

Advanced Power Supply solutions Meeting High Standard for Fusion Research

SiC-Based Power Supply System for Resistive-Wall-Mode Control

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Abstract—The control of resistive-wall- mode (RWM) instabilities can be realized with a dedicated active control system based on in-vessel sector coils. Each coil is fed independently by a dedicated fast inverter. Due to the outstanding dynamic performance required, new insulated-gate bipolar transistor modules based on silicon carbide technology (SiC) is adopted. Switching at 30 kHz these components, together with a fast control system, allow reaching the required high dynamic. This paper gives an overview of the final design of the RWM-PS, its special features and the solutions implemented to satisfy the critical requirements. The issues related with the high switching frequency and the peculiar nature of the load will be treated in detail.

Index Terms—Insulated gate bipolar transistors, plasma stability, power supplies, pulse-width modulated power converters.

INTRODUCTION

One of the main objectives of these power converters is the control of the instabilities called resistive- wall modes (RWMs) in order to reach the desired plasma performance and confine steady-state high-beta plasmas [1]. To this extent a dedicated active control system based on in-vessel sector coils (RWM control coils) has been devised. The standard active control of the plasma instabilities is normally implemented in the experiments but the peculiarity of the RWM-CC is that they can be placed on the plasma side of the stabilizing plate, just behind the tiles of the first wall and around the ports, therefore, due to the plasma proximity and the low shielding effect of the surrounding passive structures, they can efficiently generate fast magnetic fields if properly driven. The strategy is to succeed in controlling RWMs when their amplitude is still low, so that low magnetic field components and relevant current to produce them are sufficient. To achieve the highest flexibility, each coil will be fed independently by a dedicated converter, which has to follow in real time an arbitrary reference generated by the central controller of the tokamak. The required coil current and dynamics have been estimated, the results were a current peak of 275 A, a closed-loop bandwidth of 3 kHz and a latency between reference and output lower than 50 μ s [3]. To exploit the simple and compact H-bridge topology, a switching frequency higher than that sustainable by standard silicon insulated-gate bipolar transistors (IGBTs) is necessary, semiconductors based on silicon carbide (SiC) are used to satisfy the requirements.

I. LOAD DESCRIPTION

The load of the RWM-PS is represented by the RWM-CC.

VOLTAGE REQUIREMENTS

The voltage across the RWM-CC necessary to achieve the required current with the specified bandwidth has been

calculated on the basis of the impedance characteristic achieved through the finite-element (FE) analyses carried out in the past years. The rated peak current and voltage at the inverter output are set at 300 A and 240 V, respectively.

II. DESCRIPTION OF THE RWM-PS

The following section describes the design of the Power Supplies

A. Block Diagram

The block diagram of the RWM-PS is shown in Fig. 1. The system is composed by AC disconnecter, step-down transformer, AC/DC rectifiers, water-cooled fast inverters, and a local control cubicle (LCC).

The fast inverters are divided in two groups, each fed by one ac/dc converter, fed in turn by a dedicated secondary winding of the step-down transformer.

