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A Modular 200kW-25kV DC Medium Frequency Resonant Converter for RF Power Amplifiers

X. Bonnin, D. Aguglia, L. De Mallac, S. Pittet

CERN - European Organization for Nuclear Research, Technology Department, Electrical Power Converter Group
1211 Geneva 23, Switzerland

E-mails: xavier.bonnin@cern.ch, davide.aguglia@cern.ch, louis.de.mallac@cern.ch, serge.pittet@cern.ch

Abstract— This paper focuses on the study and the implementation of a 25kV / 200kW / 20kHz rectifier intended to supply radio frequency power amplifiers with a DC voltage in a precision range of 1000ppm. The topology is based on three LCC resonant modules, and the high voltage part uses three 100kW / 20kHz power transformers connected to 72 diode full-bridge rectifiers connected in series. The design of such transformers as well as the management of the voltage balancing between the rectifiers and between the modules constitute new challenges addressed in this paper. The key design points of the transformers are described. Then, a simulation based analysis presents the issues in balancing powers and voltages between the modules. All the presented results are validated by experimental measurements on a full scale system.

Keywords— Rectifiers; High-voltage techniques; Resonant inverters; Power transformers; Electronic switching systems; Circuit topology;

I. INTRODUCTION

The energy upgrade of existing particle accelerators, and requests for more cost-effective solutions in new large scale facilities, leads to the need of more and more compact high voltage power converters for power amplifiers. Combining this with the increasing needs in terms of reliability, modularity and redundancy (availability of large accelerators), results in challenging power converter design efforts. Topologies based on resonant LCC DC/AC converters connected to multi-secondary step-up transformers with series connected diode rectifiers generally offer good performances for such applications. Modularity can be achieved by using several multi-secondary windings medium frequency transformers with a high number of output rectifiers. This modular approach allows degraded operation with a faulty module [1] since a faulty module can be shunted without jeopardizing the operation of the converter. Moreover, using a soft-switched LCC resonant converter allows achieving a relatively high switching frequency with moderate losses [2], leading to reduced step-up transformers volume.

This work focuses on the design of the high voltage stage of a modular 25 kV, 20 kHz resonant converter used to supplying a 200 kW RF tube. It addresses:

- *The high voltage stage design.* The number of secondary windings shall consider the diodes characteristics as well as stray capacitance and inductances. Designing such a

high frequency and high voltage transformer for high power is challenging [3], issues and limitations are presented;

- *The balancing of voltage between the modules and among the rectifiers.* The high voltage requirement leads to connect in series three modules and to use a large number of rectifiers. Diodes parameters dispersion as well as dispersion in the resonant components play a key role in the voltage distribution. This analysis shows how the diode should be chosen in order to avoid destructive overvoltages and proposes a control strategy to compensate these dispersions.

The design analysis is complemented and compared with experimental measurements on a full scale working prototype.

II. PRINCIPLE OF OPERATION AND DESIGN

A. Specifications

The specifications for the output voltage and current are determined by the operation of the RF tube which needs a power up to 200kW. The main specifications of the power converter are presented in TABLE I. Three modules are used, but the converter must tolerate a degraded mode operation, with two modules only; so each module is rated at 100kW. To achieve that, the topology presented on Fig.1 is chosen. Three LCC resonant converters are used to supply their own multi-secondary step-up transformer. Each secondary is connected to a diode rectifier. The capacitor C_F stands for the output filtering capacitor. Its value and technology are such that its voltage ripple is less than 1000ppm of 25kV. The resonant converters' switching frequency is chosen between 14kHz and 22kHz in order to get both non-bulky resonant cells and transformers, and to provide a large bandwidth to regulate the output voltage.

