Hybrid Active Power Filter with GaN Power Stage for 5kW Single Phase Inverter

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***Abstract*—This paper presents a hybrid active power filter (APF) with DrGaNplus module for a 5kW single phase inverter. Considering the low voltage stress on the devices in hybrid APF, a module integrated with gate driver is selected to achieve high power density and high efficiency for the overall system. An effective control is proposed to keep the APF capacitor from depleting, while at the same time managing the energy ripple to keep the DC link voltage ripple low. A hardware prototype of a 5 kW single phase inverter with a 400 VA hybrid APF has been demonstrated in the lab. Simulation and experimental results have been provided to verify the feasibility of the proposed hybrid APF.**

Keywords—hybrid; Active Power Filter; GaN

I. Introduction

Double-line frequency power pulsation propagates from the AC side to the DC side in single-phase power converters. This ripple energy must be stored and released to/from an energy buffer: either a bulky dc capacitor or an extra active power filter (APF) so that DC bus can be kept with a small voltage ripple, which is very important for certain applications such as photovoltaic (PV) inverters, critical dc load, etc [1]. Compared with bulky dc capacitor, an APF uses smaller dc capacitors and can reduce the overall system. Four typical APFs including shunt boost type, shunt buck type, series type and hybrid type have been proposed [2]-[5]. Among them, the hybrid APF is a good option due to its low voltage stress on devices [5]. Moreover, it provides a good opportunity to use low voltage GaN devices to improve the system power density. This paper applies DrGaN^{PLUS} modules with integrated gate driver from EPC for the hybrid APF, which helps to reduce the electromagnetic interference (EMI) issues and enhances design flexibility.

In addition, a new control strategy has been developed to control the dc voltage of the H-bridge converter in the hybrid APF and manage the ripple energy to flow through the hybrid APF. The functionality of the hybrid APF has been verified and a 5kW single-phase inverter with 400VA hybrid APF has been demonstrated. The system power loss without power filter, with hybrid APF, and with traditional bulky capacitors have been compared in this paper.

II. System Design

A. System description

In this paper, the hybrid APF is connected to a 5kW single-phase inverter with 400Vdc and 240Vac as shown Fig. 1. The hybrid APF is composed of an auxiliary capacitor "C_{aux}" and a compensating power converter, where an H-bridge converter is

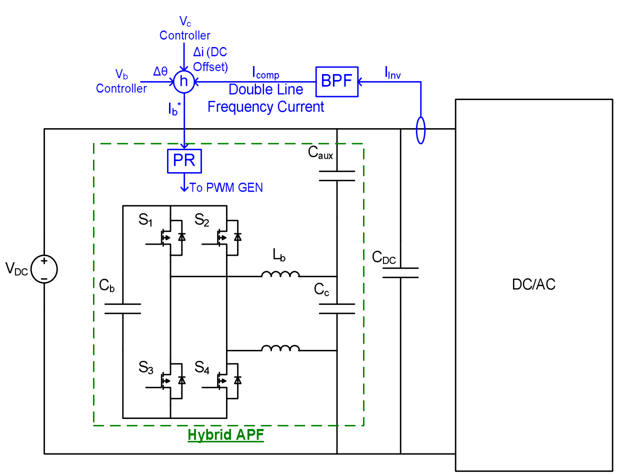
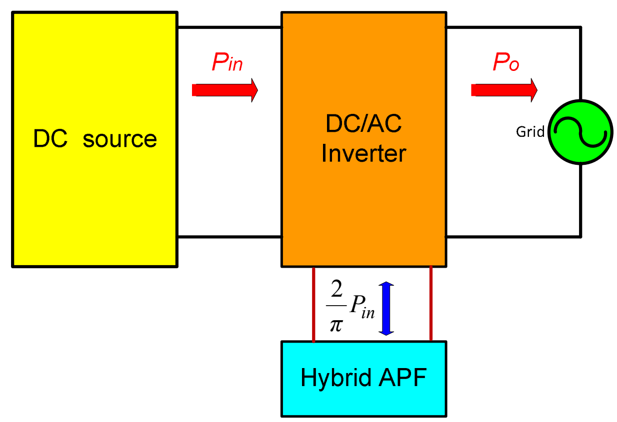
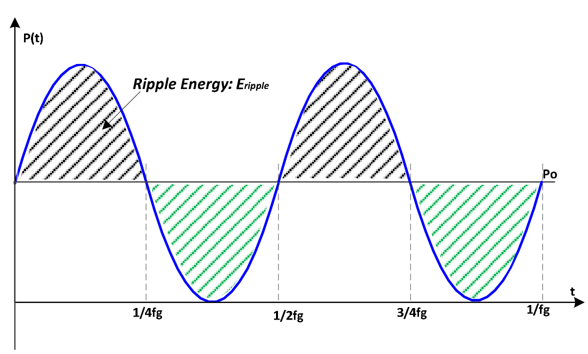


