Transformer-less PWM High Power Medium Voltage Variable Speed Drive

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Abstract

This paper deals with the performances of a Variable Speed Drive based on High Power PWM Inverters connected to a distribution network without transformer. This architecture represents a step forward in the field of full-integrated production and power conversion solution to optimize efficiency, power quality, availability, space and compactness. We detail the key points of this solution design and we present main results to validate our topology comparing to conventional solutions with transformers.

Introduction

Transformers are typically used to reduce the common mode voltage and mitigate harmonics with multi-pulses configurations. However, transformers increase the size, cost, complexity and power losses in the driver system. With PWM Active Front End drive and dedicated common mode impedance these original goals can be fulfilled but without sacrificing space, and achieving reductions in size, weight, costs and maintenance. Additionally, the development of a specific PWM strategy on both AFE and Inverter bridges allow to keep the standard motor insulation design and to control the residual network common mode voltage as well as the network voltage THD.

I. Propulsion system overview

This propulsion system especially dedicated to cruise ship is made of two single winding propulsion motors each fed by one PWM IGBT medium voltage drive. Each Motor shaft line is directly coupled to the propeller.

Main features of the propulsion system are:

- Each drive is made of a PWM AFE (Active Front End) based on 3 levels NPP topology and Press-Pack IGBT
- Each drive is sized to deliver the rated torque of the propulsion system. For a 24MW propulsion motor, 6.6kV 24MW drive is used
- This architecture has a full redundant feature (full or partial) as 1 spare drive is maintained in back-up for both propulsion systems
- Generators can be designed for an increased power factor close to 0.95 due to the capability of the drives to operate at 1 power factor
- Braking capability is achieved thanks to the reversibility of the system. This gives high performance in crash stop tests and high maneuverability of the ship
- Motorized Isolator Switch allow to separate a drive from the propulsion system in case of maintenance
- Low Inverter output inductance is used to limit the voltage gradient dv/dt at motor Input

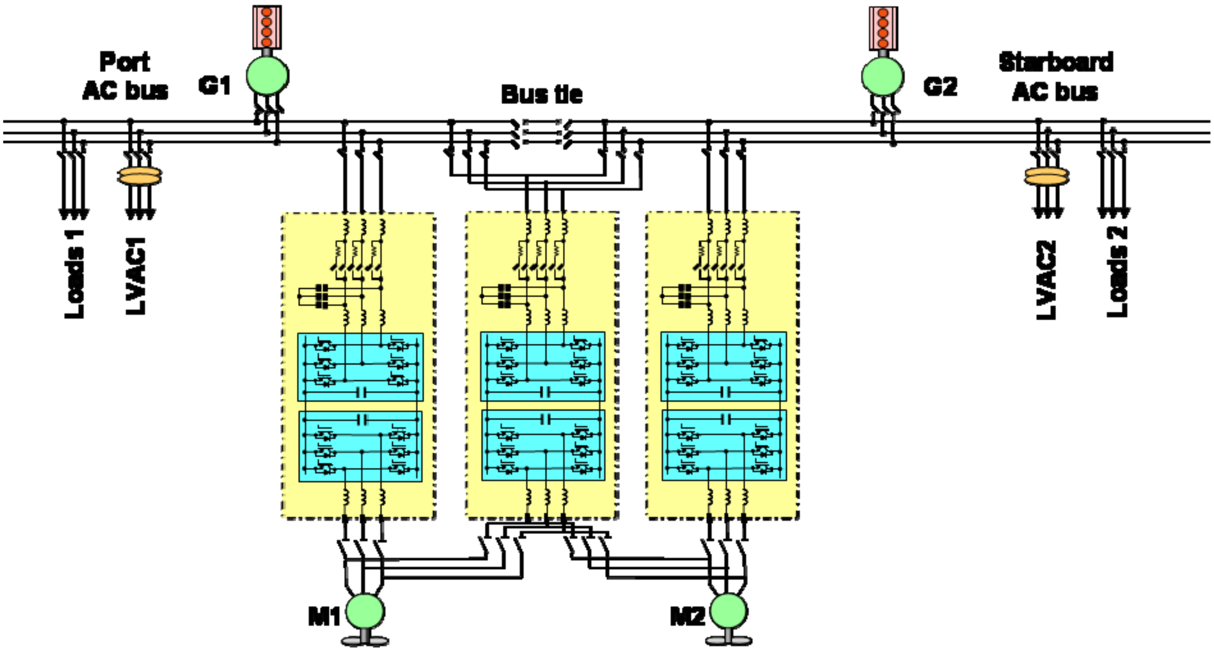

Fig. 1: Global electrical scheme overview

Compared to a conventional solution based on the use of LCIs driven double winding synchronous machines this architecture allows to increase the efficiency of 2%. For a 2 times 24MW propulsion system, we make the following savings: 1300tons a year of fuel, 170tons weight, 40m² space & 40% cable.

