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SiC MOSFET and IGBT Hybrid Shunt Active Filter and its Application on a 10 KVA Harmonic Load System

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ABSTRACT

This paper introduces a energy efficient, cost effective hybrid shunt active filter (SAF) concept and it application on a 10 kVA harmonic load system, with current harmonic rejection capability compared to IGBT based SAF solutions. Normally, IGBT based Shunt Active Filter designs face difficulty in higher order harmonics mitigations due to restricted switching frequency of operation (typically limited to 10 kHz). In this paper, a hybrid shunt active filter (HSAF) solution is introduced where one IGBT based inverter removes lower order harmonics (5th and 7th) and a SiC MOSFET based inverter removes the other higher order harmonics (11th, 13th…). The IGBT is rated for 90% of the total load kVA rating but is switched at 5 kHz switching frequency. On the other hand, SiC MOSFET based inverter is rated for a small percentage of total kVA load but is switched at 30 kHz to remove the higher order harmonics more effectively. The introduced concept is verified by simulation results.

KEYWORDS: *Shunt Active Filter (SAF), IGBT, SiC MOSFET, Hybrid Shunt Active Filter (HSAF)*

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I. INTRODUCTION

Advanced IGBT SAFs are incorporated in factories/industries to overcome the current harmonics arise from non-linear loads (Refer Fig.1). Normally lower order harmonics (5th and 7th) contributes to the larger percentage of the harmonic current of these loads. However, the higher order harmonics are less in magnitude in percentage share, their existence is not prudent. So according to IEEE 519 grid code the bandwidth of the current controller of SAF is clocked at a very high frequency to remove higher order harmonics. Larger bandwidth of the current controller can be obtained if the switching frequency of the SAF is high. However, IGBT cannot be clocked at very high frequency because of high switching loss. Attaining 20 kHz for a 100 kVA IGBT based converter is challenging.

Lately proposed SiC MOSFET is a device which can be clocked easily beyond 30-40 kHz. At present, to obtain a 100 kVA SAF using SiC MOSFET modules are not at all cost effective, however they can overcome the current harmonics more effectively and efficiently. In this paper a hybrid SAF solution is introduced where a SiC MOSFET based SAF of small kVA rating operates in integration with IGBT based SAF. The IGBT SAF is designed to remove only the 5th and 7th harmonic components of the total load. A 10 kVA non-linear load with diode bridge rectifier is simulated where the IGBT based SAF contributes to almost 90%. Henceforth kVA rating of the IGBT based SAF is also around 9 kVA. Anyhow the requirement of the current controller bandwidth for these harmonics is low which allows to bring down the switching frequency of operation to 5 kHz. This improves the efficiency of the converter. A small SiC MOSFET based SAF (around 20 kVA) switching at 30 kHz removes the higher order harmonics near to 47th and 49th efficiently. Due to this, the loss of the system is much less in comparison to an IGBT based SAF. The increase in the cost of the system because of SiC MOSFET based SAF can be supported by energy savings in run time.

II. AN OVERVIEW OF THE INTRODUCED CONCEPT

A. Power Architecture of Introduced Concept

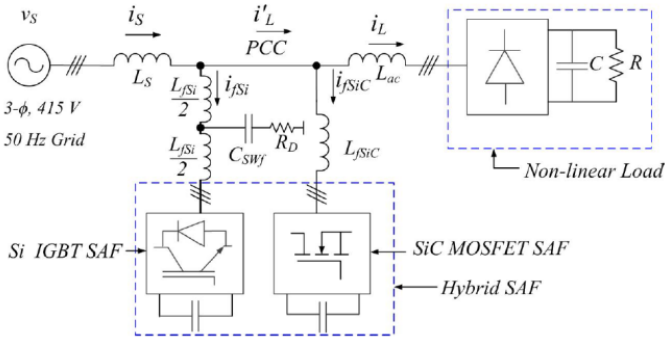

Fig. 1: Power Line Diagram of the introduced HSAF

TABLE I: System Specification

Parameters	Design Values	Specification
L_s	110 µH	2% of phase voltage drop (240V)
Lf_{Si}	110 µH	2% of phase voltage drop
Lf_{SiC}	30 µH	0.66% of phase voltage drop
L_{ac}	90 µH	2% of phase voltage drop
C_{swf}	1mF	$f_{res}= \frac{1}{2\pi\sqrt{Leq\ Csw_f}}$ where,
$R\ D$	0.02Ω	$f_{res}\approx$ 700 Hz, where $Leq = \frac{L_{fSi}}{2}$

