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FINITE ELEMENT ANALYSIS OF A FLEXIBLE DUAL-SPEED SALIENT POLE SYNCHRONOUS MACHINE

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Keywords: Dual-speed synchronous machine; Finite element analysis; Motor operation; Generator operation.

This paper deals with the performance analysis of a DC-excited dual-speed synchronous machine (DSSM) with salient poles equipped with a damper winding. The proposed DSSM can operate at two speeds when connected to the mains. The number of pole pairs can be adjusted while running by the special design of the stator and rotor windings, which can commute between *p* = 1 and *p* = 2 pole pairs (by adjusting simultaneously the stator and rotor coil connections). The presence of the damper winding is helpful for the machine to self-start when directly connected to the grid as a motor and to pass smoothly from one speed to the other. The 2D finite element computations used to estimate the machine transient regimes and to determine its specific characteristics were carried out using the professional software package Flux® dedicated to electromagnetic field analysis. The proposed machine was analyzed both as a motor and as a generator.

1. INTRODUCTION

The synchronous machine (SM) is one of the most used electrical machines in various applications characterized by constant or variable speed, such as the automotive industry, urban or interurban electric transportation systems, industrial electric drive systems, wind turbines, etc. [1–8].

The uncertainty related to the rare earth permanent magnets (PMs) in terms of price stability and supply chain trustworthiness determined some electric machine producers to prefer, for some applications, the DC-excited synchronous machines or the reluctance synchronous machines rather than the permanent magnet solutions [9–16]. Besides the independence from rare earth PMs, another critical advantage of the DC-excited SM comes from the field current regulation possibility that allows the regulation of the armature voltage in case of generator operation or of the excitation magnetic flux in case of motor operation (*e.g.*, in case of field weakening applied for a higher motor speed range) [17–18].

The classical SM is known for its inflexibility in terms of rotor speed (n_s) when directly connected to the grid ($n_s = 60f/p$, where f is the supply frequency, which is supposed constant, and p is the number of pole pairs imposed by the SM construction and also assumed constant. By comparison, the three-phase Induction Motor (IM) is much more flexible regarding rotor speed when the machine is directly connected to the grid. IMs with two speeds, for example (even with three speeds), are already used in various applications such as elevators, pumps, fans and blowers, washing machines, cranes, hair dryers, cooking robots, etc. The speed change of three-phase IMs is carried out by adjusting the number of pole pairs p (*e.g.*, from $p = 1$ to $p = 2$ and vice-versa) by modifying the stator coil connections, which is possible during the motor operation. Since the number of rotor poles for squirrel cage IMs is automatically adjusted by electromagnetic induction, the speed change by modifying the stator coil connections (by changing the number of poles) is a feasible solution [19–21]. In the case of a classical SM, the number of rotor poles is typically imposed by its design, and it is not as flexible as in the case of IM.

This paper analyzes a solution to increase the flexibility of a DC-excited SM: transform it into a dual-speed synchronous machine (DSSM) by supplying the rotor winding in two different ways. This allows the change of several rotor poles simultaneously with the shift in the number of stator poles (obtained by modifying the coil connections of the special stator winding).

The studied DSSM is equipped with a damper cage that will enable the machine to develop starting torque as an IM, which will be an additional advantage.

The damper cage may also be helpful when passing from high to low speed and vice-versa (from $p = 1$ to $p = 2$ and vice-versa) since it is expected to improve the dynamics of the machine and reduce the oscillations. In the generator operation regime, the damper cage could also contribute positively by lowering the machine's speed oscillations in case of a sudden increase or decrease in driving mechanical torque.

While dual-speed IMs are extensively studied in many scientific papers [19–27], the research related to the DSSM is much less, and they refer mainly to the performance analysis of PM solutions [28–32].

The DSSM operating as a generator can also be used in various applications such as wind power plants as wind generators, electric vehicles as motor or as generators (*e.g.*, during regenerative braking), hydroelectric power plants as hydro-generators, etc.

The salient pole DSSM analyzed in this paper is a small power three-phase machine with the following main data: rated voltage 220 V, rated current 5 A, rated power as generator 1.9 kVA, rated speeds n_{n1} = 3 000 rpm and n_{n2} = 1 500 rpm.