II. Transformer-less synoptic

The transformer-less solution was developed to propose a global system with cost, size & foot-print reduction. This solution allows us to use an AFE converter without additional cost comparing to classical Stand-Alone solution with DFE. The target of our Transformer-less topology is a standardization of the system:

- We have to supply classical HV motors keeping the insulation voltage level of classical solutions (2/3*Vdc without over-voltage). We don't need additional insulation.
- For the same reason, we have to limit the over-voltage between motor phase-ground
- We have to mitigate zero-sequence components on the main network (zero-sequence current & voltage)
- We use a carriage filter to keep harmonic distortion in accordance with classification society.

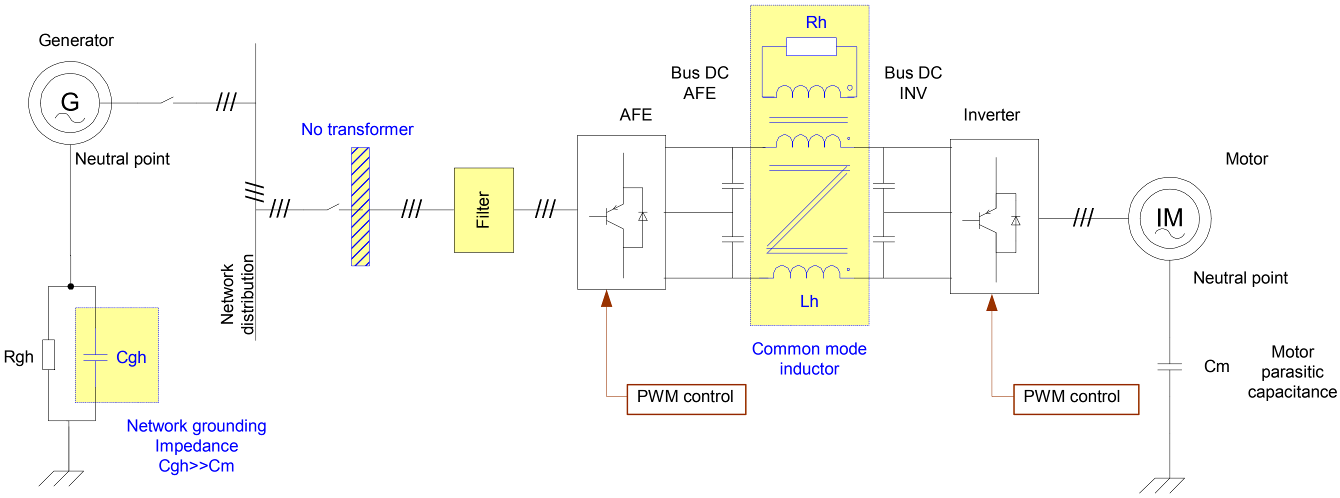

Fig. 2: Single-line diagram of the transformer-less solution

In Fig. 2, we present the equivalent single-line diagram of our transformer-less solution; with 3 key-points:

- A common mode inductor 'Lh' connected to a damping resistor 'Rh', placed on the DC bus.
- A grounding impedance 'Rgh' & 'Cgh' which makes the main grounding of the system on the network side
- A PWM command on AFE & Inverter studied to limit the global zero-sequence voltage generated by them.

The 3 mentioned key-points are useful only for this architecture & they are inseparables to respect low insulation level on motor, low common mode voltage & current on the network and to ensure motor over-voltage damping.

We present the equivalent common mode diagram of our transformer-less system in Fig. 3, where we retrieve:

- The grounding impedance containing the 'Rgh' resistor & the 'Cgh' capacitor
- The common mode impedance of the generator, the filter & the motor
- The equivalent parasitic capacitance of the motor 'Cmotor'
- The common mode inductor connected to the damping resistor ('Lh' & 'Rh')

We can see that there is one zero-sequence loop for the common mode current. In this loop, we use the common mode inductor to introduce the damping resistor. This is just a «common mode interface».

