Overview of PAM&PWM Control Strategies for Controlling High-Speed Electrical Machines

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Abstract

This paper presents the control strategy for a high speed PMSM with the focus on combining PAM&PWM (as it was shown before that it will minimize the power losses by decreasing the inrush current peak). In PAM control strategy, the terminal voltage of Permanent Magnet Synchronous Motor (PMSM) increases with rotor speed. This means that the rotor speed of PMSM is constrained by the DC link voltage of inverter. simulation results for PAM & PWM control method, and steps to improve the PAM control are reported. The simulations were performed with data for PMSM (nominal speed: 25 000 min-1, power: 3.1 kW, load: 1.2 Nm).

Keyword: high-speed electrical machines, frequency inverter, SiC, IGBT, power losses, static losses, dynamic losses.

1. Introduction

High-speed machines are being developed for many uses during the last perioud, such as machine tools, compressors, vacuum pumps, friction welding units, turbine generators, and many more. The interest in these high-speed machines is increasing over and over, since the mechanical gear can be removed, and they provide smaller size for the given power. Induction motors, switched reluctance motors, and permanent-magnet (PM) motors are the choice to use for high-speed operation, especially when variable speed is required. More over, a special design must be used when the motors have to operate at high speed range [1]. These machines are usually controlled by using a frequency inverter, where the speed and the power can be controlled. This paper is an overview for the ways that we can use to control these high-speed machines, with the focus on the control topology that is used in the frequency inverter. The aim is to show the possible ways for controlling these machines and state which control method is the best to use with these machines according to the application that are used for. Inorder to explain the uses, speed limits and methods for controlling these high speed electrical machines, many papers has to be presented:

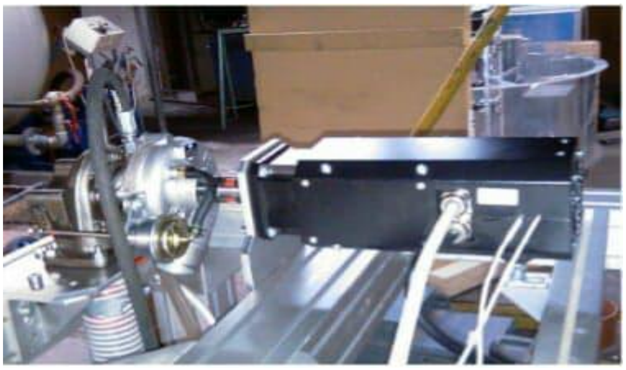

Figure 1. *high speed electrical machine [3]*

"High speed PM machines: applications, trends and limits" [2], This paper gives an introduction to high-speed permanent magnet machines, it analyzes many applications of these machines, defines the attribute “high-speed” and presents a general theoretical study of speed limits of PM machines. This paper also clarifies speed, power and size of PM machines, an example of a high-speed machine can be seen in (Fig.1), with speed 40 000 RPM, torque 7 Nm.

"An SiC inverter for high-speed permanent magnet synchronous machine"[4], when dealing with high speed machines, current with higher frequency should be provided when comparing it to the normal electrical machines, It was needed to use frequency inverter, but IGBT based on the experiment showed much switching losses (especially turn-off loss) and less efficiency when compared to the SIC MOSFET in the field of the higher frequencies. SIC inverter showed great results even up to 500kHz switching frequency, and the target was only 100kHz. So it can be seen that in the high frequencies SiC transistors can be the best option because it has lower switching losses when compared to the other transistors technologies.

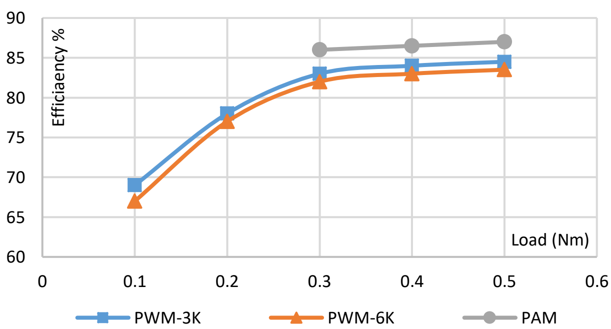

Figure 2. *Comparison results of efficiency between PWM 3000 HZ-6000 HZ, and PAM (Speed = 4600 rpm, full load = 0.5 N-m) [11]*

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"Combined heat and power generator with high-speed permanent magnet synchronous machine"[5], This paper presents the description and the results during the development of a small combined heat and power unit, wich consists of a turbine and a high-speed permanent magnet synchronous machine, it also shows the main problems and issues that is needed to solve in this unit (The main problem of the unit is its mechanics). In this work the main goal was to create an affordable power supply for combined electrical energy and heat production, it was possible to reduce the speed using some transmission but this decreases the efficiency and makes mechanical problems so the turbine was connected directly to the generator and use PMSM controlled with an inverter.

