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Hybrid FEA-Simulink Modelling of Permanent Magnet Assisted Synchronous Reluctance Motor with Unbalanced Magnet Flux

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***Abstract* — Nowadays, the research and industry societies showing their interest on permanent magnet assisted synchronous reluctance motors. One of the main disadvantages of using permanent magnets in electrical machines is a risk of demagnetization. This paper discusses a hybrid FEA-Simulink model with damaged permanent magnets in rotor flux barriers. Three sets of interpolation tables were computed using two-dimensional finite element analysis, calculated flux linkages and electromagnetic torque were used for development of Simulink model. Proposed model gives more accurate results in comparing to analytical one. The model opens the possibility of studying the machine under more realistic situations.**

***Index Terms* — fault detection, permanent magnet motors, magnetic flux**

I. Nomenclature

v_d, v_q	voltage in *dq* frame
i_d, i_q	current in *dq* frame
I_N	nominal current
ϕ_d, ϕ_q	flux in *dq* frame
ω	rotor angular velocity
ω_e	electrical angular velocity
T_e	electromagnetic torque
T_L	load torque
J	rotor inertia
R_s	stator resistance
F_R	viscous friction coefficient
p	pole pairs
L_d	direct-axis inductance
L_q	quadrature-axis inductance
ψ	flux provided by magnets
i^*_d	direct axis current reference
T_s	simulation time step
k	discrete step index
z	Z-transform variable

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II. Introduction

THE interest towards synchronous reluctance motors (SynRMs) has increased, since ABB started the commercial production of SynRMs for pumps, fans, compressors, extruders, conveyors, and mixers in 2012. Permanent magnets in the rotor flux barriers noticeably improve performance of SynRM [1], even if low-energy magnets such as ferrites are employed. The main advantages [2] of the permanent magnet (PM) assistance for SynRM (PMaSynRM) is an increase of the main torque density and of the power factor, that turn the machine to a valuable alternative for traction applications [2]–[4].

One of the important limitation of PM assistance is the risk of demagnetization at overload [5], compared with the rare-earth PM, the ferrite PM is more susceptible to demagnetization [6]. PM demagnetization may be caused by different factors [7] such as temperature, armature current magnitude, design operating points and deep flux weakening, as shown in [8]. The risk of demagnetization of PM is different at each PM position for PMaSynRM. Literature study shows, that some researchers [9] suggest to remove the PMs and work as SynRM, in order to avoid irreversible PM demagnetization, if PMaSynRM is used for high overload condition. In [6], [10] adjusting the structural parameters of motor (ex. winding optimization) method has been proposed to improve the anti-demagnetization ability of PMaSynRM. It is necessary to detect the demagnetization situation of PMaSynRM in an early stage, to prevent further damage of the motor-drive system due motor fault propagation.

The paper compares two models of PMaSynRM, first healthy, second with a sector of demagnetized PMs on the rotor side. A FEA model based flux density maps are presented and implemented into Matlab/Simulink model. Then, different conditions of damaged magnets are introduced, in order to study the effect on the behavior of the machine. The differences found could help to develop a diagnose procedure to avoid further damage to the machine.

III. Finite Element Analysis

For the actual analysis part, three sets of interpolation tables were first computed using two-dimensional finite element analysis (FEA). The first set was computed for the undamaged machine, and the second and third ones for the partially demagnetized machine. Fig. 1 shows the analyzed geometry along with the mesh used. The partially demagnetized magnets have been highlighted with red. The demagnetization was modelled by reducing the remanence of the damaged magnets to 10 % and 50 % of their nominal value. Both interpolation tables consisted of a total of 121 different operating points. At each point, the waveforms of the electromagnetic torque as well as d- and q-axis flux linkage were computed over one electrical period and stored. Perfectly balanced sinusoidal three-phase currents were supplied, corresponding to a fixed (i_d, i_q) point. The q-axis currents ranged from 0 to I_N, while the d-axis currents ranged from -0.75 I_N to 0.75 I_N. Both intervals were uniformly discretized with 11 points and their tensor product was computed, resulting in the aforementioned 121 operating points.

The open-source SMEKlib framework was used for the analysis [11]. A purely current-supplied model was used, meaning eddy-current effects were not considered. A total of 600 steps were used for analyzing each operating point, corresponding to a 0.6 el. degree difference between successive points. The entire cross-section was modelled, due to the non-symmetry induced by the damaged magnets. The moving band approach was used for the rotor movement [12], and the torque was computed using the weighted Maxwell stress tensor or Arkkio's method [13], [14]. First-order triangular elements were used.