The study of the machine is carried out using the finite element (FE) method in a 2D approach (transient magnetic regime) using the professional software package Flux® [33]. The numerical analysis was used to estimate the dynamic performance of the machine when passing from $p = 1$ to $p = 2$ (from 3 000 rpm to 1 500 rpm) and *vice-versa*, with or without load.

The DSSM was analyzed when operating both as a motor and a generator. The influence of the damper cage was also investigated.

The overview of the paper is as follows: section 2 describes the numerical modeling technique based on the FE method used to analyze the studied DSSM; sections 3 and 4 present the numerical results for motor operation of the SM and generator operation, respectively. The conclusions and the references close the work.

2. FINITE ELEMENT MODELS USED FOR THE ANALYSIS OF THE DSSM

A FE numerical analysis in the 2D approach was carried

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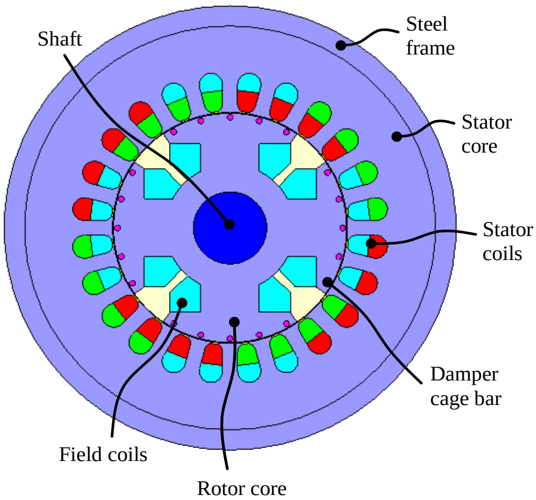
out to determine the performance of the proposed DSSM in both motor and generator operation modes.

The computation domain (Fig. 1a) is represented by a cross-section through the machine (including the rotor, the stator, the steel frame, etc.), and the FE discretization of the computation domain is shown in Fig. 1b. The stator winding diagram is shown in Fig. 2. The outer diameter of the stator is 154 mm, the bore diameter is 80 mm, the axial length of the magnetic core is 100 mm, Z = 24 stator slots, airgap length is 0.3 mm.

For p = 2 there is only one supply scenario of field coils to generate 4 alternating magnetic poles (Fig. 3a), but for p = 1, there are two different supply scenarios: only two field coils are supplied (Fig. 3b); all four field coils are supplied (Fig. 3c).



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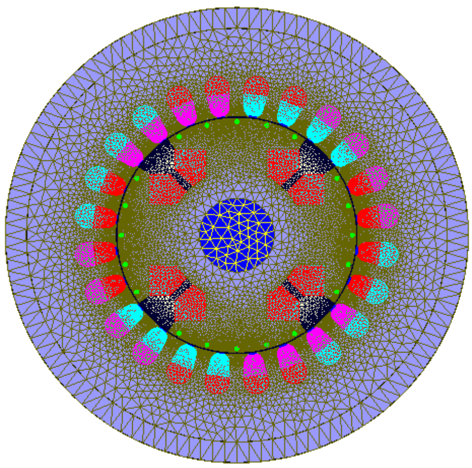


b)

Fig. 1 – FE computation domain (a) and FE discretization (b).

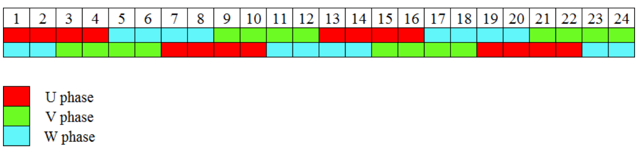


Fig. 2 – Stator winding diagram used to analyze the DSSM with m = 3 phases, Z = 24 stator slots, p = 1 and p = 2 pole pairs.

The electromagnetic field analysis that is carried out in the paper is of 2D transient magnetics type, and it is governed by the following partial differential equation expressed in magnetic vector potential **A**:

$$\mathrm{rot}[(1/\mu)\cdot \mathrm{rot}\,\mathbf{A}] = \mathbf{J_s} - \sigma\cdot \partial\mathbf{A}/\partial t - \sigma\cdot \mathrm{grad}V, \qquad (1)$$

where μ is the magnetic permeability, $\mathbf{J_s}$ is the imposed current density in coil regions, σ solid conductors' electric conductivity, and V is the electric scalar potential.