TABLE I. MAIN POWER CONVERTER SPECIFICATIONS

Parameter	Min	Max	Unit
Output DC voltage	5	25	kV
Output nominal current		8	A
Voltage accuracy	1000		ppm
Input voltage (3 phase-network)	360	440	V
Input current per phase		400	A
Switching frequency	14	22	kHz

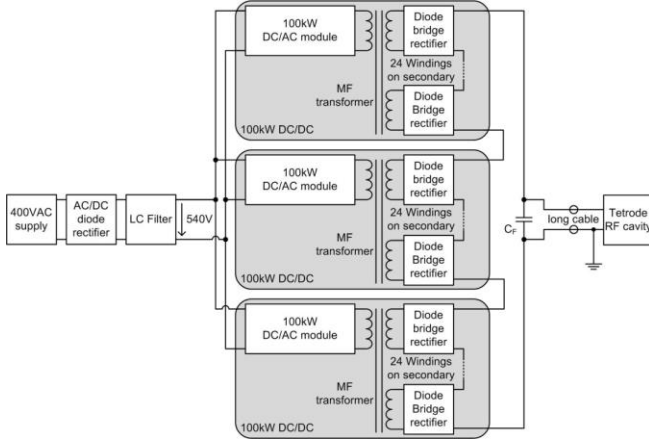


Fig.1 Schematic of the converter

B. Choice of the components

The analytical study of this converter leads to rough calculations [3] so the components choice issue should be quite tricky. In this work, a simulation based analysis is proposed to guide the components choice. The circuit considered for a preliminary study is presented in Fig.2.

The resonant cell is made of the inductor L , the equivalent serial resistor r , the parallel resonant capacitor C_p which can include parasitic capacitances of the transformer, and the equivalent (non-linear) load R_{eq} brought back by the transformer, the rectifier, the load capacitance C_L and the load resistance R_L . It is assumed that C_L is large enough so the voltage V_o has no ripple. A linear study of this second order circuit performed at the resonant frequency, assuming that R_{eq} is constant, shows that the power transferred to R_{eq} is maximal when $R_{eq} = Z^2/r = QZ$, where $Z = \sqrt{L/C_p}$ is the characteristic impedance of the resonant cell and Q is its quality factor. In this case, the half of the power would be dissipated in r and the efficiency of the system would be below 50%. Then, in this study, it is assumed that $R_{eq} \ll Z^2/r$, so the power transferred is an increasing function of R_{eq} at the resonant frequency of the circuit. Simulated waveforms of a first harmonic analysis (only the first harmonic of V_{in} is considered) are plotted on Fig.3. The components are assumed to be perfect and the transformer ratio is equal to 1. The quality factor Q of the resonant cell is chosen equal to 200 which is a realistic value. The normalized load resistance R_L/Z is chosen equal to 8 which is much lower than Q . The voltages are normalized by V_{in1} , the amplitude of the first harmonic of V_{in} , and the currents are normalized by V_{in1}/Z . The power transfer occurs during a short period Θ_{on} . Therefore, during the remaining time, power is transferred from the load capacitor C_L to the resistor R_L . Under the assumptions that V_{Cp} is constant (C_p is large enough) and that $\Theta_{on} \ll \Pi$, one can estimate W_1 , the normalized energy transferred to the load during one half-period in steady state:

$$W_1 \approx (V_o/V_{in1})^2 \Pi / (R_L/Z). \quad (1)$$

If an equivalent resistance R_{eq} is used instead of the rectifier circuit, the normalized energy transferred during one half-period becomes:

$$W_2 \approx (V_o/V_{in1})^2 \Pi / (2R_{eq}/Z), \quad (2)$$

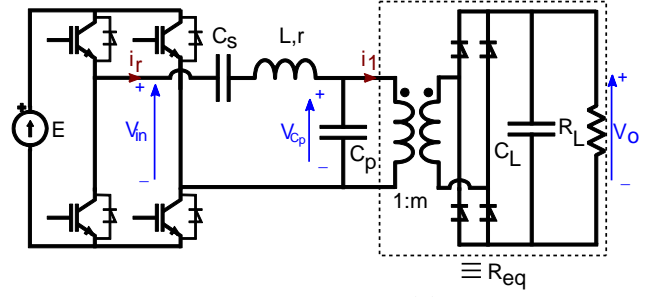


Fig.2. Equivalent circuit of the converter's module.

