Dual-Channel Switched Reluctance Motor for Safety-Critical Applications Using Two 3-Phase Standard Inverters

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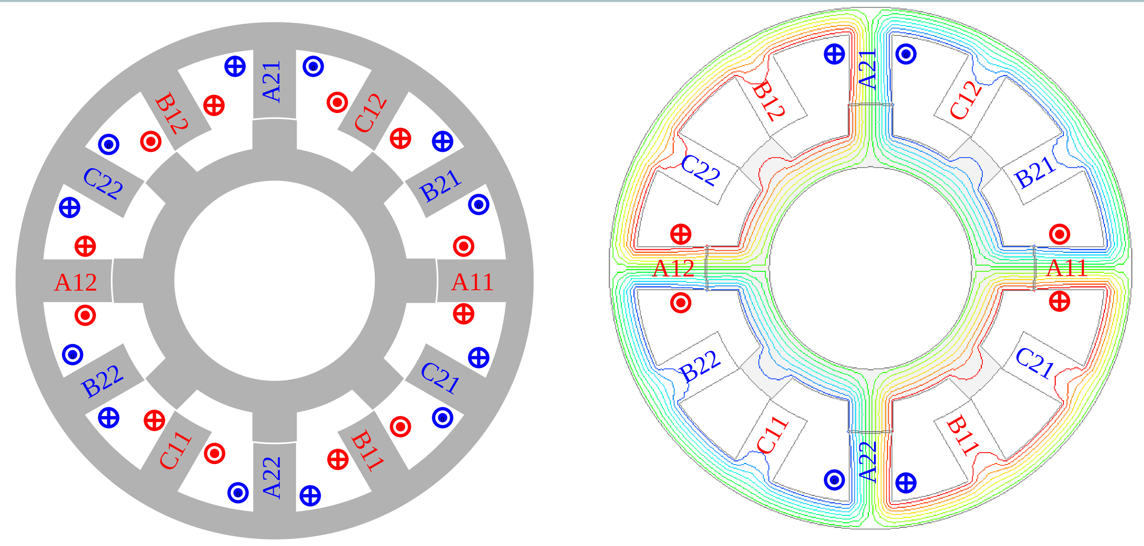
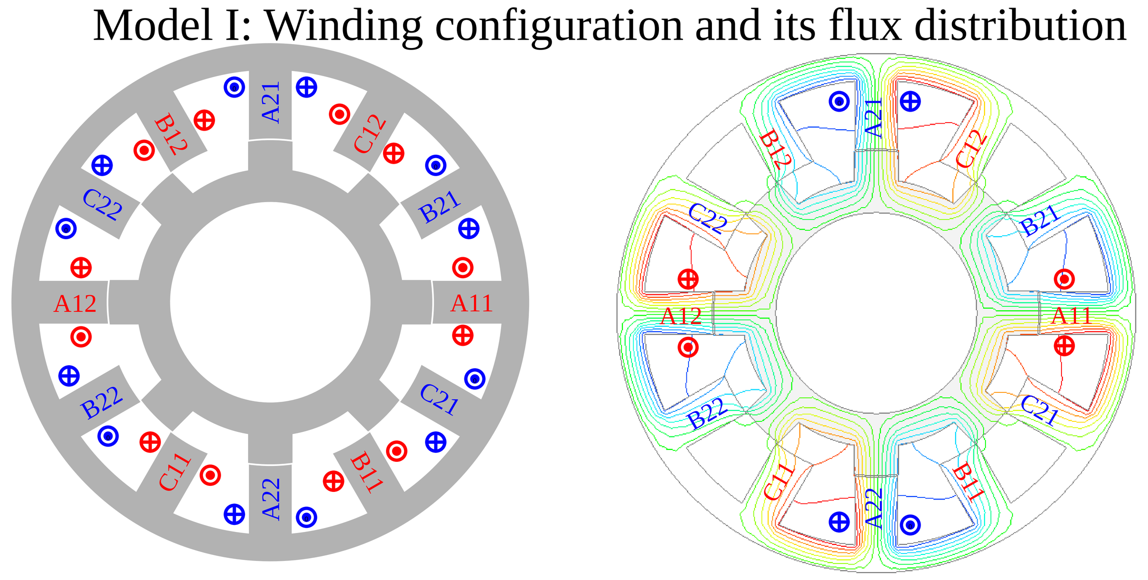
Summary