The Power line diagram is of the introduced concept is depicted in Fig. 1. An IGBT based SAF and a SiC MOSFET based SAF is connected in parallel with the grid. The filter inductors of the SiC MOSFET based SAF and IGBT based SAF are *Lf SiC* and *Lf Si* respectively. The combination of filter inductors in parallel with the grid brings down the combined grid inductance as seen from the load. Thus, an inductor (*Lac* ≈ 2% of the phase voltage drop) is connected in series with the load. The currents are denoted by *i'L* for IGBT SAF and by *iL*. The filter currents of SiC MOSFET and IGBT based SAF are *if SiC* (remove all harmonics except 5th and 7th) and *if Si* (remove 5th and 7th harmonics) respectively and makes the source current (*is*) purely sinusoidal. A series of 5 kHz ripples are injected into the grid by IGBT SAF which increases the Total Harmonic Distortion (THD) of the grid by a huge amount. The 5 kHz ripple tries to be compensated by SiC MOSFET SAF to some extent as the bandwidth of the controller is high enough to compensate the 5 kHz ripple. Anyhow resulting in increase in kVA rating of SiC based SAF which again adds up the cost and therefore not advisable. So, an LCL filter is added in series with the IGBT based SAF to reduce the 5 kHz switching frequency ripples effectively. A damping resistor *RD* is connected in series with the capacitor *C swf* of LCL filter to damp any sustained oscillations.

B. Control Architecture of Introduced Concept

The control of IGBT based SAF employs 3 PI controllers for controlling *vdc_Si*, *if Si 1d* and if *if Si 1q* respectively. As a result, dc bus voltage can be regulated by controlling active and reactive power can also be controlled. In addition to this, the elimination of 5th harmonic component from the grid current requires 2 PI controllers for controlling *if Si 5d* and *if Si 5q* respectively. Similarly, the elimination of 7th harmonic component from the grid current requires 2 PI controllers for controlling *if Si 7d* and *if Si 7q* respectively.

In SiC MOSFET based SAF, 3 PI controllers are employed for controlling *vdc_SiC*, *if SiC d* and if *if SiC q* respectively. Thus, active and reactive power can be controlled, and higher-order harmonics can be compensated simultaneously. The PI controllers used in vector control are provided with output limiters. Output limiters ensure that the currents and voltages of the both the SAFs are always within rated limits. The control parameters for IGBT based SAF are summarized in Table II. The control parameter design is done considering phase margin = 60 degrees. Thus, the ζ value obtained is 0.57. Similarly, the control parameters for SiC MOSFET based SAF are summarized in Table III.

TABLE II: Control Parameters for IGBT based SAF

Parameters	Values
Damping Ratio (ζ)	0.57
LPF (Reference For 5thHarmonic) Bandwidth	1 Hz
LPF (Reference For 7thHarmonic) Bandwidth	0.1 Hz
LPF (Reference For 5thand 7thHarmonic) Bandwidth (we)	188.4 rad/sec
Natural Frequency (wn)	165 rad/sec
Closed-loop Bandwidth of Current Controller	42.5 Hz
Phase Margin	60 deg

TABLE III: Control Parameters for SiC MOSFET based SAF

Current Controller Bandwidth	Simulation Model
f_{ccSiC}	3 kHz
HPF (Reference for higher-order harmonic) Bandwidth	10 kHz

The switching frequency (*fsw*) of IGBT based SAF is taken to be 5 kHz and for SiC MOSFET based SAF is taken to be 30 kHz.

In order to transform 3-phase AC voltages and the currents to the reference frame which rotates at synchronous speed, position details of the utility grid voltage at any time instant is required.

TABLE IV: Harmonic Discussion (in %)

Concept	*fsw*	THD	5th	7th	11th	13th
Without SAF	-	75.27	62.94	39.28	8.08	6.81
IGBT SAF	10 kHz	15.74	11.85	5.39	4.56	2.58
IGBT SAF	15 kHz	8.6	5.02	1.93	3.62	1.92
IGBT SAF & SiC MOSFET SAF	05 kHz 30 kHz	3.5	0.34	0.23	0.43	0.35

TABLE V: Loss Discussion (in kW)

Concept	f_{sw}	P_{sw}	P_{con}	P_t	η%
IGBT SAF	10 kHz	0.96	0.44	1.4	98.34
IGBT SAF	15 kHz	1.48	0.48	1.96	97.7
IGBT SAF & SiC MOSFET SAF	05 kHz 30 kHz	0.590 0.016	0.645 0.120	- -	- -
TOTAL LOSSES	-	0.606	0.765	1.371	98.38

III. SIMULATION RESULTS

The source current without harmonic compensation, having a THD of 75.27% (shown in Table IV), is presented in Fig. 2.1. The combination of the HSAF has considerably brought down the THD to 3.5% (see Table IV) and made the source current sinusoidal (see Fig. 2.2). IGBT SAF removes the 5th and 7th harmonics which is the main element of load current (see Fig. 2.4). So, IGBT SAF needs 90% of the total kVA load rating. It is inferred from Fig. 2.6 that SiC MOSFET SAF removes the least important higher order harmonics. Therefore, the kVA necessary for SiC MOSFET SAF is 15% of total kVA load rating. The DC bus voltage controller is integrated with both the SAFs to maintain the DC bus voltage at 800 V.