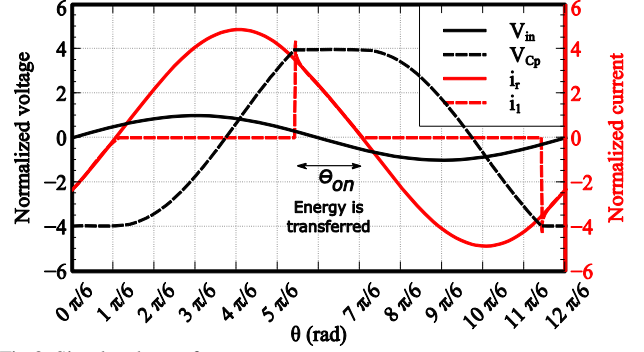


Fig.3. Simulated waveforms

since V_{Cp} 's shape is close to a sine waveform of amplitude V_o . Considering (1) and (2) under the previous assumptions, one obtains:

$$R_{eq} \approx R_L/2. \quad (3)$$

This relationship remains true as far as $\Theta_{on} \ll \Pi$. If a transformer of turn-ratio m is inserted, (3) becomes $R_{eq} \approx R_L/(2m^2)$. Equation (3) is validated in simulation by computing the average power of $V_{Cp} \cdot i_l$ and identifying it to $V_{Cp,rms}^2 / (2R_{eq})$. The error in the estimation of R_{eq} is kept below 20% for $2 < R_L/Z < 4$ and below 10% for $4 < R_L/Z < 50$.

The actual converter operates with 2 or 3 modules in series at 25kV-8A, therefore $R_L = 1.6k\Omega$ or $R_L = 1k\Omega$ for 2 or 3 modules respectively. In addition, for technical reasons that are explained in section III, the step-up transformer is made of 24 secondary windings, and its total turn-ratio is 12 when the secondary are connected in series. Then, using (3) and taking into account the transformer turn-ratio leads to $R_{eq} = 5.4\Omega$ (2 modules) and $R_{eq} = 3.5\Omega$ (3 modules). The available voltage is 540V, so the maximal 1st harmonic amplitude of V_{in} is 690V. Calculations based on the linear equivalent resonant circuit and assuming that $R_{eq}/Z > 1/\sqrt{2}$ show that the maximal voltage that can be reached is given by:

$$V_o^{max} = m(R_{eq}/Z) V_{in1} [1 - 1/(2(R_{eq}/Z)^2)]^{-0.5}. \quad (4)$$

It shows that R_{eq}/Z must be greater than 1.4 to meet our requirements. It leads to $Z < 3.9\Omega$. Since the resonant frequency is chosen at 14kHz, we get $L = 44\mu H$ and $C = 2.9\mu F$.

III. DESIGN CONSIDERATIONS OF THE HIGH-VOLTAGE STEP-UP TRANSFORMERS-RECTIFIER SYSTEM

The design challenges of the Medium Frequency Transformer (MFT) lies in the high-power – medium-frequency – high-voltage triplet specifications. For the sake of design simplicity, it has been decided to avoid using the MFT parasitic inductances and capacitances to ensure the resonance, by using an LCC topology. However, the MFT designer has to make sure that the resonance frequency of the MFT itself does not affect the LCC frequency characteristic in the 14kHz-20kHz operation region. The MFT resonant frequency shall be then much higher than 20kHz to ensure a constant gain of the V_2/V_1 transfer function (V_1 and V_2 being the primary and secondary voltages respectively). Considering the equivalent circuit of the MFT illustrated in Fig.4, the MFT resonant frequency f_{res} can be approximated by (5).

$$f_{res} = \frac{1}{2\pi\sqrt{(L_1+L_2)C_2'}} \quad (5)$$

Notice that both the total leakage inductance and secondary stray (distributed and to ground) capacitance have to be minimized. The total leakage inductance can be minimized by reducing:

- The insulation distances between primary and secondary windings;
- The number of turns.