The cross-section geometry of the studied DSSM results from previous analytical and FE calculations that are not described in the text.

The boundary conditions imposed on the outer contour of the computation domain are of Dirichlet type (**A** = 0).

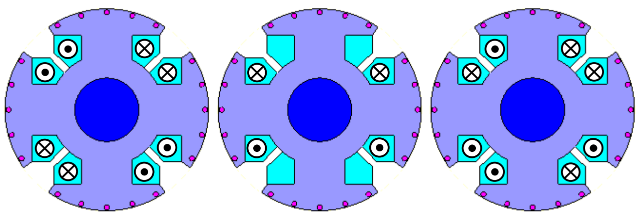
The electric circuit model of the DSSM associated with the electromagnetic field analysis is shown in Fig. 4 for grid-connected motor operation.

In the off-grid no-load SG operation mode, the voltage sources in the stator circuit in Fig. 4 should be replaced by electric loads (R, L, C types, etc.).

The damper winding of the machine is modeled by 20 copper-made solid conductors inter-connected by RL circuits at both ends (short-circuit ring segments).

The stator circuit includes three voltage sources (for grid-connected motor operation), stator coils, associated resistances and end-winding inductances, and several switches that commute from p = 1 to p = 2 stator windings.

The field circuit includes the field coils, their associated resistances, and the current sources, which allow the adjustment of several pole pairs simultaneously with the stator windings.



a) b) c)

Fig. 3 – Supply scenarios for field coils: a) p = 2; b) p = 1 and 2 supplied coils; c) p = 1 and 4 supplied coils.

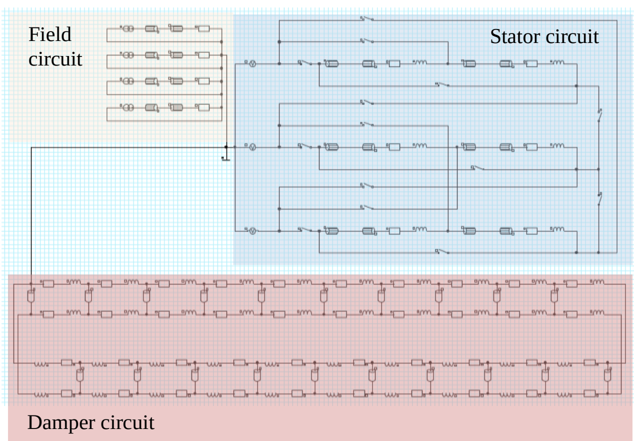


Fig. 4 – Electric circuit model associated with 2D FE analysis.

3. NUMERICAL RESULTS FOR MOTOR OPERATION

Several direct on line (DOL) start scenarios of DSSM as motor were analyzed without load, as follows:

m1) DOL start as motor for p = 1 (2 field coils supplied) and transient to $p = 2$,

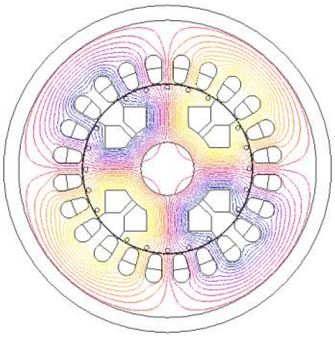
m2) DOL start as motor for $p = 1$ (4 field coils supplied) and transient to $p = 2$,

m3) DOL start as motor for $p = 2$ and transient to $p = 1$ (2 field coils supplied),

m4) DOL start as motor for $p = 2$ and transient to $p = 1$ (4 field coils supplied).

After solving the 2D transient magnetics field problem associated to the DSSM for the scenarios mentioned above, the numerical results shown in Figs. 5–7 were obtained.

Figure 5 presents the equi-flux lines in three cases: $p = 2$, $p = 1$ and 2 field coils supplied, $p = 1$ and 4 field coils supplied.