A. Discussion on Harmonic and Power Loss

The harmonic performance of the 100 kVA system removal and after removal by a normal IGBT SAF is given in Table IV. The conduction and switching losses of IGBT are calculated using a 1200 V, 150 A device (Part No: SKM150GB12T4 at *Tj* =125°C, *Vdc* = 800V, *VGE* = 15V, *RG* = 1Ω). Likewise, the loss calculation for SiC MOSFET is done on a 1200V, 24A device (Part No: C2M0080120D at *Tj* =125°C, *Vdc* = 800V, *VGE* = -5/20V, *RG* = 2.5Ω). It is found from Table II that, the increase in switching frequency from 10kHz to 15kHz improves the THD of IGBT SAF from 15.74% to 8.6%. Anyhow, when the switching frequency goes up, the total loss also goes up from 1.4kW to 1.96kW (see Table III). On the other hand, the combination of introduced HSAF (IGBT SAF + SiC SAF) further increases the harmonic performance of the system with an overall THD of 3.94%. Adding to the increased harmonic performance, the total loss is considerably reduced to 1.371kW in reference to the original architecture (see Table V). So, the introduced architecture leads to an improvised efficiency (assuming only conduction loss and switching loss of power switches) of the overall system from 97.7% to 98.38% which adds to the effective usage of energy an3d saving money.