"Comparison of electromagnetic performance and power losses of a high speed machine fed by PWM and PAM inverter strategies"[6], the maon goal from this paper is to compare and study electromagnetic performance and power losses of a high-speed surfacemounted permanent magnet (SPM) machine supplied by a pulse-width modulation (PWM) and pulse-amplitude modulation (PAM). It includes simulation for the used inverter which is operated at different DC-bus voltage levels and different modulation. The comparison focuses on the phase current and voltage, and distortion of the torque waveforms and the core, rotor and inverter losses. The result was that, at higher DC-bus voltage, higher phase current distortion is found and consequently higher torque ripple and induced harmonics in the rotor loss.

"Modeling and comparison of machine and converter losses for PWM and PAM in high speed drives"[7], this paper expaines the machine losses, where different components of the drive system needs to be known in order to choose the ideal machine and modulation combination. The rotor, copper, and core losses of the machine as well as the inverter losses are explained, taking the modulation type into account. These models are developed by considering two typical high-speed permanent-magnet synchronous motor topologies (slotted and slotless machines) driven by pulse-amplitude modulation (PAM) and pulsewidth modulation (PWM) converters. It was shown that PAM produces a higher

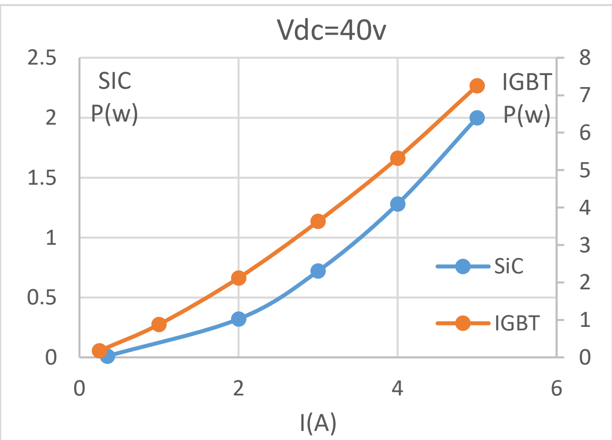

***Figure 3**. static losses comparison between SiC and IGBT(Vin= 40V)*

overall efficiency for the high-speed machines considered in this paper.

"Components selection for frequency inverter to control high speed electrical machines"[8], This paper takes many topics about high-speed electrical machines, new ways and many uses for these machines machines and theoretical study of their limits are presented. In this paper, the best components to build a frequency inverter that can be used to control the high-speed electrical machines(mainly from 0 up to 100v) in the best way with the lowest losses are presented. Moreover, The results for testing the best components to build the frequency inverter that can be used to control the high-speed electrical machines are reported. The static and dynamic losses for different kinds of transistors (SiC, IGBT) are reported.

2. Decreasing the power losses in the used inverter:

Creating a frequency inverter is a good method to control the high-speed electrical machines in the best way. When planning to design a frequency inverter, for sure good components should be used, which gives the best results with the lowest power losses. After searching and investigating about the most common transistors which are suitable to use for building frequency inverters, 3 different transistors were found, those transistors are separated into 3 different groups:

-IGBT transistors (insulated-gate bipolar transistor).
-SiC transistors (silicon carbide transistors).
-Gan transistors (Gallium nitride transistors).

SiC showed better results and lower power losses when we compare it with the IGBT transistors, moreover, Gan seems to be the best choice for decreasing the power losses, and also for having better performance and efficiency in the used application [8]. (Fig.3,4,5,6,7) show the static and dynamic losses comparison between SiC and IGBT transistors (more details about this comparison can be found in [8]).

