Comparison of 3-, 5- and 7-leg Voltage Source Inverters for low voltage applications

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***Abstract* - In the context of high power low-voltage applications as starter-generator for automotive, multi-phase drives present the attractive characteristic of reducing the current per phase and per leg. A 5- or 7-phase machine is also more suitable for using concentrated windings, attractive for their short end-windings and subsequently for a higher expected torque-to-volume density. In this perspective, the 5- and 7-leg Voltage Source Inverters (VSI) are compared with the 3-leg VSI. In the first part, for the same set of resistances and inductances coupled in different wye-coupling configurations, we examined the DC-bus currents and the power recovered by the load for a square-wave VSI control: the 7-leg VSI is the more efficient because it makes best use of the harmonics. In the second part, the torque ripples of 3-, 5- and 7-phase drives are compared: the 7-phase drive torque ripples are the lowest ones because of the less sensitivity to the harmonics of the currents. In the last part, a Pulse Width Modulation control is studied, with almost the same voltage harmonics amount as this one obtained with the square-wave mode control. Experimental results are given for the 7-leg VSI either with a passive load or with a 7-phase permanent magnet synchronous motor.**

I. INTRODUCTION

In automotive industry, despite an increase of electrical power, 42V system is not still a standard [1]-[2]. Economical constraints make pressure to use as far as possible the historical 14V system. It is the case for the StARS belt-driven starter generator developed by the automotive supplier Valeo. This system is already used in micro-hybrid systems, currently proposed to consumers by different car manufacturers on the market.

For the 3-phase machines supplied by 3-leg VSIs, the optimum use of the DC-bus voltage has been widely studied [3]-[4]-[5]. The square-wave six-step voltage waveform gives the best result but induces undesirable harmonics of current and consequently torque ripples for the drives. Then, Pulse Width Modulation (PWM) controls have to be used to get a smoother torque.

In the context of high power and low voltage applications, multiphase machines with more than three phases are attractive for several reasons. Firstly, the current per phase and per leg is lower. So, it is possible to use only one or two power electronic devices per leg instead of a set of parallel connected devices [2]-[6]-[7]. The reliability is then higher and the over-sizing unnecessary.

Secondly, the multi-leg VSI offers another way to optimize the use of DC-bus voltage. Compared with the 3-phase inverter, a higher modulation index m can be achieved and the DC-bus current ripples are lower [8]. The 5- and 7-phase systems can make more profits of the voltage harmonics than the 3-phase ones: the torque can be increased by using the third and the other harmonics without the usual drawbacks found for the three-phase machines such as torque ripples.

Multi-leg VSIs have been mainly studied in order to determine the switching times in the case of a PWM control [9]-[10]. In [11], the modulation index is studied for a 9-phase system but only by injecting a ninth harmonic: by comparison with a 3-phase VSI with $m = 0.785$ the increase of index is only of 1.5%. It appears that if the injection of a homopolar component in a 3-phase VSI has a great impact on the maximum modulation index (+15.5%), it is not the case with a 9-phase VSI (+1.5%). On the contrary, the injection of a third harmonic component has always an impact. In [10], the effect of the third harmonic on the modulation index is examined for a 5-phase VSI and a special Space Vector Pulse Width Modulation control: a maximum increase of 6.6% of the modulation index ($m = 0.967$) is found.

The aim of this paper is to compare the performances of 5- and 7-leg inverters with those of a 3-leg one. For a same kind of control and a given set of basic loads, we compare the power that can be recovered, the spectrum of one phase current and the DC-bus current.

At first, we consider the square-wave control which allows to get a maximum RMS value of the phase voltage (modulation index $m = 1$). Experimental results for the 7-phase load confirm the simulation predictions.

In the second section, a square-wave supply for multi-phase machines is simulated: torque ripples are examined. In the last section, experimental results are given for a seven-

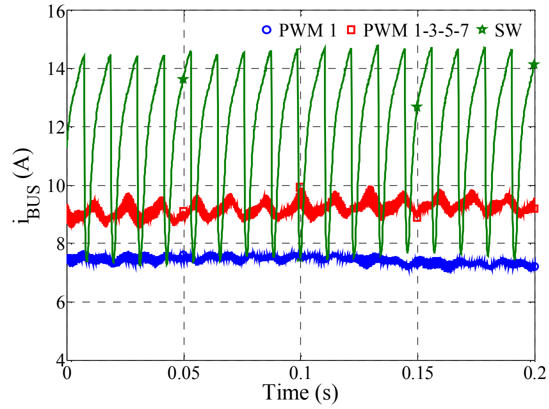

Fig. 13. Experimental currents i_{BUS} waveforms for SW, PWM 1 and PWM 1-3-5-7 controls.

TABLE III
EXPERIMENTAL CONTROLS COMPARISON: MAIN RESULTS

	PWM 1	PWM 1-3-5-7	SW
Average torque (Nm)	34.5	33.7	33
Speed (rpm)	81	97	125
Average power (W)	292.6 (+)	342.3 (++)	432 (+++)
DC-bus courant ripple (A)	0.5 (+++)	1.5 (++)	7 (+)

V. CONCLUSION

In the sections II and III we show that for wye-coupled loads it is possible to achieve a best use of the DC-bus voltage with the 5- and 7-leg VSIs. This result is particularly important for the automotive drives because of the low level of voltage. The main reason of this advantage lies on the fact that for 5- and a 7-phase machines there are no interactions between the first, the third and the fifth harmonic. Consequently, it is possible to make profit of the third and the fifth voltage harmonics without the usual drawback of torque ripples. In the last section, using the previous conclusions obtained for a square-wave control, a PWM control with special spectrum is tested on an experimental 7-phase machine. This control appears as a good compromise to get both advantages of PWM and square-wave controls.

VI. REFERENCES

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