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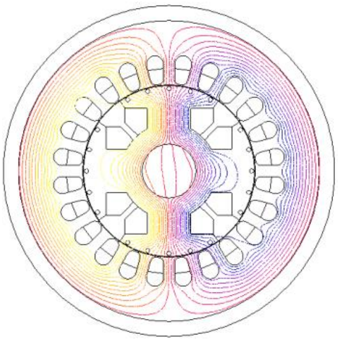

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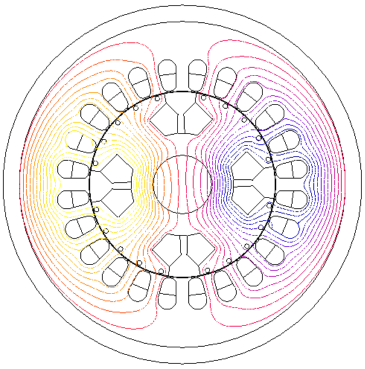
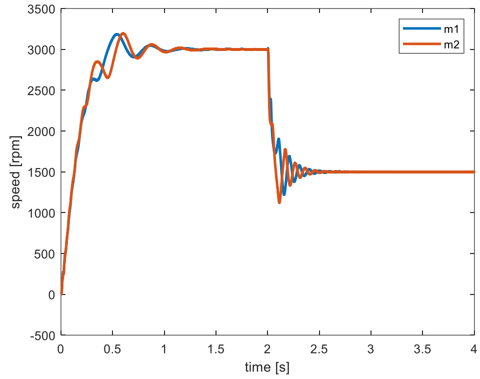


c)

Fig. 5. – Equi-flux lines for the no-load operation of the DSSM, in steady-state, in three different cases: a) $p = 2$; b) $p = 1$ with 2 field coils supplied; c) $p = 1$ with 4 field coils supplied.

The specific shapes of the equi-flux lines in Fig. 5 emphasize the presence of 4 alternating magnetic poles for $p = 2$ and 2 alternating magnetic poles for $p = 1$. The numerical results also show a difference between the equity-flux lines obtained for $p = 1$ and 2 field coils supplied and those for $p = 1$ and 4 field coils supplied.

Figures 6 and 7 present the time variations of the motor speed and the electromagnetic torque for the studied scenarios (m1 – m4). As one can notice in Fig. 6, the motor speed increases rapidly from zero, and after some oscillations, it reaches synchronous speed (steady state).



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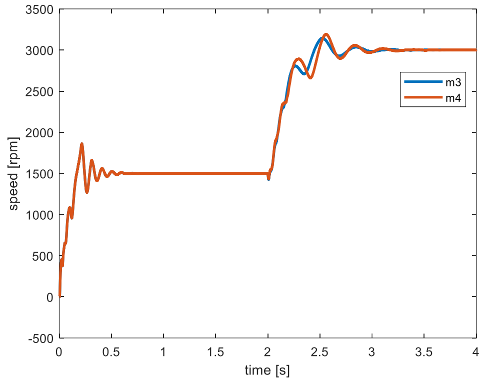

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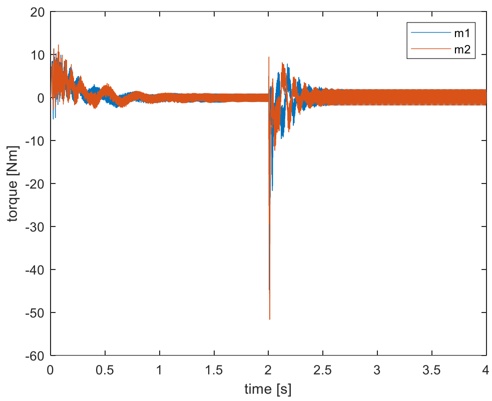
Fig. 6 – Time variation of motor speed for scenarios m1 – m4: a) scenarios m1 – m2; b) scenarios m3 – m4.



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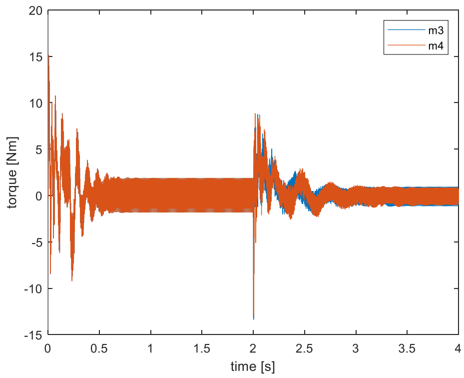
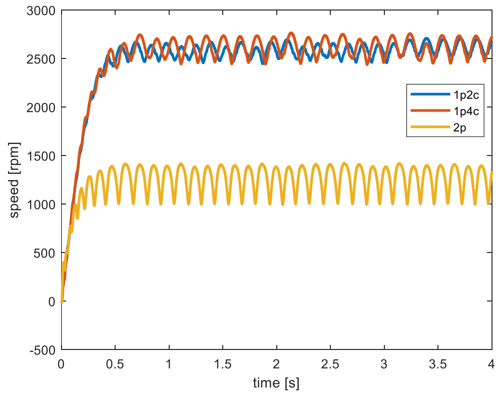


b)