This paper proposes a novel dual-channel switched reluctance motor (DCSRM) using two 3-phase standard inverters. The key of proposed DCSRM is two operational models. In first operational model (Model I), it works like one 3-phase traditional SRM supplied by H-bridge inverter, which is driven by square-wave currents. In second operational model (Model II), it can be considered as two mutually coupled SRMs which are supplied by sine-wave currents. These operational models are used to overcome different fault conditions, and the corresponding remedial current strategies are proposed, realizing fault-tolerant working. Then, Model I is adopted for power switch fault. Meanwhile, the Model II is employed for open-circuit fault. Moreover, the performances of proposed DCSRM are calculated by finite element method and the fault-tolerant performances under different fault conditions are verified by co-simulation. It turns out that the proposed DCSRM can be used for safety-critical applications by combining the advantages of traditional SRM and mutually coupled SRM.

Topologies and Principle



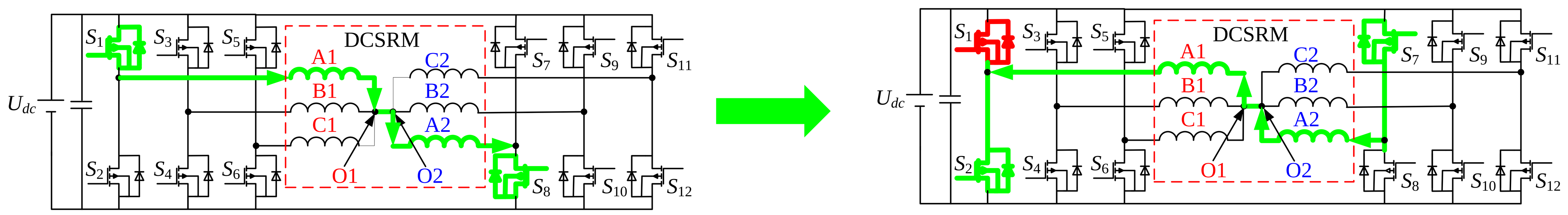
Model I: Winding configuration and its flux distribution



Model II: Winding configuration and its flux distribution

The cross section of the proposed DCSRM is given, in which "–" represents a GO conductor while "+" represent a RETURN conductor. The two opposing coils on poles A11 and A12 are placed in series to form the phase A1 of channel-1, the other two coils on poles A21 and A22 are placed to form the phase A2 of channel-2. In the Model I, it leads to an "NSNSNSNSNSNS" magnetic polarity on the stator poles. While the magnetic polarity on the stator poles is ""NNNNNNNNNNNN" in Model II. Although the directions of injected currents of channel-2 are opposite in two models, the positions of channel-2 are fixed. Then, the flux distributions of two operational models are obtained when 10A dc current are injected into the channel-1 and channel-2 properly. The flux distribution of Model I is same with that of conventional SRM. While the flux distribution of Model I is same with that of mutually coupled SRM. In the Model I, the flux path of channel-1 and channel 2 is in serial, while flux path of channel-1 and channel 2 is in parallel.

Fault-tolerant of model I



$$T_e = \frac{1}{2}\left(\frac{dL_A}{d\theta} i_A^2 + \frac{dL_B}{d\theta} i_B^2 + \frac{dL_C}{d\theta} i_C^2\right) + \left(\frac{dM_{AB}}{d\theta} i_A i_B + \frac{dM_{AC}}{d\theta} i_A i_C + \frac{dM_{BC}}{d\theta} i_B i_C\right)$$

Since the mutual-inductances between phases are very low under Model I, and then the torque contributed by mutual-inductance can be omitted. The torque only has the relationship with the square of currents and rake ratio of rising side of self-inductance. Moreover, the DCSRM works like a traditional SRM in the model I, then positive and negative DC current will result in same torque when the amplitude of them are equal. The current flows following the green line and the power switches S1 and S8 are turned on under normal condition. While current will flows negatively following the green line and the power switches S2 and S7 are turned on if the power switch S1 was open. Although the currents under health and fault are negative, the amplitudes of current can be set as the same. Then, the proposed DCSRM can offer same torque under power switch fault (S1).