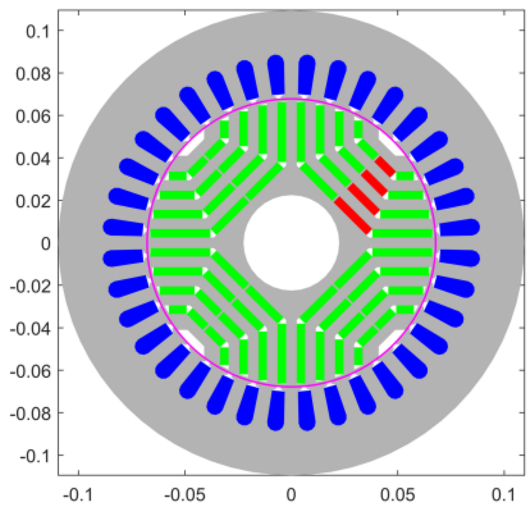

Fig. 1. Geometry of the machine analyzed. The damaged magnets have been highlighted in red. The axis labels indicate the dimensions in meters.

IV. Hybrid MATLAB/Simulink Model

The equations that model the PMaSynRM in the synchronous frame are the same that are employed in the characterization of the PM Synchronous Motor (PMSM), that is:

$$v_d = R_s i_d - \phi_q \omega_e + \frac{d\phi_d}{dt}$$
$$v_q = R_s i_q + \phi_d \omega_e + \frac{d\phi_q}{dt} \quad (1)$$

$$\phi_d = L_d i_d$$
$$\phi_q = L_q i_q \quad (2)$$

$$T_e = \frac{3}{2} p \left(\left(L_d - L_q \right) i_d i_q + \psi i_q \right)$$
$$T_e - T_L = \frac{d\omega}{dt} J + F_R \omega \quad (3)$$

For those equations to hold, some assumptions are made, especially regarding (2) and (3):

1. The stator inductive voltage drop is neglected.
2. The flux across the rotor and stator is the same.
3. There is a linear relationship between currents and fluxes.

These assumptions are reasonable in the modeling of the PMSM, but not in the one for the PMaSynRM. From Fig. 2 it can be seen that the relationship between currents and fluxes is far from linear in these type of machines. Moreover, the rotor angle shall also be taken into consideration to account for the effects of cross magnetization. To conclude, the flux linkages are multivariable functions $\phi = f(i_d, i_q, \theta)$. This makes the analytical model unusable and is the reason why a hybrid model is needed.

For the development of the model, both flux linkages and the electromagnetic torque will be provided from the FEA analysis of the machine. The output of this analysis will be data that will be used in the Simulink model by means of look up tables (LUT). Taken this into account, discretizing and solving for currents and rotor angle in equations (1-3) yields:

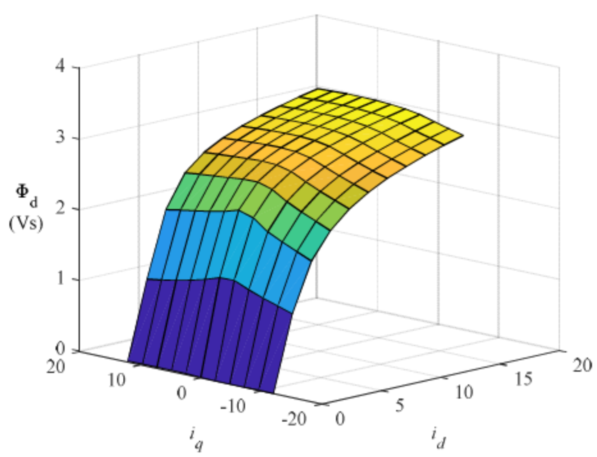

Fig. 2. Flux in the d-axis as a function of id and iq with rotor angle equal to 0 degrees. Data from FEA analysis of the machine.

$$i_{dk} = \frac{v_{dk} + \phi_{qk}\omega_k - \left(\frac{\phi_{dk} - \phi_{dk-1}}{T_s}\right)}{R_s}$$
$$i_{qk} = \frac{v_{qk} - \phi_{dk}\omega_k + \left(\frac{\phi_{qk} - \phi_{qk-1}}{T_s}\right)}{R_s} \quad (4)$$

$$\omega_k = \frac{(T_e - T_L)T_s + J\omega_{k-1}}{J + T_s F_R}$$
$$\theta_k = \frac{T_s}{z-1}\omega_k \quad (5)$$

The main scheme for this model is depicted in Fig. 3. Being a synchronous frame model, the inputs will be the voltages v_d and v_q, together with the load torque T_L. The outputs will be the currents i_d and i_q, the angular speed ω and the rotor angle θ. The currents and the angle are also used as search variables for the look up tables. The rotor angle is used for the transformation of the voltages into field coordinates as well as the transformation of the currents to the stator frame.

For the validation of this model, it has been compared with a model elaborated from the equations (1-3), using continuous time transfer function modelling. Both models are controlled by means of a Field Oriented Control (FOC), where the speed and direct axis current are the control variables. The PI controllers used to implement the FOC are kept the same for the two models. A fast acceleration ramp of 0.1 s is applied for the speed, from still up to nominal speed (157 rad/s). The results are shown in Fig. 4, where the behavior of the hybrid model can be validated. Moreover, it can be observed that the torque has the ripple expected from this kind of machine and how can affect the speed loop. The main parameters for the motor and control can be found in Table I.