Reducing the number of turns directly affects the magnetizing inductance which minimum value has to be specified at the lowest operating frequency (14kHz). Therefore a tradeoff between leakage and magnetizing inductance has to be addressed.

The secondary capacitance is also minimized via a small turn's number. The insulating materials as well as secondary winding structures and configuration greatly affect the secondary stray capacitance.

Two solutions for can be adopted to integrate the diodes rectifier as illustrated in Fig. 5. This significantly affects the transformer design, especially in terms of HV connections. For the sake of flexibility to use the same module for different applications, it has been decided to adopt a multi secondary winding structure. This allows to only partially use the secondary winding and thus modify the transformer ratio. This structure present some advantages in the electric field stresses on the insulating material [4].

The number of secondary windings is mostly imposed by the diode rectifier technology. Fast and soft recovery diodes are the preferred characteristics for such an application. However, no wide choice is offered in industry for such current ranges (>8A).

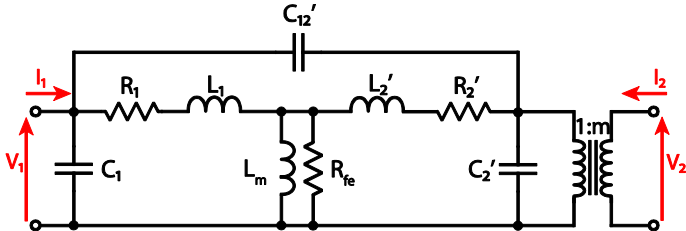


Fig.4. Imbalances between the diodes voltages. Simulation of 24 diodes voltages (left) and measurements of 3 diodes voltages(right).

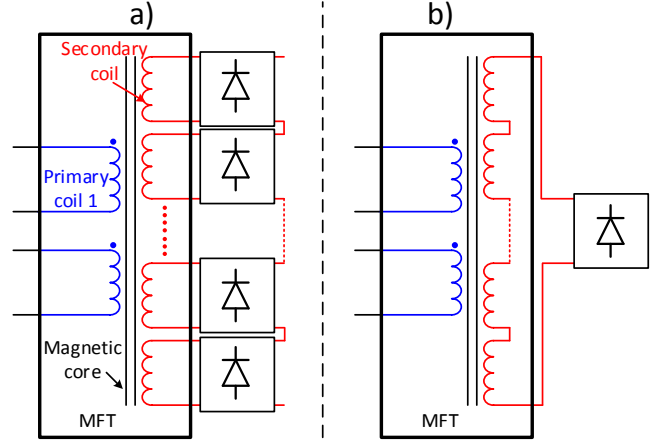


Fig.5. Possible integration of the diode rectifier –a) Multi secondary winding MFT with dedicated rectifiers, b) single secondary winding with single rectifier.

Such diode often present a wide spread in their reverse characteristics. This is why it is a good practice to consider that only one of the two blocking diodes in a full bridge rectifier has to withstand the blocking voltage. The selected diode for this application is the IXYS DH2x61-18A (1.8kV, fast and soft recovery). This implies a maximum rectified theoretical voltage of 900V. However a margin has to be considered. A maximum rectifier voltage of 540V has been chosen. Therefore, to ensure the production of 12.5kV per module, 24 secondary windings have been selected, and the total ration of the MFT is $m=12$.

IV. IMBALANCES ISSUES

The converter is made of at most three independent resonant modules connected in series, and sharing the same load. In each module, 24 rectifiers are connected in series and no individual control of the diodes voltages is performed. This leads to power and voltage imbalances that must be carefully addressed.

A. Diodes voltages

Because of its principle of operation (Fig.3), there is a period during which all the rectifiers diodes are blocked (ie no current from the resonant cell to the output). During this period, the diodes voltages are only defined by diodes physical parameters. As stated in the previous section a dispersions in these parameters lead to imbalances in the diodes voltages which could be destructive if no care is taken. One can distinguish the static parameters, the diode reverse current, and the dynamic parameters, the junction capacitance and the reverse recovery charge. Unfortunately, these parameters are not well documented in the datasheets and are temperature dependent.