The grounding impedance is designed to limit the zero-sequence voltage on the network neutral point. It also reduces the fault current if there is a phase-ground fault on the system.

We can see that the AFE & the Inverter generate the main common mode voltage sources.

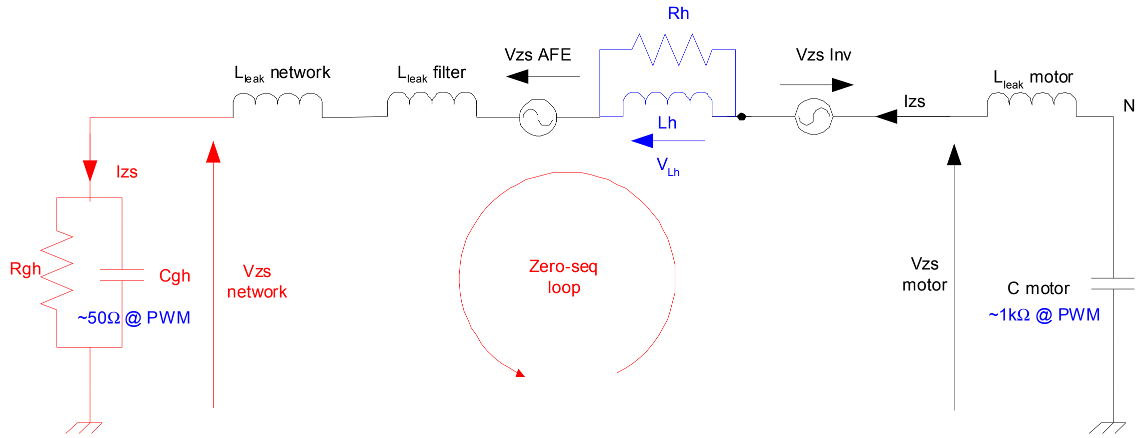

Fig. 3: Zero-sequence equivalent diagram of the AFE Transformer-less architecture

III. Design key points

The different steps of the design of our Transformer-less architecture will be detailed in the final paper. It will include the grounding impedance, the low common mode voltage PWM strategy & the common mode inductor study.

Grounding impedance

The grounding impedance is made by a parallel circuit with a resistor Rgh & an inductance Lgh.
The transformer-less solution is based on the grounding made on network side, that is why we have to impose Cgh highly greater than the motor parasitic capacitance Cm. It is the first key-point. (see Fig. 4 which illustrates the influence of the Cgh/Cmot ratio on zero-sequence voltage measured on network neutral point)

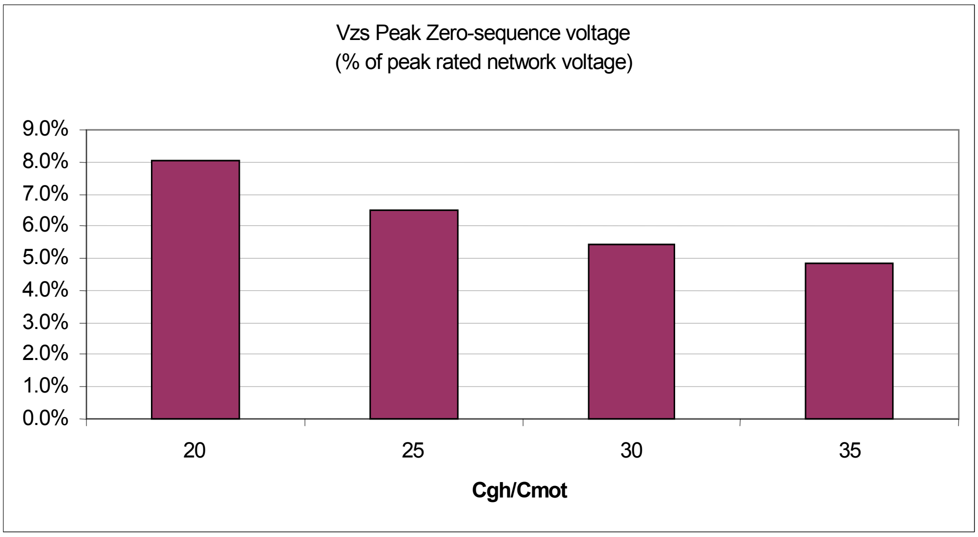

Fig. 4: Influence of the Cgh/Cmot ratio on zero-sequence voltage measured on network neutral point