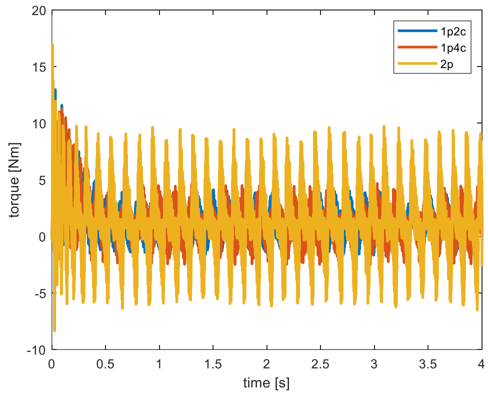
Fig. 7 – Time variation of electromagnetic torque for scenarios m1 – m4; a) scenarios m1 – m2; b) scenarios m3 – m4.

The transient from 1 500 rpm to 3 000 rpm (Fig. 6a) or vice-versa (Fig. 6b) is accompanied again by some oscillations until the steady state speed is finally reached. The electromagnetic torque oscillations around zero are smaller in the case of 1 500 rpm speed than those for 3 000 rpm speed (Fig. 7). The numerical results presented in Figs. 6 and 7 also show that the scenarios m1 and m2 lead to similar results regarding motor speed and electromagnetic torque. The similarity is much stronger between the results of scenarios m3 – m4.

DOL start of the DSSM as motor without load raises no problem (no matter the scenario, $p = 1$ or $p = 2$) as indicated by the numerical analysis results in Fig. 6. If the machine is DOL started under load conditions, difficulties, and instabilities may occur. For example, suppose the load torque is too large. In that case, the asynchronous torque (which helps the DSSM to start like a squirrel cage induction motor due to the damper winding) will not be able to accelerate the motor at a speed sufficiently close to the synchronous one. In this case, the synchronous torque will not be able to accelerate and stabilize the rotor at synchronism. Therefore, the machine cannot reach synchronism, but it will oscillate around a sub-synchronous speed (Fig. 8a).



a)



b)

Fig. 8 – Time variation of rotor speed and electromagnetic torque when the motor is DOL started and overloaded, without reaching the synchronous speed; a) rotor speed; b) electromagnetic torque (1p2c = 1 pole pair and 2 supplied coils; 1p4c = 1 pole pair and 4 supplied coils; 2p = 2 pole pairs).

The electromagnetic torque oscillations will also be significant in this scenario, Fig. 8b. A solution to avoid this situation is to pay special attention to the damper winding design to develop an asynchronous torque that is strong enough to accelerate the machine close to the synchronous speed under heavy load conditions.

If the DSSM is integrated into a closed-loop drive system that controls the motor speed, the abovementioned issues can be easily solved.

4. NUMERICAL RESULTS FOR GENERATOR OPERATION

The proposed DSSM can also be used as a generator when two different speeds and the same frequency are necessary, such as wind turbines.

Several operation scenarios were analyzed for the on-grid operation of the DSSM as a generator at imposed mechanical torque, as follows:

g1) on-grid transient of generator from $p = 1$ (2 field coils supplied) to $p = 2$,

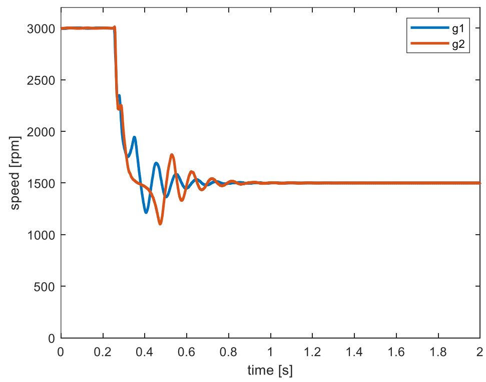
g2) on-grid transient of generator from $p = 1$ (4 field coils supplied) to $p = 2$,

g3) on-grid transient of generator from $p = 2$ to p = 1 (2 field coils supplied),

g4) on-grid transient of generator from $p = 2$ to $p = 1$ (4 field coils supplied).