Fig. 1 Hybrid APF System structure with control diagram



a) Power flow



Output power

Fig. 2 Power conversion with hybrid APF

used due to small power rating requirement. The auxiliary

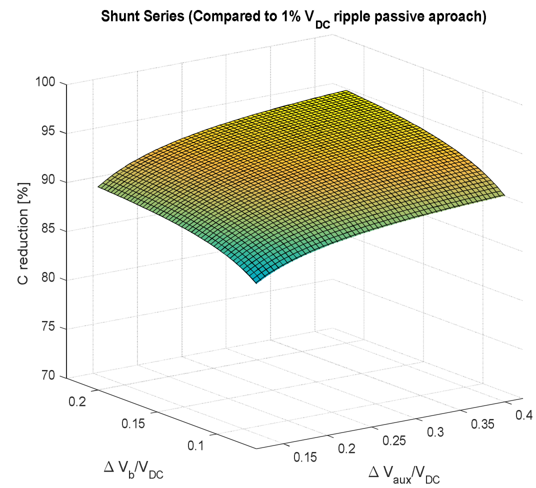


Fig. 3 DC capacitance vs. voltage ripple

capacitor provides most of ripple energy, and the compensating power converter follows the double-line frequency current ripple requirement and generates the rest of ripple energy. As a result, the voltage stress on the devices in hybrid APF can be quite small, which is less than 20% of DC voltage "V_{DC}" on "C_{DC}". Here, the small C_{DC} is only used to filter switching transients. In addition, one expects to operate the APF at higher switching frequency to improve system power density. Considering the voltage rating, fast switching capability, low power loss and simplified layout design, GaN devices with low voltage are good option to be used in the hybrid APF. The inductor "L_b" is designed based on higher switching frequency, such as 250 kHz. Therefore, a planar design is viable for this inductor, which also helps to reduce the overall system cost.

As mentioned before, the selection of "C_{aux}" is related to the ripple energy. The power flow is shown in Fig. 2 , where only unit power factor is considered in this paper. If reactive power is generated from the inverter, the decoupling power should be $\frac{2}{\pi}\frac{P_{in}}{cos\theta}$, where θ is the phase angle between grid current and voltage. The ripple energy is delivered from hybrid APF and stored in the hybrid APF in each half grid cycle. Therefore, it can be derived as:

$$E_{ripple} = \int_{0}^{\frac{.5}{2f_g}} P_0 sin(2\omega t) \qquad (1)$$

where P_0 is output power, f_g is grid frequency. For example, when $P_0 = 5kW$ and $f_g = 50Hz$, then $E_{ripple} \approx 16J$.

The ripple energy can also be written as:

$$E_{ripple} = \frac{1}{2} C_{aux}\left(V_{DC\_max}^2 - V_{DC\_min}^2\right) \qquad (2)$$

where V_{DC_max} and V_{DC_min} are the maximum and minimum of the dc voltage on capacitor C_{aux} .

Therefore, the auxiliary capacitor value can be calculated as:

$$C_{aux} = \frac{E_{ripple}}{V_{DC}\Delta V_{aux}} \qquad (3)$$

where if DC voltage $V_{DC} = 400V$, maximum peak-peak ripple voltage $\Delta V_{aux} = 100V$ and $E_{ripple} \approx 16J$, then $C_{aux} = 400uF$.