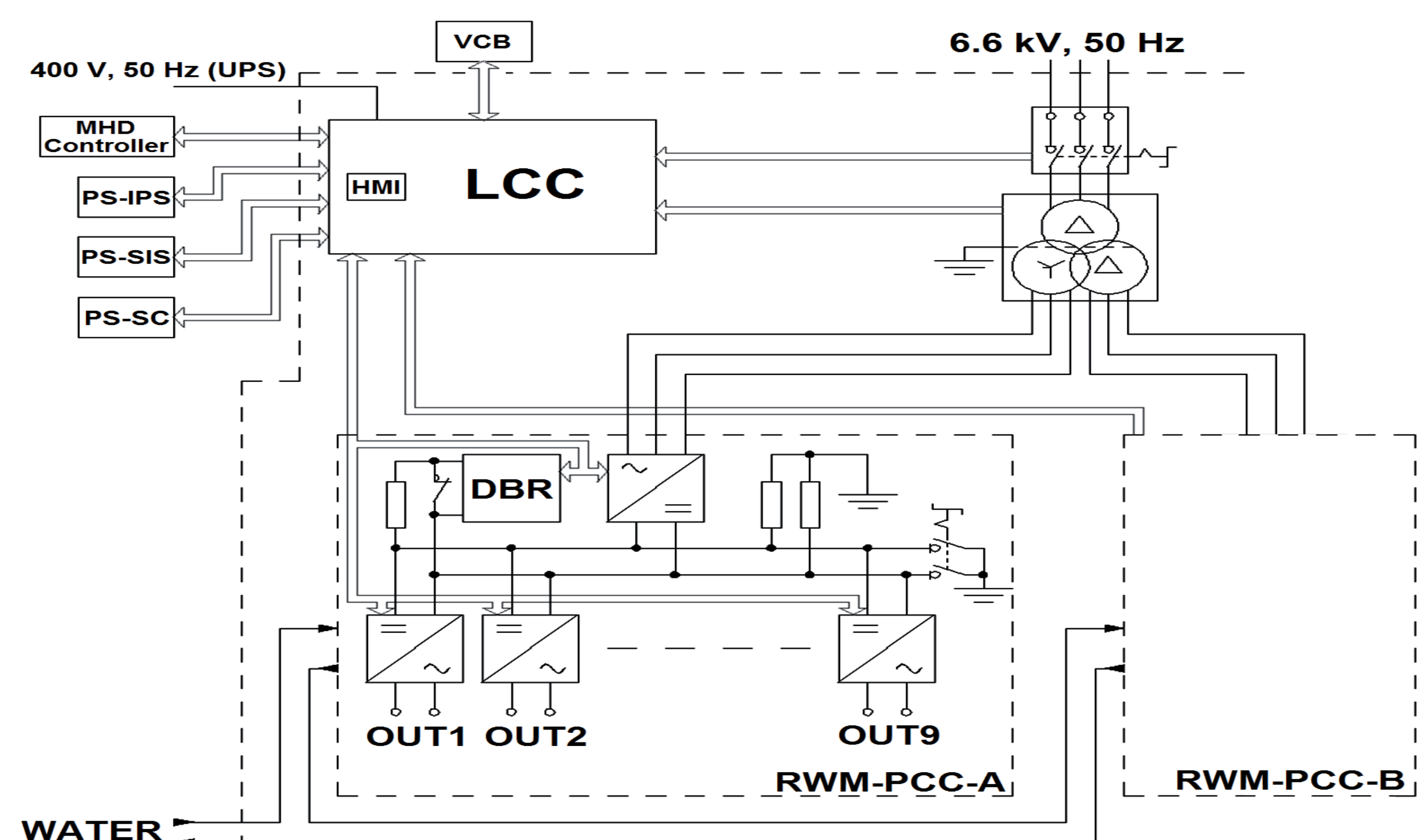


Fig. 1. Overall block diagram of RWM-PS.

B. Fast Inverter Module

Each fast inverter, with its dc-link filter, capacitor bank, and output filters, is enclosed in a self-contained compact module, as shown in Fig. 2.

Fig. 2. Overall view of the RWM-PS



Common-Mode Output Filter

The chosen modulation technique (unipolar PWM) produces large CM voltage oscillations at the output. In order to reduce the risks associated with electromagnetic emissions a CM filter has been introduced. The scheme of the inverter, including the common-mode output filter is shown in Fig. 3, and the reduction of the CM voltage amplitude is presented in Fig. 4.

