UNCONTROLLED GENERATION IN NINE-PHASE MACHINE DRIVE

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Uncontrolled generation (UCG) is a phenomenon that occurs in electric drives when operating in a field-weakening and a gate signal is suddenly removed from switches. When the induced voltage is higher than the DC link voltage, a path is created for current to flow from the machine through the freewheeling diodes of the converter back into the DC link. While UCG is commonly associated with three-phase drives, the topology of some multiphase machine drives—comprising separate three-phase winding sets—enables the manifestation of UCG in only one winding set. This arrangement allows the remaining two winding sets to facilitate post-fault operation.

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I Introduction

Multiphase machines (MM) with the number of phases equal to a multiple of 3, can have their phases organised into three-phase winding sets. Each winding set (WS) consists of three phases, which have a spatial distribution of $2\pi/3$. The division into three-phase winding sets has the advantage of treating each WS as a three-phase machine and we can use the already known and accessible technology for the control.

During field weakening operation various faults can occur in the MM drive. One of the ways to control these is to deactivate the winding set in which the respective faulty phase is located. Deactivating one of the winding sets can lead to uncontrolled generation, i.e. a reverse current occurs which flows from the machine back into the DC link through free-wheeling diodes. This large diode current can damage the inverter or shorten the service life of the power devices. This phenomenon is mainly described for three-phase machine drives [1], but in this article, the focus is on a MM drive.

II Nine-phase machine DRIVE

The UCG in a MM drive is described for a nine-phase synchronous machine with surface-mounted permanent magnets (9SPM). The nine phases are organized into three winding sets. Each WS has an isolated neutral point. The sets are mutualy weakly magnetically coupled and electrically aligned. A layout of the WS alignment in a 9SPM is shown on the right-hand side of Fig. 1. This type of MM can also be found in the literature under the name modular triple three-phase machine [2].

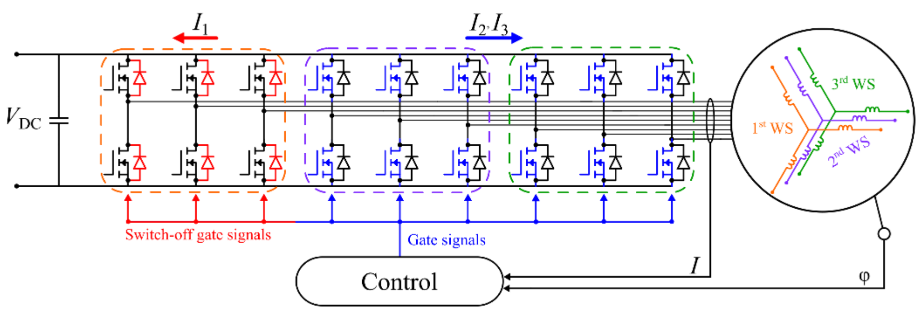

Figure 1: Schematic diagram of an uncontrolled generation in a 9SPM machine drive

III Uncontrolled generation

The UCG phenomenon in a MM drive is described with the help of Fig. 1. As shown in the figure, a nine-phase machine drive consists of a 9SPM, a nine-phase inverter, a DC link and control.

Various faults (e.g. overcurrent) in the machine drive can occur during the rotation of the machine in a high-speed range, i.e. deep in the field weakening region. Since the analysed MM consists of three winding sets that have isolated neutral points, one of the ways to protect the drive from the inevitable faults is to simply disable the faulty WS. The faulty WS is deactivated by applying switch-off gate signals to the corresponding transistors in the nine-phase inverter.

Consequently, the deactivation of certain transistors when the 9SPM rotates at high-speed causes UCG. A relatively large current (I_1 in Fig. 1) can be generated in the deactivated WS, which then flows back into the DC link via the uncontrolled rectifier (marked as red freewheeling diodes in Fig. 1) and poses a great risk to the power devices. This diode current results from the fact that the rotor speed is much higher than the base speed n_{base}, which marks the highest threshold value of the constant-torque speed range. Consequently, the amplitude of the line-to-line back electromotive force exceeds the DC link voltage V_{DC}, which means that the disabled WS operates as a generator and charges the DC circuit via the uncontrolled rectifier [1].