When the capacitor Cgh is chosen, we have to calculate the appropriate resistor Rgh to limit the fault current in case of a phase-ground fault on the network (see equations (1), (2) & (3)).

$$Z_{gh} = \frac{V_{zs}}{I_{zs}} = \frac{R_{gh}}{1 + j.\omega R_{gh} C_{gh}} \tag{1}$$

$$\left|Z_{gh}\right| = \frac{U_n \big/ \sqrt{3}}{I_{fault}} = \frac{R_{gh}}{\sqrt{2}} \quad \text{, with} \quad \omega R_{gh} C_{gh} = 1 \tag{2}$$

$$R_{gh} = \frac{U_n \times \sqrt{2}}{\sqrt{3} \times I_{fault}} \tag{3}$$

PWM strategy

To limit the phase to ground voltage at the motor terminals and keep the voltage level provided by a conventional solution of a VSI with transformer (Vphase-ground ≤ 2/3*Vdc without over-voltage), we use a suitable PWM control on our converters. This PWM allows, one hand, to reduce the motor phase-ground voltage, on another hand, to mitigate the zero-sequence voltage on the neutral-point of the network.

With our transformer-less topology, the motor phase-to-ground voltage may be calculated with the following method :

- The first approximation is to consider the grounding capacitor like a simple «short-circuit cable» for the main switching frequencies of the drive
- We assume there is no over-voltage on the motor only in this study method (no need to damp, so the common mode inductor is not included in the equivalent diagram of the fig. 5).
- The voltages between the converter phases and their own DC bus neutral points ($Vu0_{AFE}$, $Vv0_{AFE}$, $Vw0_{AFE}$, $Vu0_{INV}$, $Vv0_{INV}$, $Vw0_{INV}$) are assimilated to some controlled voltage sources depending on the DC bus voltage & their switching functions (S) (see the example for the U phase in eq. (4))
- The equivalent diagram (fig. 5) of the transformer-less solution gives the motor phase-to-ground voltage expression (cf. eq. (5))

$$Vu0_{AFE} = S_U . \frac{Vdc}{2} \tag{4}$$

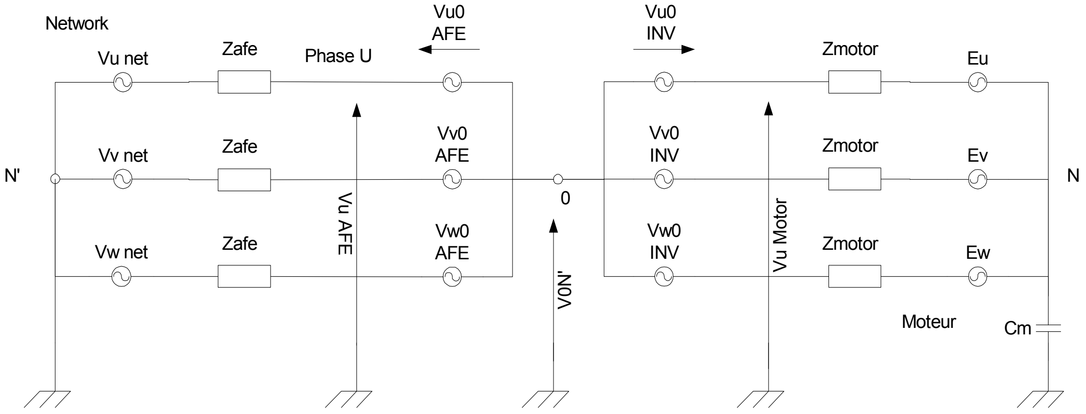

Fig. 5: Equivalent diagram of the transformer-less solution giving the motor phase-to-ground voltage expression

$$Vu_{Motor} = Vu0_{INV} + V_{0N'}$$

$$\begin{cases} V_{0N'} = Vu_{AFE} - Vu0_{AFE} \\ V_{0N'} = Vv_{AFE} - Vv0_{AFE} \\ V_{0N'} = Vw_{AFE} - Vw0_{AFE} \end{cases} \Rightarrow \begin{cases} V_{0N'} = \frac{1}{3}\left(Vu_{AFE} + Vv_{AFE} + Vw_{AFE} - (Vu0_{AFE} + Vv0_{AFE} + Vw0_{AFE})\right) \\ V_{0N'} = \frac{1}{3}\left(0 - (Vu0_{AFE} + Vv0_{AFE} + Vw0_{AFE})\right) = -Vh_{AFE} \end{cases} \qquad (5)$$