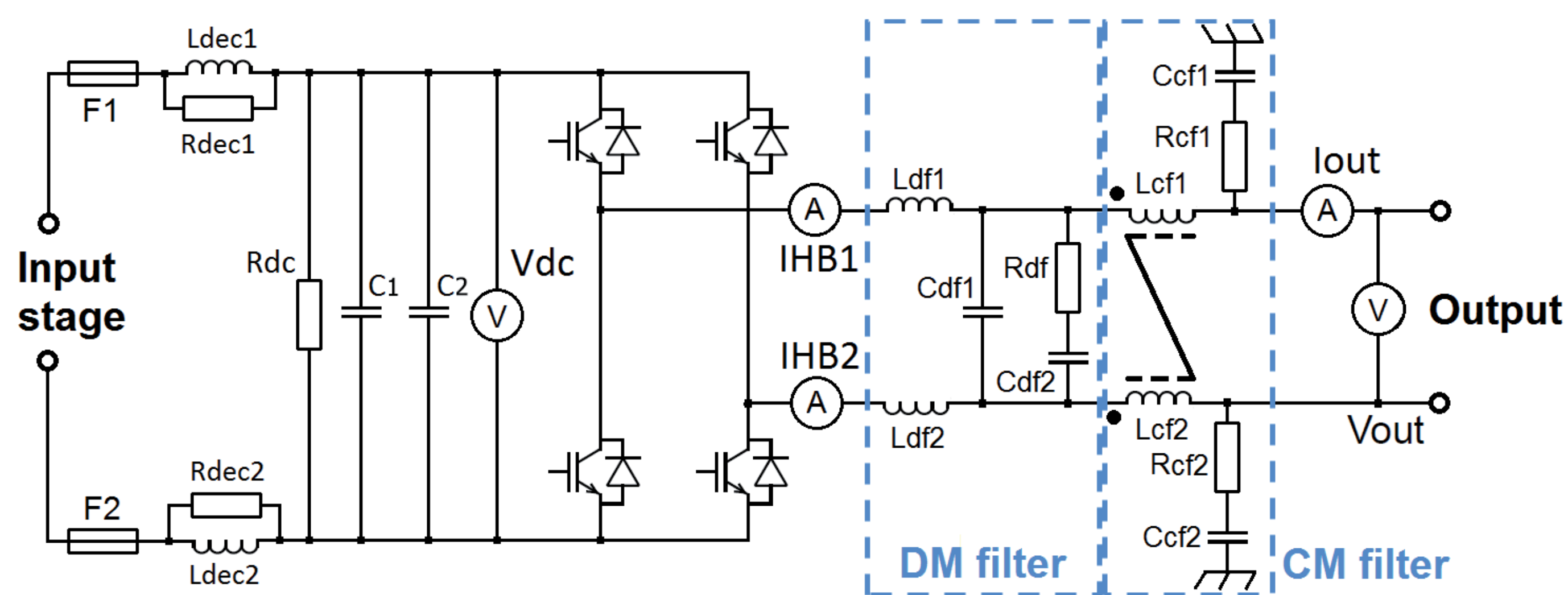


Fig. 3. Simplified scheme of a fast inverter module

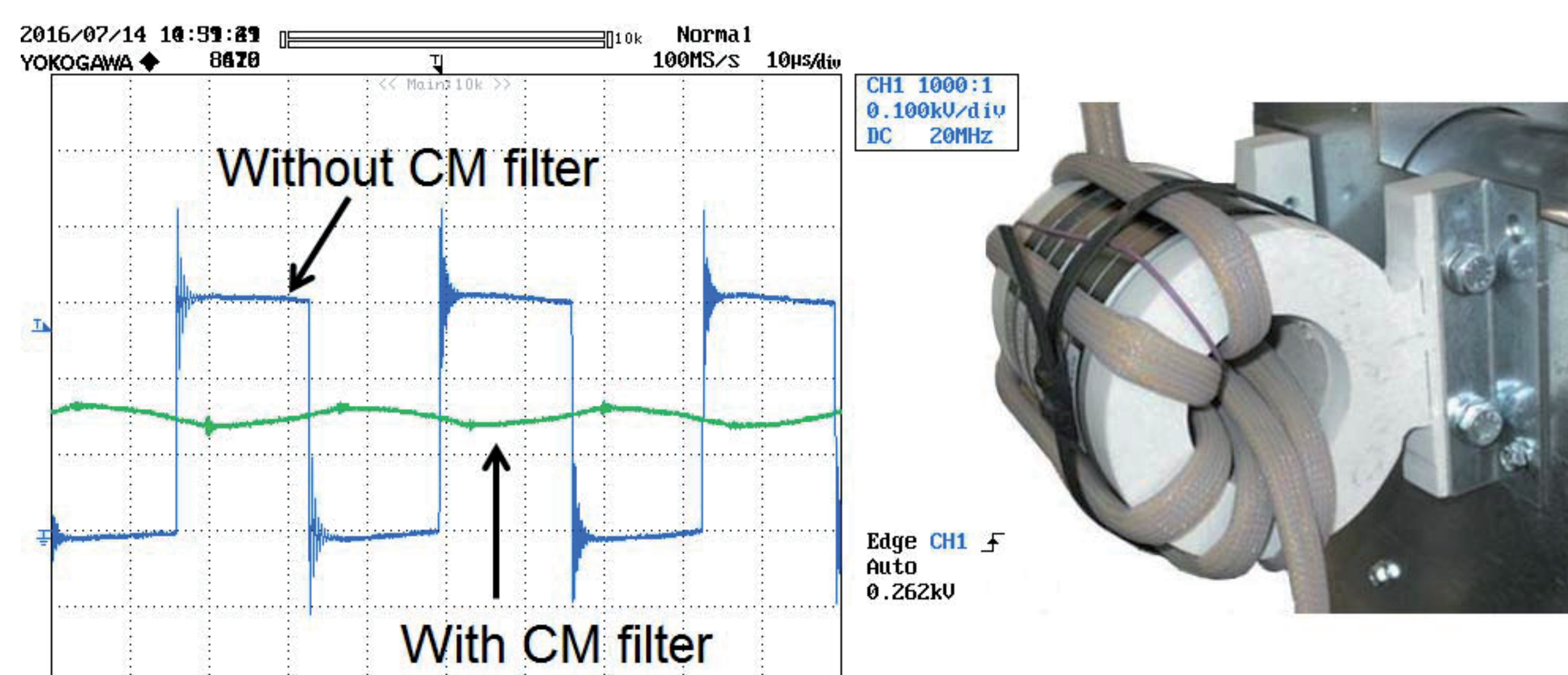


Fig. 4. Voltage measured between one inverter output terminal and negative rail of dc link (left). Prototype of CM filter inductor (right).

C. Main Parameters

The main parameters of the power supply are listed in Table A. The maximum operation duty corresponds to the maximum duration of the plasma flat-top that was estimated.

TABLE I
MAIN PARAMETERS OF THE RWM-PS

Description	Value
Input ac power voltage	6.6 kV 3-phase 50 Hz
Rated power of the step-down transformer	100 kVA continuous, 300 kVA overload (100 s)
Maximum operation duty	100 s every 1800 s
Number of ac/dc rectifiers	2
Nominal active power of each ac/dc rectifier	100 kW
Nominal dc-link voltage	300 V
Dc-link fluctuations in normal conditions	within -6% ÷ +3%
Dc-link overvoltage in case of max induced voltage pulse in all RWM-CCs	< +15%
Number of fast inverter units	18
Type of control for each inverter	Current Control Loop or Voltage Control (open loop)
Type of reference	Arbitrary
Nominal output voltage of each inverter	240 V
Max peak voltage between coil terminals	±550 V, in transients
Max voltage slope at coil terminals	20 MV/s
Maximum pulsed voltage induced into the load	±170 V for 15 ms
Maximum peak output current of each inverter	300 A (1)
Nominal inverter output current in dc operation	> 100 A
Maximum output current ripple of the inverter	±30 A
Inverter bandwidth of the current at -1 dB	1 kHz, in current control
Inverter bandwidth of the current at -3 dB	3 kHz, in current control
Latency between reference and output voltage	< 50 μs
Accuracy of the load current in steady-state	±12 A, up to 100 Hz
Output voltage/current overshoot with reference step variation	< +15%
Output current overshoot in case of max e.m.f. induced in the RWM-CC	< 90 A

(1) With sinusoidal reference waveform for the maximum operation duty

D. H-Bridge

The H-bridges represent the heart of the RWM-PS. In order to guarantee the required dynamic performance with a single H-bridge per inverter, a switching frequency of at least 30 kHz has to be adopted, with unipolar pulsewidth modulation (PWM), fast hybrid Si-SiC power modules have been adopted (Infineon FF600R12IS4F). As shown in Fig.5 the measured latency time matches the required <50 μs.