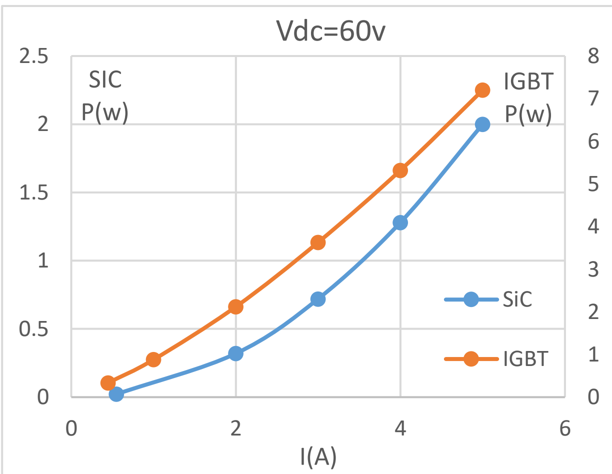

***Figure 4**. static losses comparison between SiC and IGBT(Vin= 60V)*

3. Steps to improove the PAM control

Inorder to improove the PAM control method that can be used in the frequency inverter to control the high-speed electrical machines, Several points were taken under consideration, “Fig.8”, shows a simulation of PAM & PWM control for a PMSM, the PAM controller uses the actual speed as an input to generate a controlled DC voltage to feed the inverter. Tab.1 shows the used PMSM parameters. And it is clear that when using PAM control the current peak will be lower “Fig. 9”.

3.1. Starting DC voltage value

It can be seen that when starting the dc voltage for the inverter with the value of 50V (approximately 10% of Vdc), the phase current peak will not exceed 15 A (Fig.9), and if we compare it with the peek when applying the full dc voltage (500V), we can see that it is almost 26 A (1.8x), however when we start from the value of 100V, the phase current peak will be around 18.5 A (when we apply no load, and when the full DC voltage is reached when the motor is at 50% of the maximal speed). (Fig.10) shows a comparison between phase current peak when applying (50 up to 500)V at the beginning.

