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Effect of Multi-phase Winding on Surface Permanent-Magnet Machine with Low Space Harmonics for Electric Steering Gear

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Surface permanent-magnet (SPM) machines with a fractional-slot concentrated winding (FSCW) present several advantages, such as high copper packing factor, short end-winding length, low cogging torque, small volume and good fault-tolerant capability, because of which SPM machines have been increasingly applied in aerospace applications. However, the key challenge of utilizing FSCW is abundant magneto-motive force (MMF) harmonics. These MMF harmonics result in high rotor eddy-current loss, acoustic noise and vibrations. In this paper, an analytical equation is derived to present the relationship between MMF harmonics and phase numbers. Finally, a 24-slot and 22-poles SPM FCSW machine is designed, adopting three, six and twenty-phase for validation, respectively. The slot-pole combination of 24-slot and 22-pole is selected. And the FCSW is adopted to improve copper utilization rate and reduce copper loss. In order to maximize torque density, the SPM rotor topology is employed and entire stator structure has been optimally designed. Besides, the machine adopts three, six and twelve phase, which is able to cancel some MMF harmonics with increased phase number. At the same time, the shape, size and pole-arc coefficient have been optimally designed to obtain better electromagnetic performance. Analytical method is adopted to derive the relationship between MMF harmonics and phase number. And finite-element analysis is employed to verify the electromagnetic performance of the designed SPM machine. The 1th, 5th and 7th harmonics are sub-harmonic, while 13th, 35th and 37th are the main slot harmonics. By using the multi-phase winding, the sub-harmonics are completely almost eliminated compared with those of three-phase winding. Also, the greatly decrease of the MMF harmonics, contributes to significantly reduce the PMs eddy-current loss. Besides, the unbalance magnetic force of nine-phase winding is smaller than that of three-phase winding due to the absence of sub-harmonics.

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