$$\Rightarrow \quad Vu_{Motor} = Vu0_{INV} - Vh_{AFE}$$

From the phase-to-ground voltage expression (eq. (5)), we are able to find a strategy to obtain the desired magnitude level of the motor phase-ground voltage (i.e. (Vphase-ground ≤ 2/3*Vdc without over-voltage). In the diagram of Fig. 6, we show that this strategy consist to limit only the zero-sequence voltage generated by the Active Front-End. So the PWM strategy of the AFE has to limit $|Vh_{AFE}| <= 1/6.Vdc$.
This result is only available with our transformer-less topology.

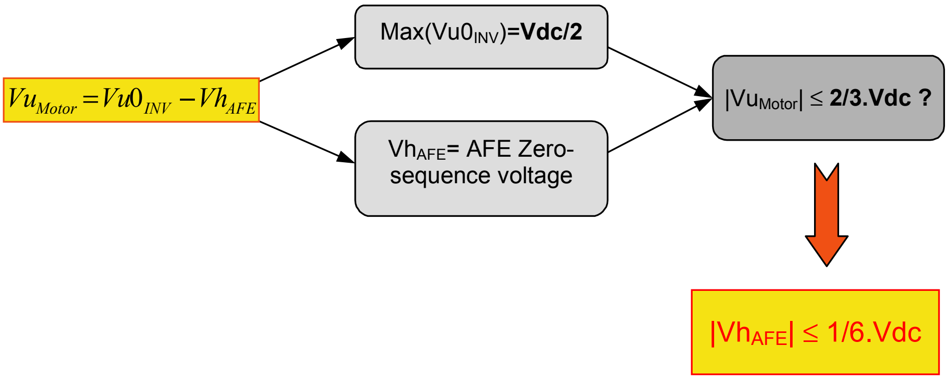

Fig. 6: Demonstration of the essential freedom degree that allows to minimize Vu_{Motor}

Common mode inductor

In this part, we specify the common mode inductor design. This component is considered like a DC single-phase transformer (cf. Fig. 7). This component has a primary side connected on the DC bus and a secondary side connected to the damping resistor.
The three main characteristics in the common mode inductor design are:

- The magnetizing inductance value (Lm) of this component.
- The leakage inductance value (Lk)
- The damping resistor value (Rh).

The magnetizing inductance has to be highly greater than the total leakage inductances of the zero-sequence circuit (cf. Fig. 8). In that case the main zero-sequence components are present in the zero-sequence voltage applied to the common mode inductor, so this common mode inductor has more influence to introduce the damping resistor effect in the zero-sequence circuit.

The leakage inductor, in Fig. 7, is specified to limit the current on a DC short-circuit fault and also to tune the resonant frequency of the DC bus to avoid converter switching frequencies.

The damping resistor value is chosen to be the same order than the magnetizing reactance value (in the case of a unit transformer ratio for the common mode inductor we retrieve the expression of eq.)