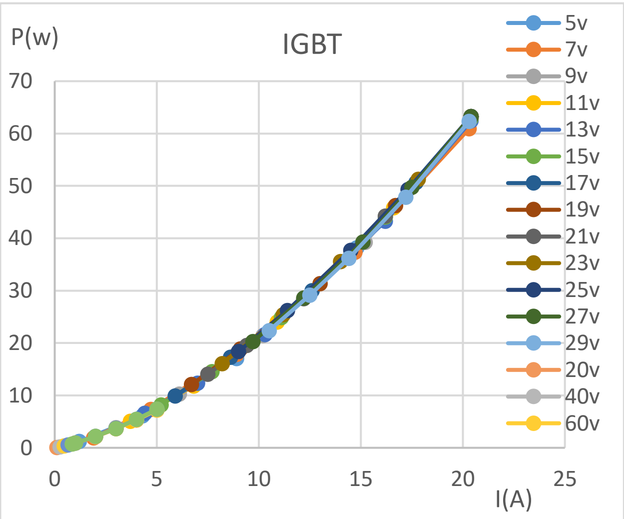

Figure 5. *static losses for all the voltages(0->100)V for IGBT*

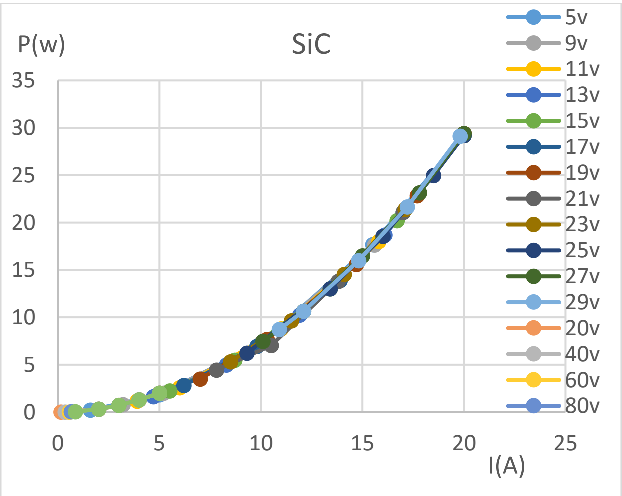

Figure 6*. static losses for all the voltages (0->100)V for SiC*

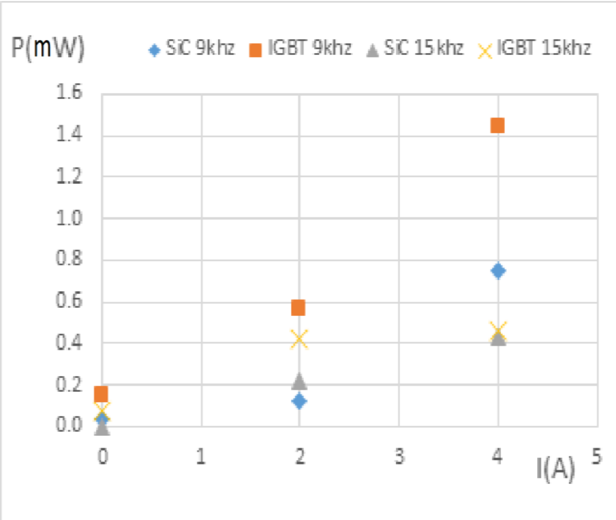

Figure 7*. dynamic losses comparison between SiC and IGBT when switching off(Vin=60V, f=9kHz, 15kHz)*

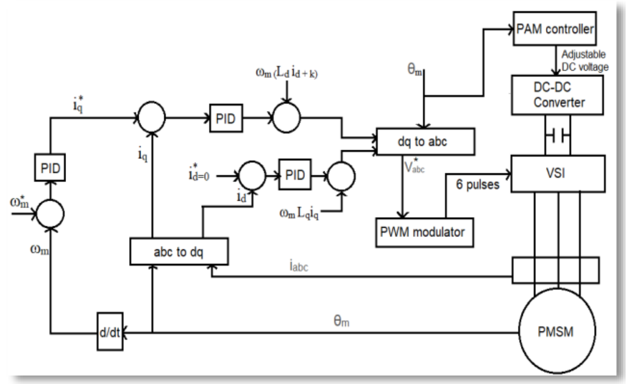

Figure 8*. PAM & PWM simulation using Matlab to control PMSM*

Table 1. *The used PMSM parameters*

Symbol	Quantity	Value
V_{dc}	DC Voltage	560 [V]
V_n	Nominal Voltage	179 [V]
I_n	Nominal Current	12.2 [A]
T_n	Nominal Torque	1.2 [Nm]
T_{max}	Maximal Torque	7 [Nm]
n_n	Nominal Speed	25 000 [min^{-1}]
n_{max}	Maximal Speed	40 000 [min^{-1}]
$R_{U\text{-}V}$	Winding Resistance	0.396 [Ω]
L	Winding Induction	0.0025 [H] (for I = I_n)
J	Moment of Inertia	0.00011 [kgm^2]

3.2. The best time to reach the full DC voltage in the PAM controller

It was concluded that:

1) when applying the full DC voltage when reaching 25% of the maximal speed, the current peak will be 16.5A, and the motor will need almost 0.87 s to reach the full speed (whereas the time needed to reach the full speed 42 krpm without applying the PAM control is 0.4 s) (Fig.11).

2) when applying the full DC voltage when reaching 50% of the maximal speed, the current peak will be 15A, and the motor will need almost 0.88 s to reach the full speed (42 krpm) (Fig.11).

3) However, when applying the full DC voltage when reaching 75% of the maximal speed, the current peak will be 19.5A, and the motor will need almost 0.92s to reach the full speed (42 krpm), but it will be less stable because it will not get enough DC voltage while the speed increasing (the speed fluctuates) (Fig.11).

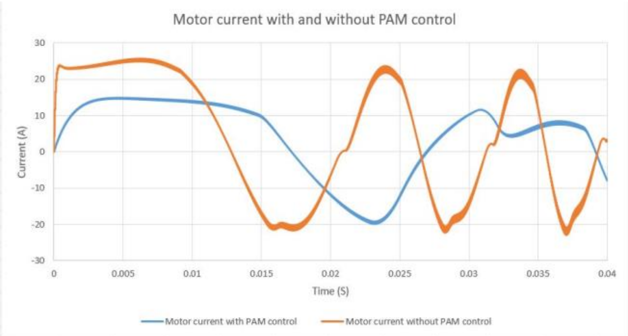

Figure 9. *Comparison between motor currents when running the motor with and without the PAM control, with no load, the PAM controller is set so the full dc voltage is reached when the motor is on 50% of its maximal speed, and starting DC voltage is 50V*