Simulation Results

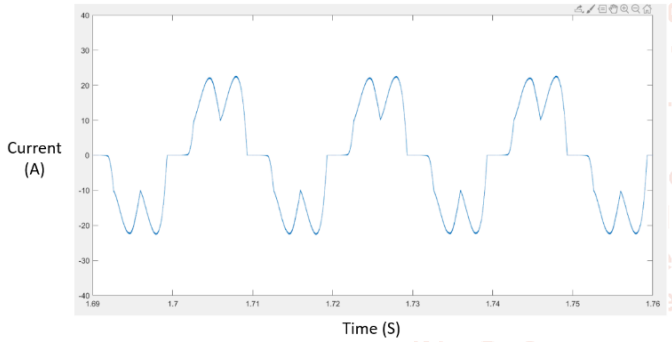

Fig. 2.1: Current without Filter

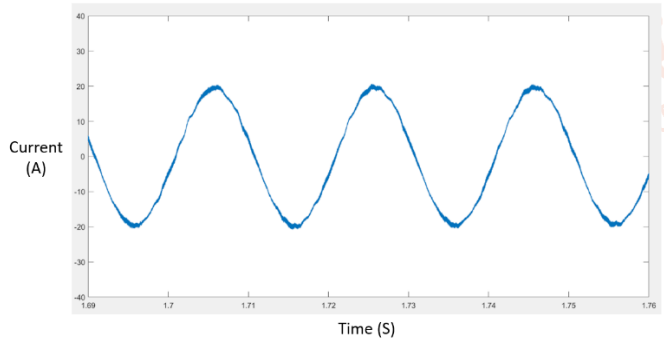

Fig. 2.2: Current with Filter

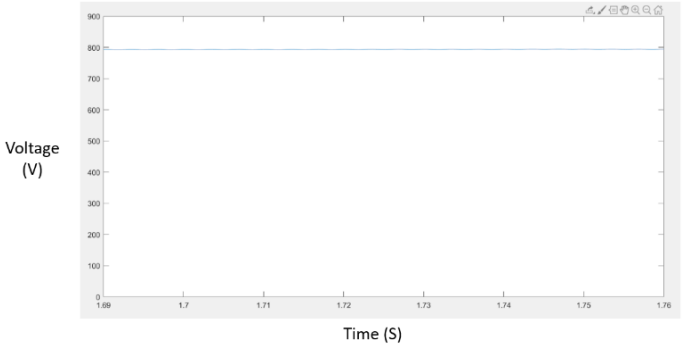

Fig. 2.3: Si Inverter DC Bus Voltage

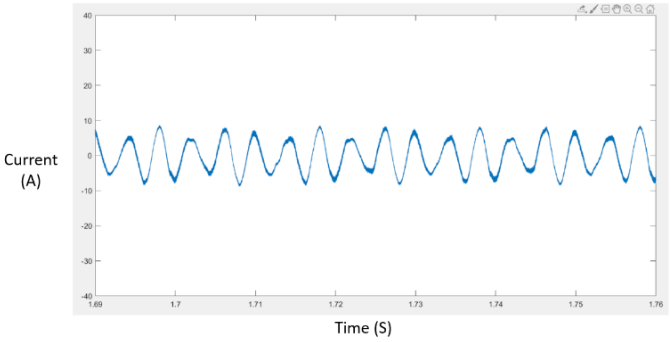

Fig. 2.4: Si Inverter filter Current

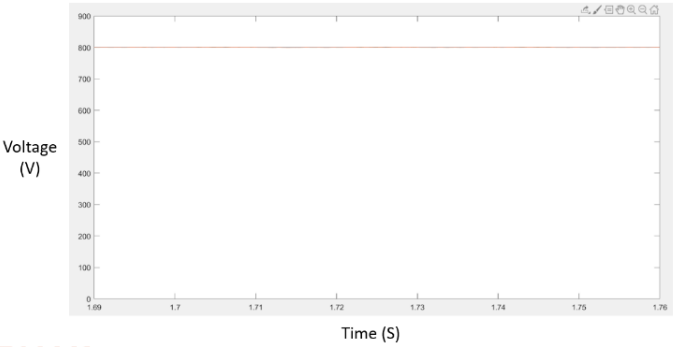

Fig. 2.5: SiC DC Bus Voltage

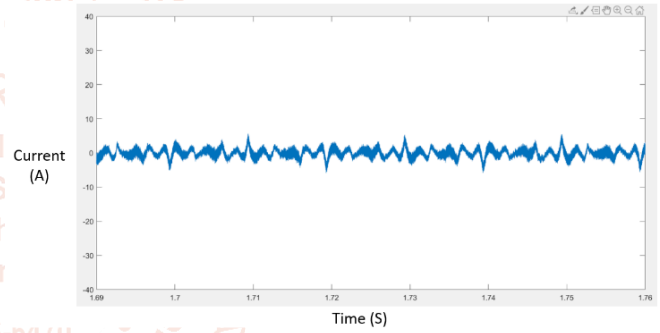

Fig. 2.6: SiC Inverter filter Current

IV. EXPERIMENTAL VALIDATION

The control outline for IGBT based SAF SiC MOSFET based SAF is experimented on a 10kVA system. The verification is done taking *iL* as the reference current for both SiC MOSFET based SAF and IGBT based SAF. The aspects for the calculation are *Lf Si* = 2.5mH, *Lf SiC* = 400μH and *Lac* = 5mH. SiC MOSFET based SAF was made to clock at 20kHz switching frequency.

It is seen from the FFT features that 6k±1 harmonic are pre-existing in load currents. The 5th harmonic has 35% and 7th harmonic has 5.5% share in the fundamental current which exceeds IEEE standards. In the same way, 11th harmonic has 3.6% and 13th harmonic has 2.1% share in the fundamental current. When IGBT SAF is added in parallel with the load which is used to remove the 5th and the 7th harmonics results in decrement of percentage of 5th harmonic from 35% to less than 1% and for the 7th harmonic, the amount decreases from 5.5% to less than 1%. Even then the higher order harmonics such as, 11th, 13th remain in the original current signal. In the introduced concept, the removal for 11th, 13th and other higher harmonics is allocated to SiC MOSFET based SAF which obtains the source current fully sinusoidal. The addition of SiC MOSFET based SAF has reduced the 11th harmonic component from 3.6% to 1.6% and 13th harmonic component from 2.1% to less than 1%. So, after these reduction in the harmonic levels, they are found to be within

the limits. Hence, the obtained source current after harmonic removal by introduced HSAF is sinusoidal in comparison with initial load currents. IGBT SAF removes 5th and 7th harmonics which dominates the load current. Hence, IGBT based SAF needs 35.5% of total load kVA rating. It is also obtained that SiC MOSFET removes the least significant higher order harmonic, which needs 4.2% of total load kVA rating. The DC bus voltage controller is installed in both IGBT SAF and SiC MOSFET SAF to maintain the DC bus voltage at 600V respectively.

V. CONCLUSION

In the introduced architecture, a total of THD of 3.5% is obtained with the small value of filter inductances. An extra feature of the system is that the total losses bared by the system is lower compared to conventional IGBT SAF. The simulation results, displaying the harmonic removal were supported with the experimental results obtained from 10kVA system. It is obtained from the results that harmonic share of SiC MOSFET based SAF is less, which results in lowering the kVA rating needed of SiC MOSFET based SAF in introduced in HSAF concept. Adding to the low rating of SiC SAF, the increase in the cost due to SiC SAF can be overlooked by the energy and cost savings due to improved efficiency of the new system.

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