Fault-tolerant of model II

Channel-1

$$\begin{cases} i_a = 0 \\ i_b = i_m \cos(\theta + \gamma) \\ i_c = -i_m \cos(\theta + \gamma) \end{cases}$$

$$\begin{cases} i_{d1} = \dfrac{i_m}{\sqrt{3}}[\sin(2\theta + \gamma) - \sin(\gamma)] \\ i_{q1} = \dfrac{i_m}{\sqrt{3}}[\cos(2\theta + \gamma) + \cos(\gamma)] \end{cases}$$

$$\begin{aligned} T_{e1} &= \frac{3}{2} p(L_d - L_q) i_d i_q \\ &= \frac{3}{2} p(L_d - L_q)\frac{i_m^2}{3}[\sin(2\theta + \gamma) - \sin(\gamma)][\cos(2\theta + \gamma) + \cos(\gamma)] \\ &= \frac{p}{2}(L_d - L_q) i_m^2 [\sin(2\theta) + \frac{1}{2}\sin(4\theta + 2\gamma) - \frac{1}{2}\sin(2\gamma)] \\ &= \frac{p}{2}(L_d - L_q) i_m^2 [\sin(2\theta) - \frac{1}{2}\cos(4\theta) + \frac{1}{2}] \end{aligned}$$

Channel-2

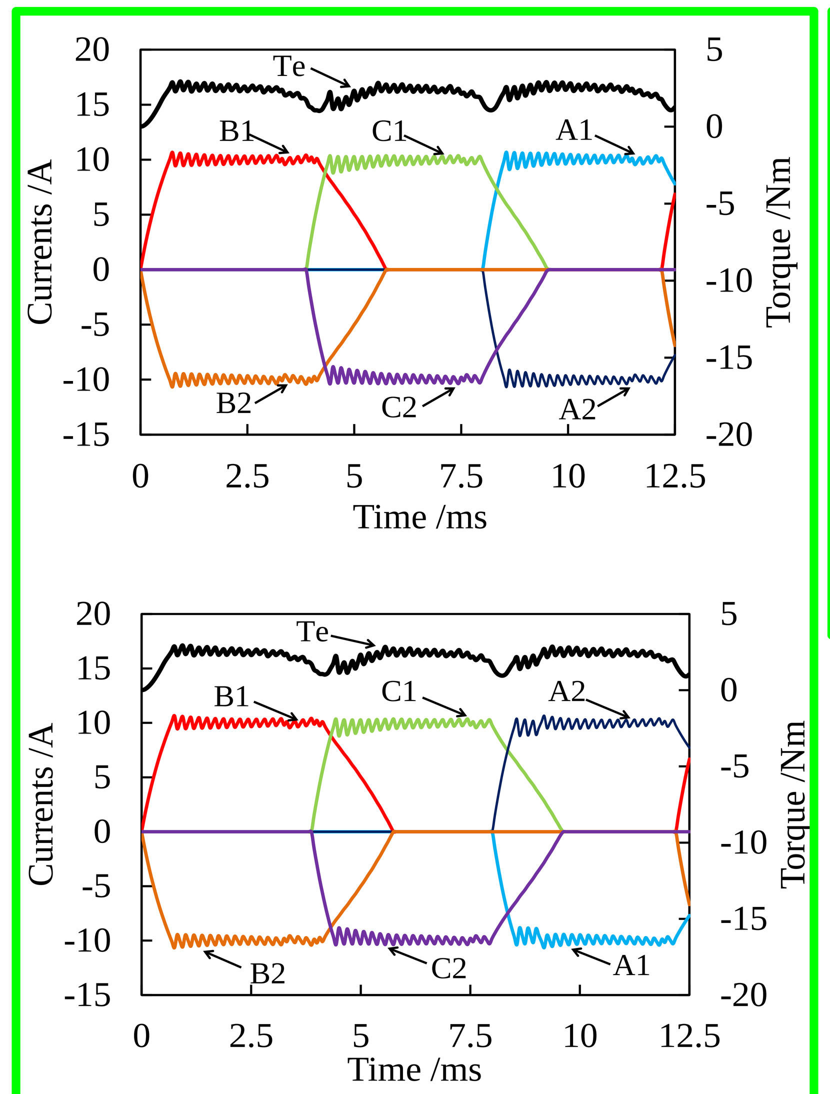
$$\begin{aligned} T_{e2} &= T_{e\Sigma} - T_{e1} \\ &= \frac{3}{2} p(L_d - L_q) i_s^2 \\ &\quad - \frac{p}{2}(L_d - L_q) i_m^2 [\sin(2\theta) - \frac{1}{2}\cos(4\theta) + \frac{1}{2}] \end{aligned}$$

$$\begin{aligned} T_{e2} &= T_{e\Sigma} - T_{e1} \\ &= \frac{3}{2} p(L_d - L_q) i_s^2 \\ &\quad - \frac{p}{2}(L_d - L_q) i_m^2 [\sin(2\theta) - \frac{1}{2}\cos(4\theta) + \frac{1}{2}] \end{aligned}$$

