

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