To better understand DC capacitor selection, DC capacitance reduction in the hybrid APF is compared with the bulky capacitor in the passive approach. For example, the dc voltage ripple on C_{DC} is within 1% of V_{DC} .The percentage of total main DC capacitance reduction (z-axis), dc side voltage variation ΔV_b on "C_b" in the H-bridge converter (x-axis), and voltage variation ΔV_{aux} on "C_{aux}" (y-axis) are shown in Fig. 3. The main DC capacitance includes the capacitance of "C_{aux}" with main dc voltage and the capacitance of "C_b" with low dc voltage (for example, 12.5% of the main dc voltage in this paper). Due to the low voltage, the capacitor size of C_b is much smaller than one of C_{aux}. It is obvious that the main DC capacitance reduction is increased with the allowed the voltage variation ΔV_{aux} and ΔV_b. Therefore, the total capacitance in the hybrid APF is much smaller than in the bulky capacitor.

B. *Control system design*

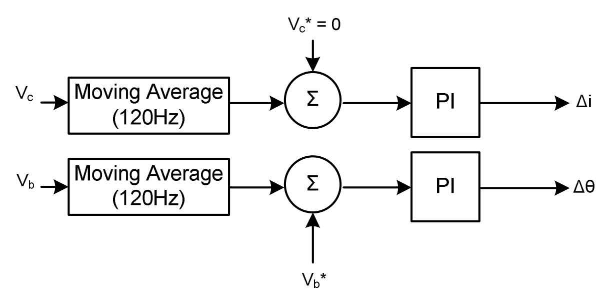


Fig. 4 V_b and V_c compensation controllers

As shown in Fig. 4 , APF is controlled to provide the required ripple energy. With the inner proportional-resonant (PR) control loop, the APF behaves like a current source to follow I_{comp} and provides the required ripple current. The reference to this controller is composed of the filtered the inverter input current, and the control output of the dc side and ac side voltage "V_b" and "V_c" of H-bridge converter in the hybrid APF. The two outer controllers of "V_b" and "V_c are shown in Fig. 4 . Ideally the average power supplied by the APF and the compensating power converter is zero, so the average value of the voltage "V_b" should remain constant. In reality, the losses in the system will cause the capacitor voltage drop if there is no real power compensation. Furthermore, if the average voltage value "V_{DC}" changes during operation, a voltage offset will build up in V_C. Therefore, the above two controllers are developed to keep these two voltages from fluctuating to undesirable values, where each controller impacts the reference current in a different way. In addition, the current "I_{inv}" of dc bus close to the main single-phase DC/AC inverter is measured. A band pass filter (BPF) removes any high frequency components and the average DC offset to extract the double line frequency current for the control system. Consequently, the compensated current reference can be obtained as follows:

$$i_b^*(t) = I_{comp}(2\omega_{line}t + \Delta\theta) + \Delta i \qquad (4)$$

where I_{comp} is the double line frequency current magnitude in the dc current of main inverter, ω_{line} is the line frequency,

$\Delta\theta$ is the phase-angle compensation for the compensating power converter output current, Δi is the dc offset of output current of the compensating power converter.

Compared with the control scheme presented in [5], this strategy uses a phase shift of the double line reference current to control V_b. The proposed control strategy is capable to achieve more power transfer, therefore reduce the V_{DC} ripple due to a mismatch from the double line current reference.

III. Simulation Results

Simulation results are provided to verify the proposed approach in a 5kW single phase inverter: grid voltage is $V_g = 240\ V\ (RMS)$, $V_{dc} = 400V$, high switching frequency for GaN module is set at $f_{sw} = 250kHz$. Table 1 shows other main components for the hybrid APF simulation and following experiments. In this simulation, the proposed approach is tested at light load and full load. It can be seen from Fig. 5 that the proposed approach offers good dynamic performance when the inverter output power changes from 5kW to 2.5kW. The variation range of V_{aux} is from 350V to 450V at 5kW power output. The "V_b" of H-bridge converter in the hybrid APF is controlled in around 50V. The variation range of V_{DC} is very small due to the compensating voltage V_C from APF, only from 395V to 405V at 5kW power output. The power of APF drops from 400 VA to 70VA when load changes from 5kW to 2.5kW, which is the double-line ripple power required by grid.