$$R_h \approx L_m.\omega \qquad (6)$$

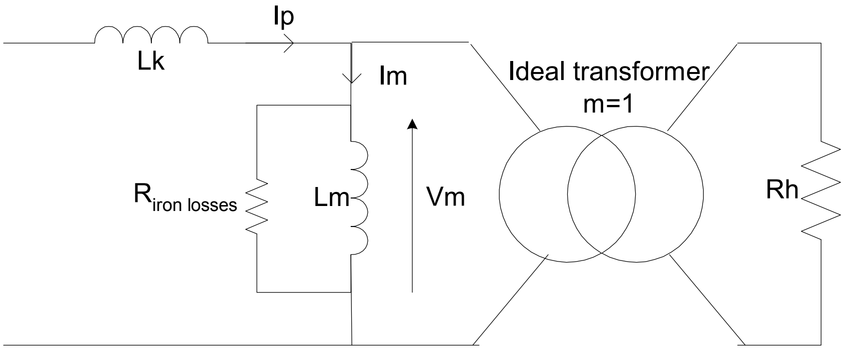

Fig. 7: Model of the common mode inductor seen as a DC single-phase transformer

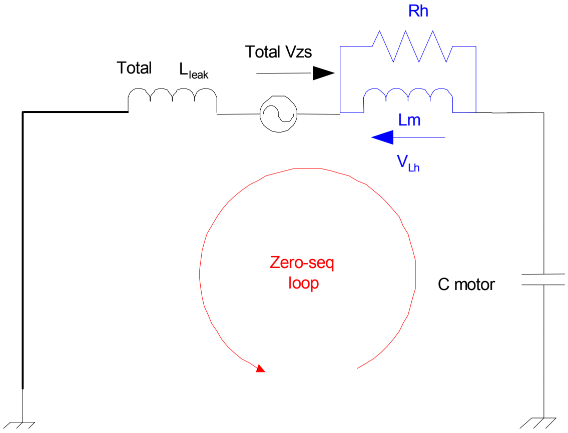

Fig. 8: Zero-sequence equivalent diagram used for the common mode inductor design

IV. Results

Simulation results

In this part, we present some results from simulation. In Fig. 9, we illustrate the common mode voltage of the network (in PU). We can see that this voltage is lower than the 5% criteria.
In Fig. 10, we can see the common mode current in the zero-sequence loop. The RMS current is about a few Amps which is acceptable and don't affect magnetizing part of machines (generator & motor).

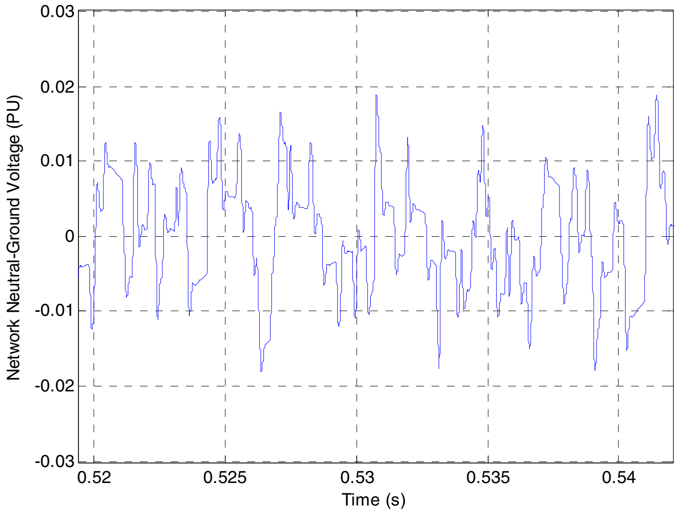

Fig. 9: Neutral point-Gnd network voltage

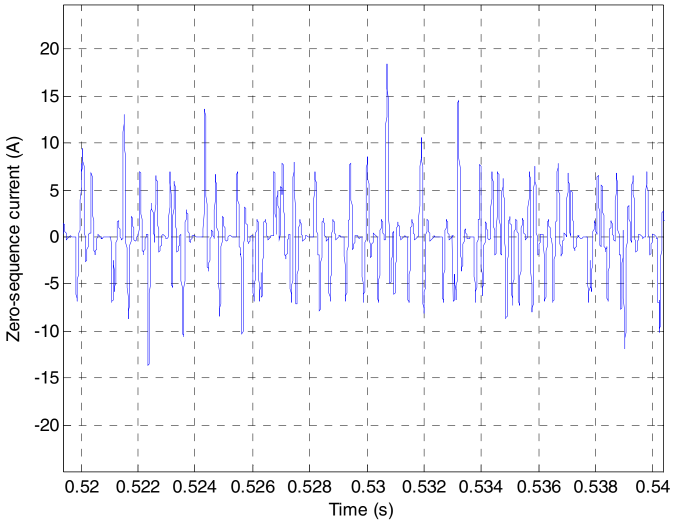

Fig. 10: Zero-sequence current in grounding impedance

In Fig. 11, we clearly show on the motor phase-ground voltage that we respect the limit of 2/3Vdc (for 10kV DC bus, it is 6.66kV). Moreover, we are able to damp the over-voltages lower than 20%.