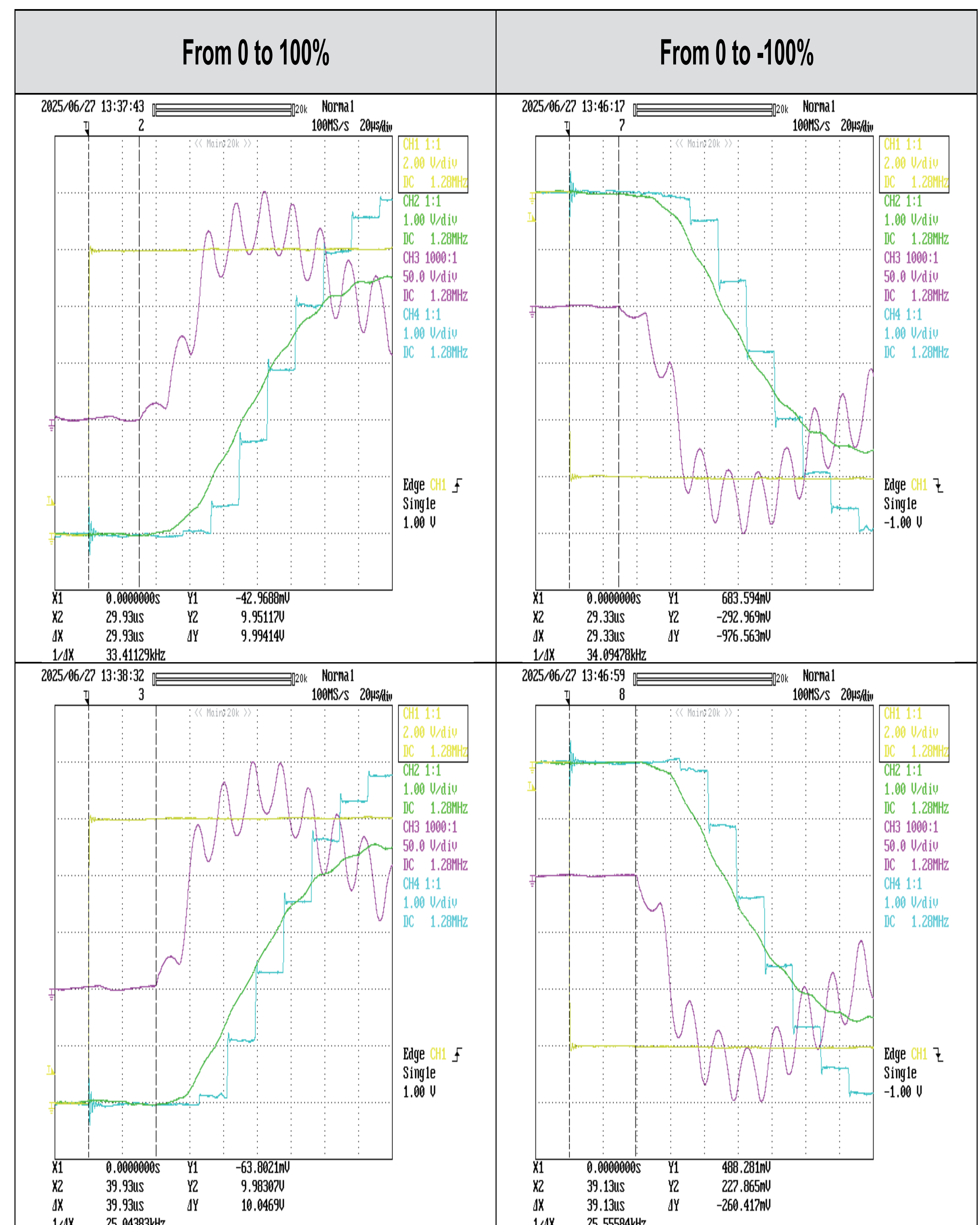


Fig.5 Measured latency time, positive and negative step

CONCLUSION

In order to perform a smart and effective control of the RWMs, a very compact, flexible, and efficient power supply (RWM-PS) has been designed, comprising a certain number of independent inverters, each one driving control coil. The very demanding requirements (current bandwidth: 3 kHz, latency 50 μs) are satisfied thanks to the adoption of high-end control hardware, advanced software control, and mostly SiC power IGBTs. This solution has been already tested and installed for site experiments this year, 2025.

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