After solving the 2D transient magnetics field problem associated with the operation of DSSM as a generator for the scenarios mentioned above, the numerical results are shown in Figs. 9–10 were obtained, referring to the time variations of rotor speed and electromagnetic torque for all g1 – g4 scenarios.

The results in Fig. 9 show that the machine operating as a generator reaches synchronism after some specific oscillations for all studied scenarios. In Fig. 10 are shown the oscillations of the electromagnetic torque during the studied transient regimes g1 – g4. The electromagnetic torque (during the transient regimes from $p = 1$ to $p = 2$ or vice-versa) has mostly an accelerating effect in the case of g1 – g2 scenarios and mostly a braking effect in the case of g3 – g4 scenarios.



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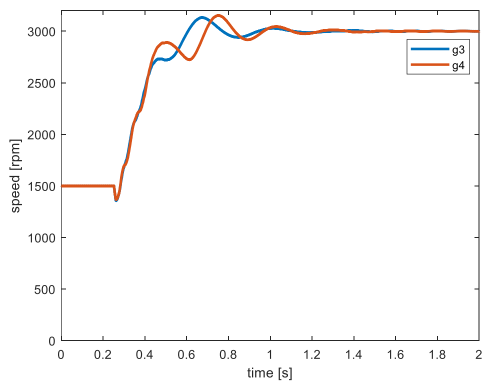

b)

Fig. 9 – Time variation of rotor speed for scenarios g1 – g4: a) scenarios g1 – g2; b) scenarios g3 – g4.

5. CONCLUSIONS

This paper deals with the finite element analysis of a dual-speed synchronous machine (DSSM) with salient poles equipped with damper winding for a direct online start.

The machine's performance was analyzed in both motor and generator operation regimes at both speeds when directly connected to the grid.

The numerical results proved the machine's versatility. When directly connected to the grid, it can start and operate at one speed and then move and operate successfully at the other.

When the proposed machine was fully loaded or overloaded, a limitation in exploiting it when directly connected to the grid was identified. In this case, the machine can start as an induction motor with the help of the damper winding, but it cannot achieve synchronism. However, this limitation can be easily surmounted if the machine is integrated into a closed-loop drive system.

The area of utilization for this machine could be extended if the field winding is not supplied. In this case, the machine will operate as a classical induction motor.

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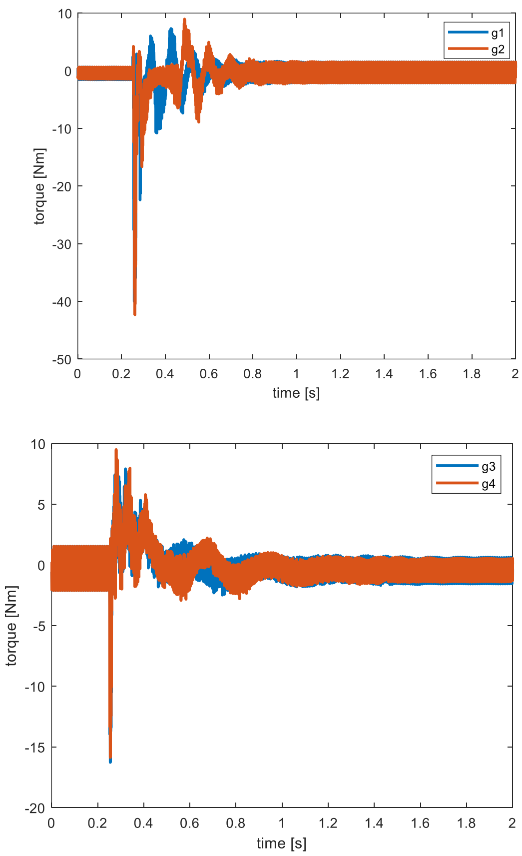

a)

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Fig. 10 – Time variation of electromagnetic torque for scenarios g1 – g4: a) scenarios g1 – g2; b) scenarios g3 – g4.

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