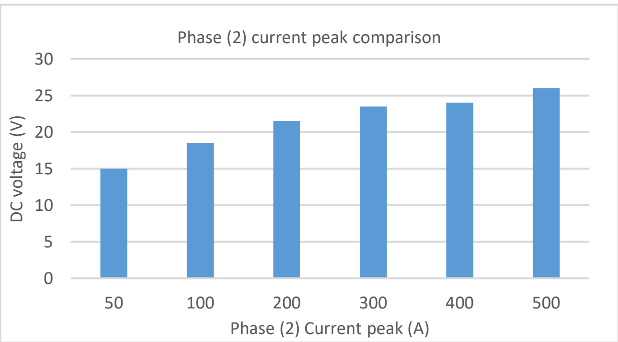

Figure 10. *Inrush current peak comparison when applying (50-500)v at the beginning, with no load, The PAM controller is set so the full dc voltage will be reached when the motor is at 50% of its maximal speed*

4. Conclusion

In this paper, it has been shown in simulation that adding the PAM controller will improve the control strategy of the high-speed PMSM by decreasing the power losses in the frequency inverter. The used PAM decreases the phase current peak till approximately ¼ of the original value (when not applying the PAM). The machine and inverter losses are explained and compared by changing the PAM parameters, from the comparison, it was found that the current peaks and consequently the inverter losses increase when higher starting value of DC voltage is used in the PAM controller. Furthermore, with the PAM controller, reaching the full DC voltage earlier will cause a higher phase current peak, wich will lead into higher power losses. Also, the higher the applied load is, the higher the current peak will be, and the more start-up time the machine will need. However, this paper has shown how the inverter modulation strategy affects these parameters. This highlights the importance particularly for high speed machines of an integrated design and optimization of power electronics together with the rotating machine, taking into account the system requirements such as DC bus voltage. Although, PWM with high switching frequency is found to result in high inverter losses, a design approach with optimized winding inductance and an inverter with low-loss switching devices, e.g. GaN, can be a solution for this issue [8].

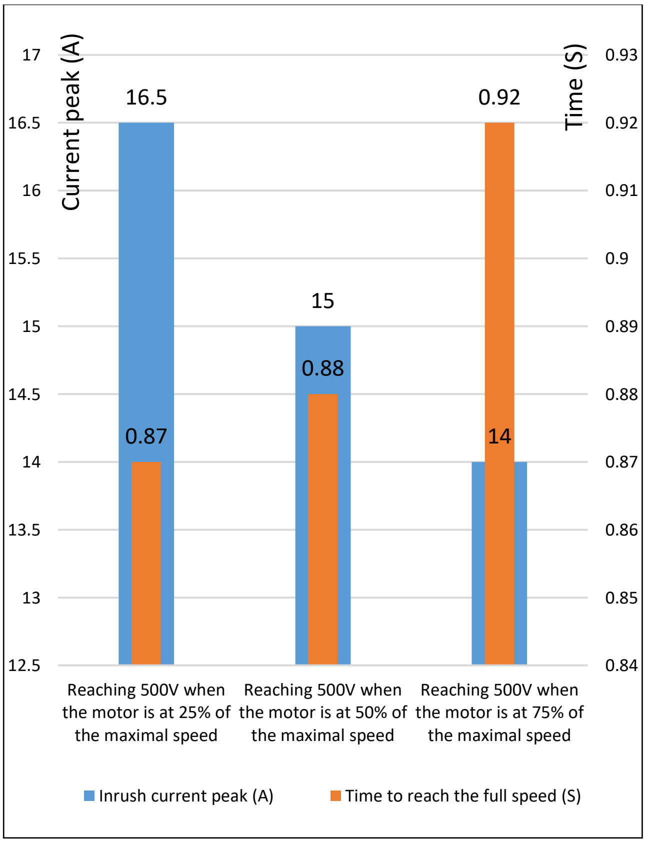

Figure 11. *Inrush current peak and time to reach the full speed comparison when applying the full dc voltage at different times, starting dc voltage in the PAM controller is 50V, no load applied*

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