1) Static imbalances

In [5], it is suggested that, for a given temperature, the reverse current I_r of a silicon diode is given as function of the reverse voltage V_r by:

$$I_r(V_r) \approx I_{rm}(k+(1-k)V_r/V_{rm}), \quad (6)$$

where I_{rm} and V_{rm} are the maximum values for I_r and V_r , and k is a parameters which can be sometimes deduced from the datasheets, or assumed to be close to 0.8 for silicon fast rectifier

diodes. In our case, with two modules, 96 diodes are connected in series and must withstand 25kV. A simple worst case analysis considering that only one diode is such that $I_{r_{mx}}=aI_{r_m}$, where a is the worst dispersion, shows that if 600V rated diodes are chosen, a dispersion of 10% in I_{r_m} is enough to provoke the diode destruction. The same applied for 1.8kV rated diodes shows that 17% of dispersion can be tolerated. As $I_{r_{rm}}$ is sensitive to temperature, this analysis highlights the importance of having a good thermal management and working with diodes taken from the same batch of a manufacturer. However, it is still possible to balance the voltage with parallel resistors, or to avoid overvoltages with parallel transil diodes; however, it is done at the cost of increased cost, footprint and losses.

2) *Dynamic imbalances*

The reverse recovery parameters are subject to dispersion too and to temperature dependence. Then, the diodes do not block at the same time and the voltages do not grow with the same slope. A similar analysis based on calculations presented in [5], and considering the IXYS DH2x61-18A (1800V fast rectifier diode) which has a low Q_{rr} shows that a dispersion of 30% in the Q_{rr} parameter leads to a maximum transient overvoltage of 300V. This imbalance can be managed by overdesigning the diodes voltage rating.

3) *Simulations and measurements and technical choices*

Monte Carlo based simulations considering 10% of dispersion in diodes' static and dynamic parameters have been run with one module, and measurements have been performed with one module and using only 8 rectifiers connected in series instead of 24. The waveforms are plotted in Fig.6.

During the power transfer phase, the diodes voltages are imposed by the transformer although during the freewheeling period, diodes voltages are mostly governed by diodes internal parameters.

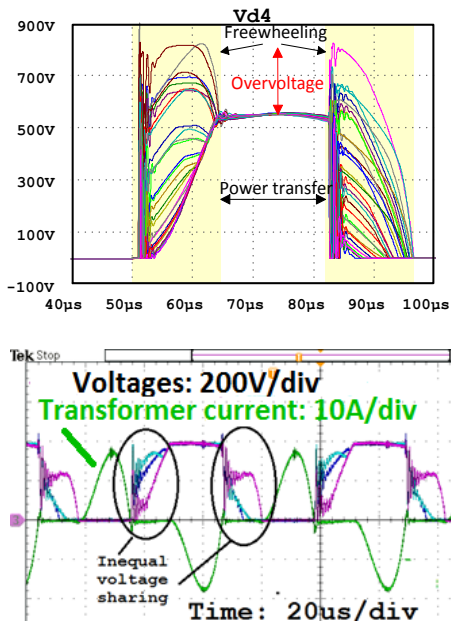


Fig 6. Imbalances between the diodes voltages. Simulation of 24 diodes voltages (left) and measurements of 3 diodes voltages(right).

In the final version of the converter, R-C snubber circuits have been used to damp the transient over-voltages due to the reverse recovery and the parasitic ringing between the diodes and the winding leakage inductance. The static equilibrium has been managed through a selection of diodes taken from the same batch, and an appropriate thermal management (Fig.7).

The 24 rectifiers are split in three columns of 8 rectifiers which are independently cooled with a fast air flow. In nominal operation, the temperature distribution in each column is similar and the difference is below 5° between the lower diodes and the upper ones.