The rotor speed at which UCG occurs can be approximated using the following equation [1], [3],

$$n_{\mathrm{UCG}} \approx \frac{V_{\mathrm{DC}}/\sqrt{3}+2\cdot V_{\mathrm{F}}}{V_{\mathrm{DC}}/\sqrt{3}} \cdot n_{\mathrm{base}}. \tag{1}$$

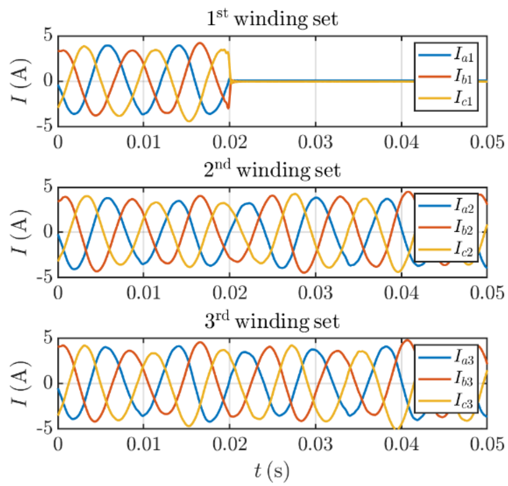

Figure 2: Phase currents of a 9SPM machine drive during a deactivation of the 1st winding set (n = 2490 rpm)

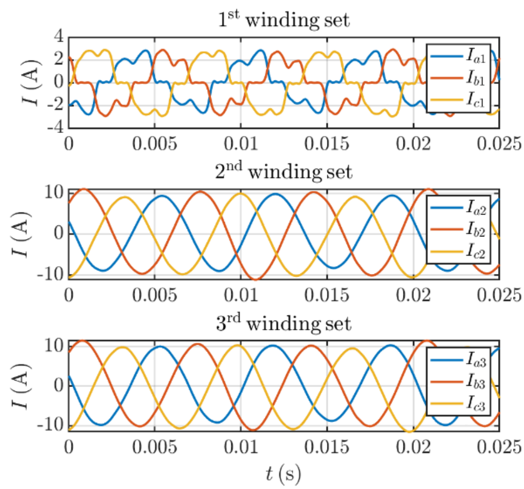

Figure 3: Phase currents of a 9SPM machine drive during uncontrolled generation (n = 3000 rpm)

The UCG can be recognised when one of the deactivated winding set's line-to-line voltages is greater than the threshold voltage $V_{\mathrm{DC}}/\sqrt{3} + 2 \cdot V_{\mathrm{F}}$, where V_{F} stands for the forward voltage drop of a freewheeling diode [1].

During the UCG in the deactivated WS, the other two (active) sets continue to operate as a motor, i.e. the currents I_2 and I_3 flow from the DC circuit through the controlled inverter (marked as blue transistors in Fig. 1) to the active winding sets in the machine.

IV Experimental results

For the experimental validation of the occurrence of UCG in a MM drive, a nine-phase machine drive with the parameters listed in Table 1 was used.

Table 1
Machine Drive Parameters

Parameter	Value	Unit
Base speed n_{base}	2217	rpm
DC circuit voltage V_{DC}	12	V
Maximum current I_{max}	16.6	A
Forward voltage of diodes V_F	0.7	V
Stator winding resistance R_s	80	mΩ
Self-inductance L_s	255	μH
Mutual inductance L_{m1}	17	μH
Mutual inductance L_{m2}	-31	μH
Permanent magnet flux linkage Ψ_{PM}	8.9	mWb
Number of pole pairs p_p	3	-

The measurements were carried out in the following sequence. The 9SPM drive was accelerated in a no-load operating mode to the referenced speed and then the transistors of the first winding set were intentionally switched off.

The rotor speed at which UCG occurs was calculated using (1) and the threshold value is n_{UCG} = 2665 rpm. If the reference speed of 9SPM drive is lower than the threshold value, UCG does not occur and there is no diode current in the deactivated WS. This can be seen in Fig. 2, where at time t = 0.02 s the 1st WS is deactivated and there are no phase currents in the 1st WS after the transistors are switched off. The other two sets are still active and the amplitude of the currents in them is slightly higher in order to compensate for the deactivated WS and maintain the operating point of the drive.

At rotor speeds slightly higher than n_{UCG}, UCG occurs, but the diode current is small. To demonstrate a large diode current, a measurement of the phase currents was carried out at the speed n = 3000 rpm (Fig. 3). It can be seen that the diode current in the switched-off 1st WS is large, its amplitude is about one third of the current amplitude in the active winding sets. The diode phase currents are not continuous, which is determined by the diode conduction characteristics of the uncontrolled rectifier [1]. An analysis of the d and q components of the diode current showed that the current generates braking torque (the q-component of I_1 was negative). Consequently, the two remaining winding sets must operate in a post-fault state, maintaining original operating point of the drive while compensating for the braking torque induced by the diode current.

V Conclusion

In this paper, a brief analysis of UCG in a nine-phase machine drive was carried out. It was shown analytically and with measurements that the rotor speed must be deep in the field weakening region for uncontrolled generation to occur.

In future work, we will focus on further analysing the phenomenon, also by disconnecting more than one winding set. It will also be beneficial to include simulation results.

Acknowledgement

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