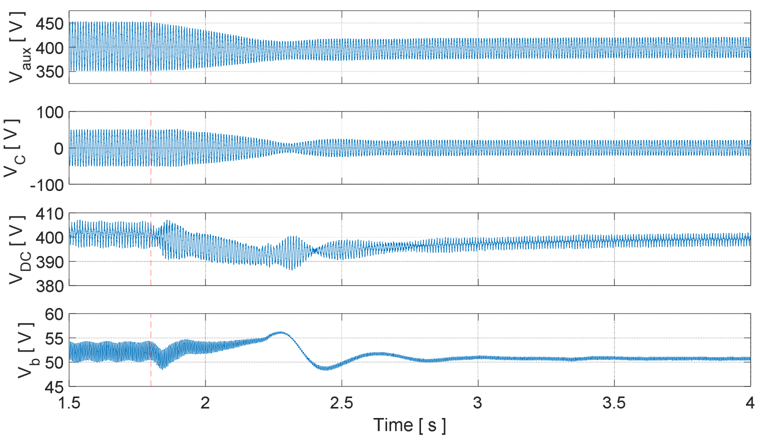
IV. Prototype and Experiments

A hardware prototype of hybrid APF has been designed to provide enough ripple energy for a 5 kW single-phase inverter in Fig. 6 and Fig. 7 .

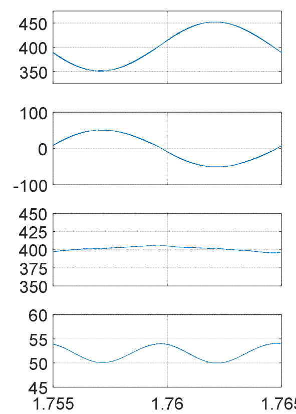
A. Component selection

1) Auxiliary Capacitors

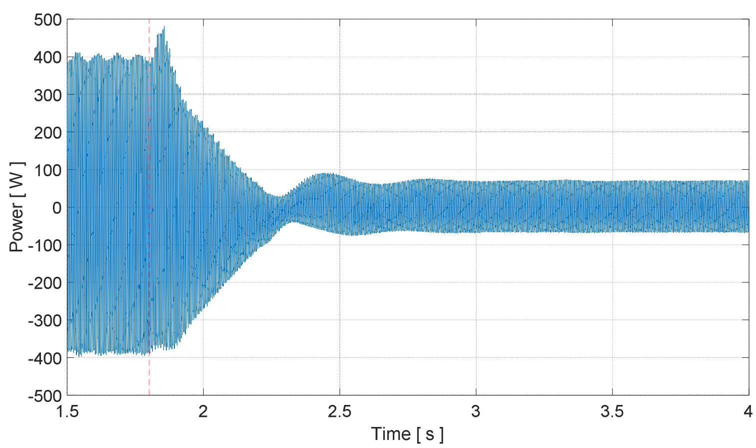
The capacitance of C_{aux} has been calculated in (3), listed in Table 1, and verified in the simulation. It is crucial that the operation hours of the capacitor are designed properly to last the life of the inverter, which for our example is around 20 years.



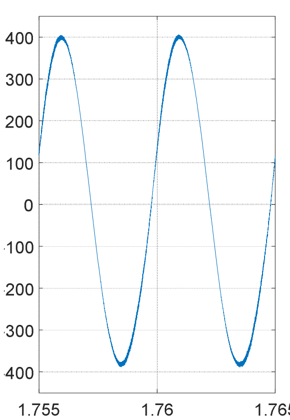
Voltage change: V_b , V_c, Vc_{aux}, V_{DC}



Zoomed waveforms



APF output power change



Zoomed waveforms

Fig. 5 Dynamic performance of APF – simulation results

Table 1 Main Components List		
Component	Value / Quantity	Part Number
Half-Bridge GaN Module	80 V, 20 A x 2	EPC9203
C_{DC}	470 µF x 2	B43601A5477M
C_{AUX}	470 µF x 4	B43601A5477M
C_b	1000 µF x 3	EKZN800ELL102MLP1S
C_c	2.2 µF x 2	C5750X6S2W225K250KA
L_b	~ 5 µH x 2	Planar Inductor Core : EILP22

For example, it is expected that the operation is only 12 hours a day in PV inverter. According to (5), the capacitor should be able to operate 90,000 hours.

$$20\ [years] * 366 \left[\frac{days}{year}\right] * 12 \left[\frac{hours}{day}\right] = 87840\ [hour]s \approx \mathbf{90,000}\ [\boldsymbol{hours}] \tag{5}$$

The load profile of a typical single-phase inverter was used to estimate the load on the capacitor ripple current and the frequency of each ripple term. With this information, it is possible to select a capacitor bank of four EPCOS TDK B43547 series with 450 V, 470 uF, and 8000 h. The bank is arranged in two parallel branches of two series capacitor for a total capacitance of 470 uF. The dimensions of each capacitor is 30 mm radius and 50 mm height, for a total area of 36 cm^2.