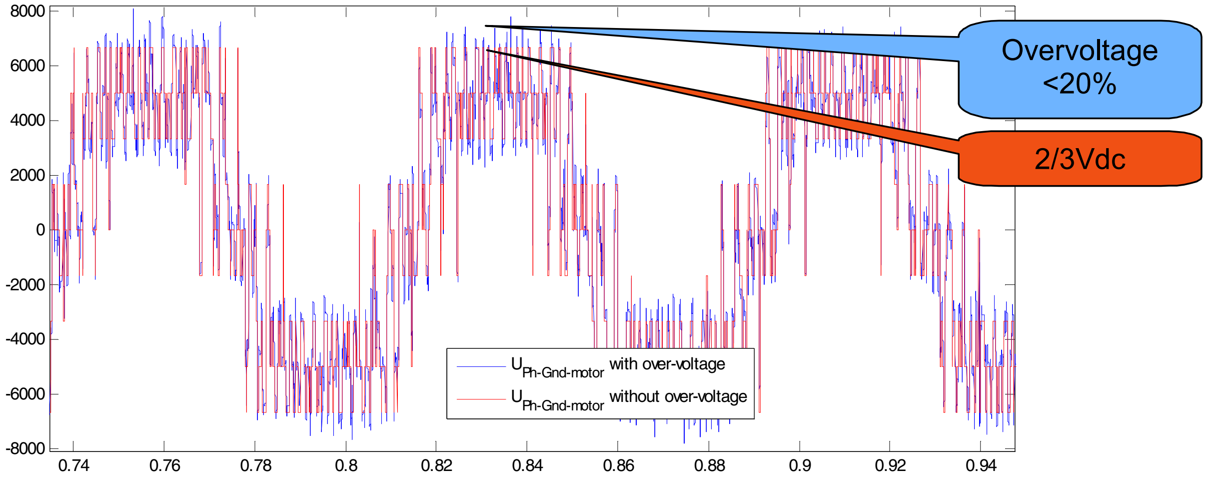

Fig. 11: Phase Ground Voltage on 6.6kV Motor – With & Without over-voltage

Experimental results

In this part, we show some experimental results. illustrate that the motor parasitic capacitance has a real influence on the zero-sequence voltage measured between the network neutral point and the ground. In this test, we change the Cm capacitor (1uF & 0.47uF) and keep the grounding capacitor value Cgh (10uF). In fact, we illustrate the influence of the ratio Cgh/Cm. When this ratio is increased we retrieve the fact that the network zero-sequence voltage decreases. That is why the network grounding is very important in our transformer-less topology.
We can notice in Fig. 13, that the resistor Rh has a real effect on the damping effect in the zero-sequence circuit. When Rh is increased, we see that the voltage on the motor parasitic capacitor is more and more damped. By considering that the main over-voltage on the motor are 'seen' by the parasitic capacitor Cm, these results show that Rh resistor can damp the motor over-voltage.