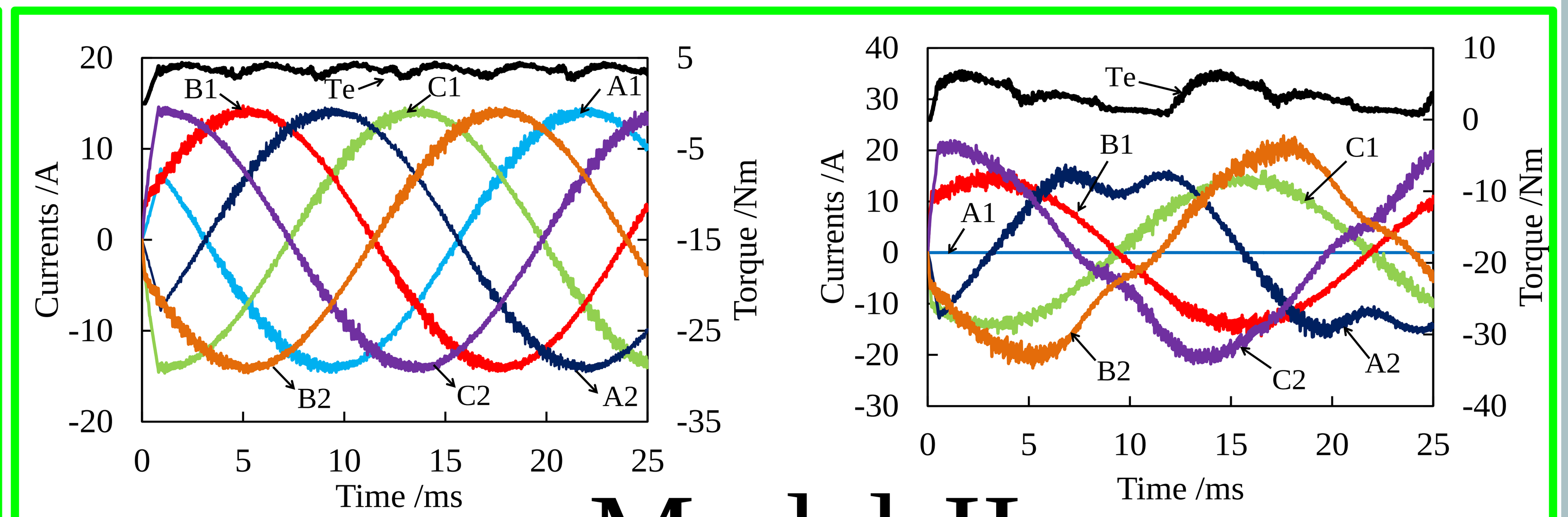
$$i_s' = \sqrt{\frac{2}{3}[\frac{5}{2} - \sin(2\theta) + \frac{1}{2}\cos(4\theta)]} i_m$$

$$\begin{cases} i_a = i_s' \cos(\theta + \gamma) \\ i_b = i_s' \cos(\theta - \frac{2}{3}\pi + \gamma) \\ i_c = i_s' \cos(\theta + \frac{2}{3}\pi + \gamma) \end{cases}$$

Verification



Model-I



Model-II

In the Model I, the proposed DCSRM is driven by H-bridge inverter and supplied by DC 10A square-wave currents. The average torque is 2.23Nm and torque ripple 1.90Nm under health. When the power switch S1 is open-circuited, DC current path in phase A1 and A2 will be changed from S1 S8 to S2 S7. The average torque is 2.19 Nm and torque ripple is 2.02 Nm. As seen from simulation results, the torque output capacity in health and fault are approximate.

When phase A1 is under open circuit in Model II, B1 and C1 are two symmetric sinusoid currents. The current amplitude of A2, B2 and C2 in healthy winding is set as variable. The average torque under fault can also be maintained as healthy condition.

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