2) DC "bulk" Capacitor

The purpose of this DC bulk capacitor C_{DC} is to sink and source any ripple current that is not match by the hybrid APF. It is obtained from the simulation that one needs at least 200 uF to keep the DC link voltage ripple below 3%. Similarly to the auxiliary capacitor bank, a bank of two EPCOS TDK B43547 series with 450 V, 470 uF, and 8000h is used in the prototype. The total capacitance is 235 uF. The total area of the bank is 18 cm^2.

3) Buffer Capacitor

The value of buffer capacitor C_b depends on how effective the controller can keep the capacitor average voltage constant. Based on the calculation and simulations, capacitor with over 2.2 mF can meet the full load requirement. To keep a margin for a slower controller, a capacitor bank with three United ChemiCon KZN series with 80 V, 1 mF, 10000h is used in the prototype. The total capacitance is 3 mF. A single capacitor dimension is 16 mm of radius and 37 mm of height, for a total area of 7.68 cm^2.

4) H-Bridge Split Planar Inductors

The GaN module in the hybrid APF is designed to operate from 200 kHz to 500 kHz. In order to keep the inductor ripple current to less than 1 A, one needs 4.94 uH on each of the split inductor as shown in . The power transfer for each inductor is design to be 400W with a saturation current of 15 A. Planar inductors is designed due to the lower price point. The design inductors are to have 4 turns (1 turn per layer), with a planar E18 core and I18 core from Mag-Inc. The air gap required is 0.43 mm to realize this airgap we are utilizing electric tape.

5) Semiconductors

GaN device is a good option in the hybrid APF due to their fast switching capability and low loss. However, to fully utilize its benefits, it requires proper gate driver, power supply, optimized layout design, etc. Otherwise, it may degrade the reliability of the hybrid APF. To alleviate the above concern, DrGaNPLUS module from EPC was used in the results of this paper. This module is a half-bridge "plug and play" evaluation board with 80V/20A, which is integrated directly into the APF board. Each module consist of two EPC2021 GaN FETs with a TI's LM5113 driver. It is easy to optimize the high frequency power commutation loop inductances due to using the two GaN modules.

6) Capacitor volume and cost comparison

Aside from the devices, the passive components of the hybrid APF can be compared with the passive filter approach in terms of price and volume. For 5kW single phase inverter, the passive filter approach needs about 3mF capacitor to limit the dc bus ripple with 3%. Table 2 shows a comparison of the required capacitors and the total size as compared to the passive filter approach. The passive filter approach needs eighteen big capacitors but the hybrid APF only requires six of the same capacitors where two capacitors for $C_{DC}$are only used as extra compensation of the hybrid APF. When considering the capacitors only, the hybrid APF has significant size and cost reduction compared to the passive approach.

Table 2 Volume and Distributor Price Comparison		
	Volume [cm^3]	
	Hybrid APF	Passive Approach
C_b	28.42	0
C_{DC}	134.75	1080.00
C_{aux}	198.00	0
Total	361.17	1080.00
Size	**33.4%**	**100%**
	Price ($)	
	Hybrid	Passive
C_b	2.53	0
C_{DC}	17.48	157.32
C_{aux}	34.96	0
Total	**54.97**	**157.32**

B. Experimental Results

A hybrid APF prototype with 400VA is developed to handle the ripple energy in 5kW single phase inverter shown in Fig. 6 . Experimental results have been obtained from the hardware prototype in Fig. 7. The functionality of the H-bridge converter has also been verified where a closed loop current control that follows the double line frequency current measurement has been implemented as shown in Fig. 8 . When there is only active power output from 5kW single phase inverter. The ripple current with double-line frequency is in phase with the inverter output current with grid frequency. The power loss of 5kW single-phase inverter is compared as follows:

Fig. 6 Proposed 400VA APF prototype

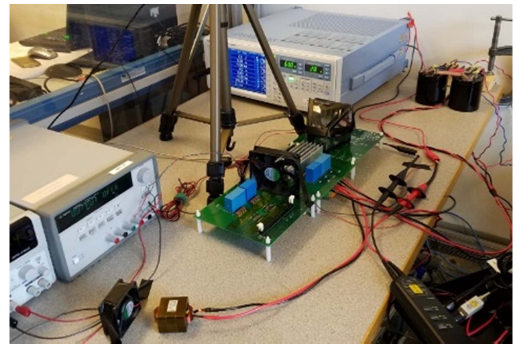
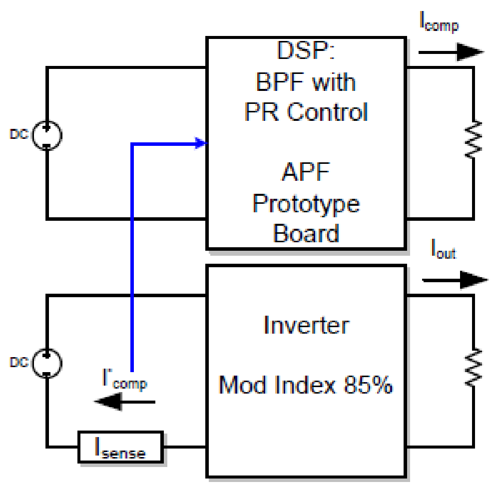
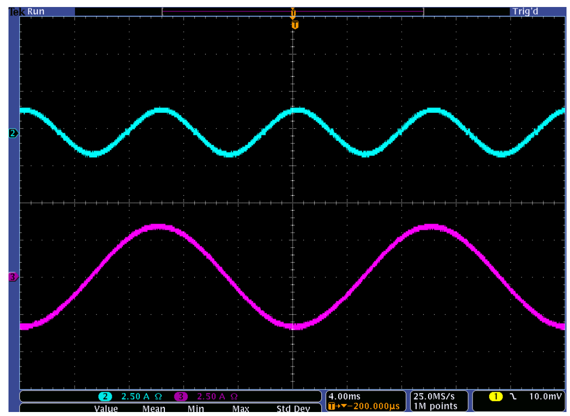


Fig. 7 Experimental setup of 5kW single-phase inverter



(a)



(b)

Fig. 8 (a) APF Functionality Test Bench schematic, (b) Inverter output current (purple), input double line frequency current (blue)

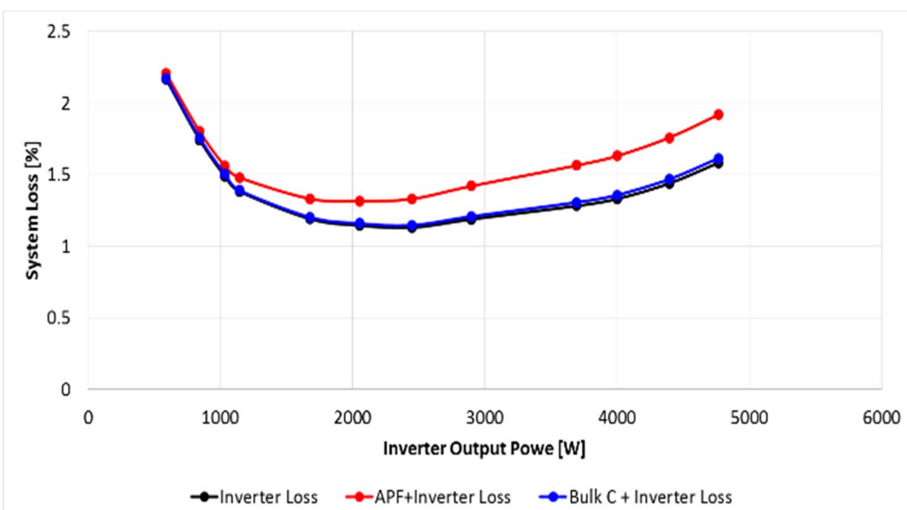


Fig. 9 Power loss comparison of 5kW single-phase inverter

without considering DC power filter loss, with the hybrid APF, and with bulky capacitors (three times or higher as one in the hybrid APF) as shown Fig. 9. It can be seen that the maximum loss penalty with APF is 0.3% comparing with one with bulky capacitors. However, the whole system with APF will save more space and cost than one with bulk capacitors.

V. CONCLUSIONS

In this paper, a 400 VA GaN based hybrid APF for a 5 kW single-phase inverter has been developed and demonstrated. A new control system has been proposed to improve the performance of the hybrid APF. The dynamic performance of APF has been verified in simulation. Experimental results validated the effectiveness of the functionality of the hybrid APF.

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