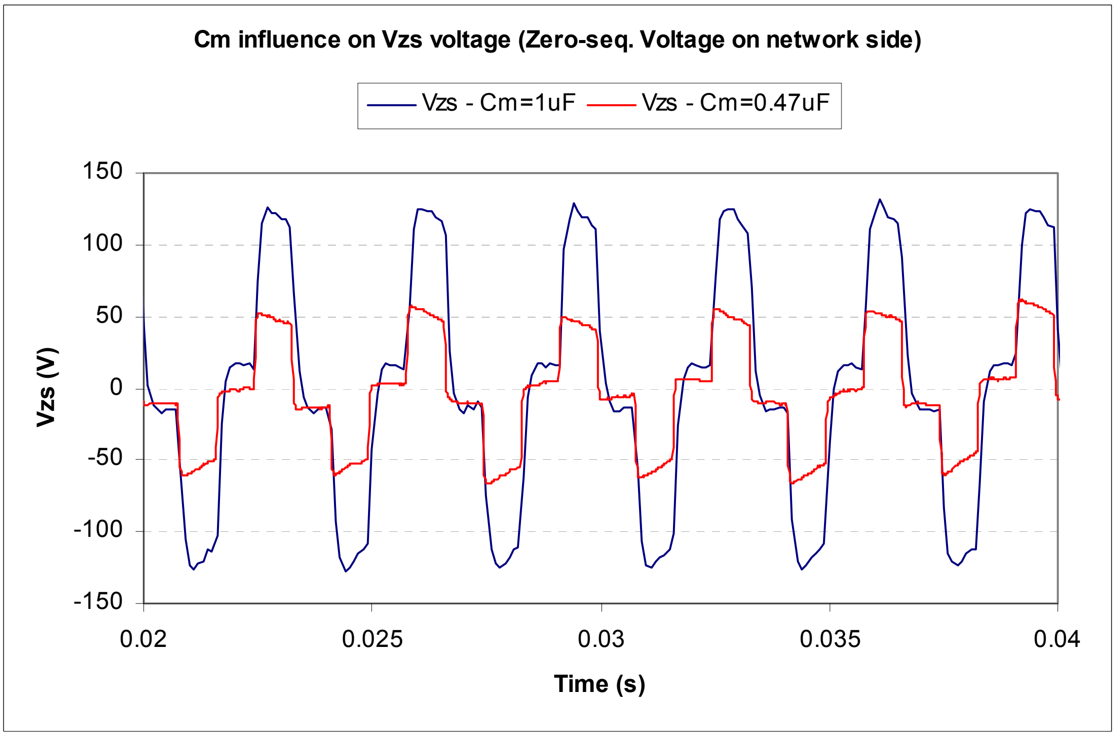

Fig. 12: Influence of the motor parasitic capacitance on the network zero-sequence voltage

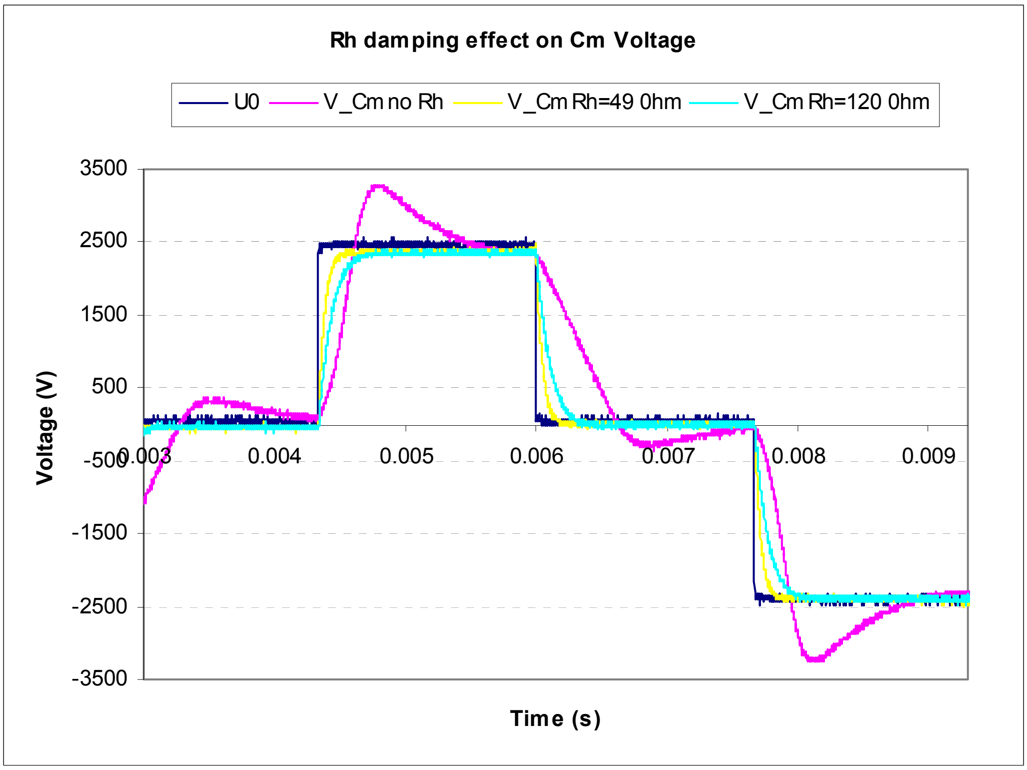

Fig. 13: Damping effect of the resistor connected to the common mode inductor

Conclusion

In this paper, we show how we have developed the transformer-less solution. We have demonstrated that this system can be integrated with classical motor, without high-dedicated insulation. This solution is a global system, which combined the 3-phase architecture design, the common mode diagram topology, and the AFE & Inverter PWM control. In this kind of transformer-less propulsion, we have to take under control all these elements. The outlooks of our transformer-less solutions are many, for example we could imagine AFE transformer-less with power factor correction to reduce the size of generators.

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