B. *Modules voltages and power transfers*

As depicted on Fig.1, the modules are connected in series. A question consists in defining if a filtering capacitor should be connected at each module output. As a matter of fact, the three resonant cells and step-up transformers are not exactly the same and, as shown in experimental waveforms presented on Fig.8, ripple in the module voltages can occur. This ripple could be reduced by connecting a filtering capacitor at each module output. Nevertheless, such a filtering capacitor offers a new path for the resonant current and creates imbalances between the module average voltages. Simulations have been run with two modules by stepping the value of the module's filtering capacitor. A difference of only 5% on the resonant inductance value, and of only 1% in the step-up transformer parameters was considered in this simulation. Results are presented on Fig.9. In accordance with intuition, the voltage ripple decreases as the filtering capacitor value increases. However, the drawback of the imbalance between the module's voltages increases since the equilibrium point $V_o/2-V_o/2$ is sensitive to asymmetries between the modules. As a matter of fact, the module which has the lower output voltage, because its resonant peak is slightly different from the other module's one, sees a lower R_{eq} , then its voltage gain is even lower. As a consequence, the power balancing must be actively controlled.

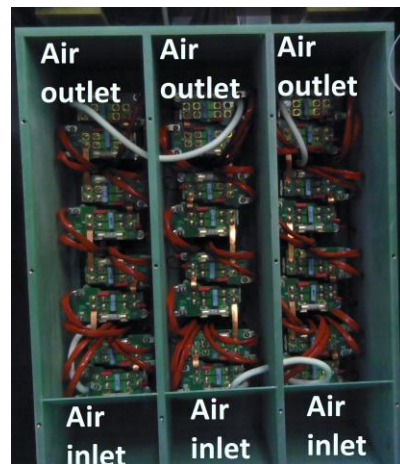


Fig.7. Diodes modules mounting to guarantee a homogeneous

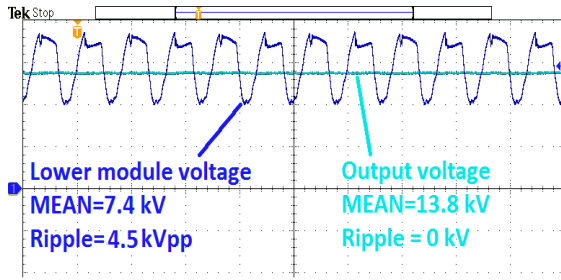


Fig.8. Modules voltages with no filtering capacitor.

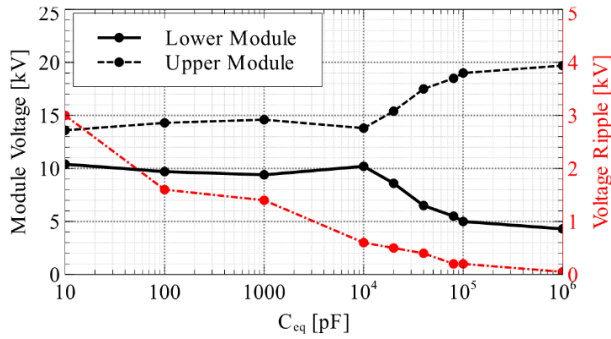


Fig.9. Modules voltages as a function of the modules filtering capacitors.

V. CONCLUSION

In this paper, the issue concerning the design and the technical choice of the high voltage side components was addressed. The need of high voltage and high power with the need of modularity led to split the usual one-module LCC topology in three independent modules, with their own 20kHz/100kVA rated resonant cells and multi-winding step-up transformers, with a large number of diode rectifiers (72).

This represents a challenges regarding the design and the choice of the components. As a matter of fact, the design of the transformer combines the issues related to the high frequency need, the losses management and to the high voltage insulation. In addition, as it is based on the behaviour of several resonant cells, this topology is also sensitive to components values deviations and this work shows that a particular care must be taken in the control of the power transfer. Moreover, because of the number of diodes connected in series during the freewheeling phase, an over dimensioning of the diode voltage rating should be considered and a particular attention must be paid to the diodes temperatures balancing.

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