It is worth mentioning that the values of the inductances and flux provided by the magnets used for the analytical model are calculated doing a linear regression of the data provided by the FEA analysis. Therefore, a maximum

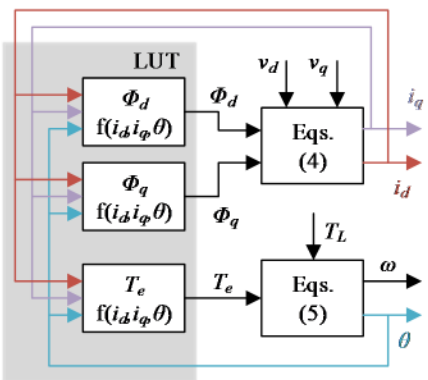

Fig. 3. Scheme for the PMaSynRM model using the data from the FEA analysis

similarity between both models is achieved and is possible to guarantee the validity of the model proposed for the operation point proposed.

TABLE I
MAIN PARAMETERS OF THE SIMULATION

Parameter	Value
J	$3.6\cdot10^{-3}$ Kg·m^2
R_s	0.7 Ω
F_r	$2.25\cdot10^{-3}$ N·m·s
p	2
L_d	0.0797
L_q	0.2607
ψ	0.7147
i^*_d	3 A
T_s	10^{-5} s

V. UNBALANCED FLUX FROM MAGNETS

To study the effect of having demagnetized magnets in the machine, the model elaborated in the previous section will be employed with the three different data sets from the FEA analysis described in section III. The first case, with healthy magnets, will be compared with two unbalanced cases: one

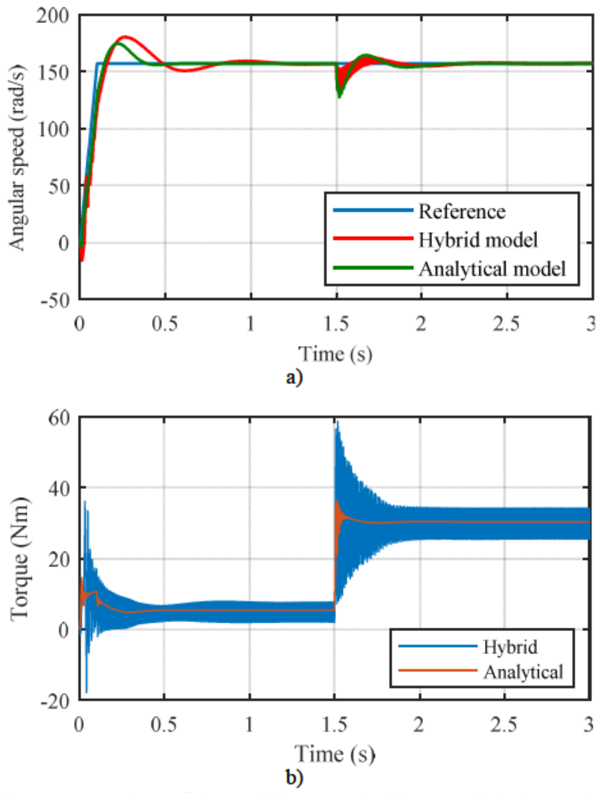

Fig. 4. Comparison of the model proposed with an analytical one. a) Speed ramp reference from 0 to nominal speed. b) Torque step from 5 to 30 Nm at $t = 1{,}5s$.

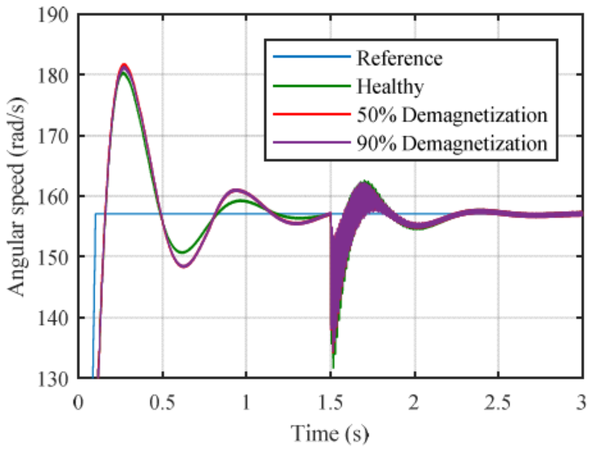

Fig. 5. Speed response of the motor from 0 up to nominal speed, for the three different conditions of the rotor.

having a 50 % demagnetization in the magnets and another with 90% demagnetization. The same scenario used in the previous section will be applied to all data sets, working with nominal speed and high torque (30 N·m) so the effects are more noticeable. In Fig. 5 the speed response for the three different cases is depicted, where it can be observed how the

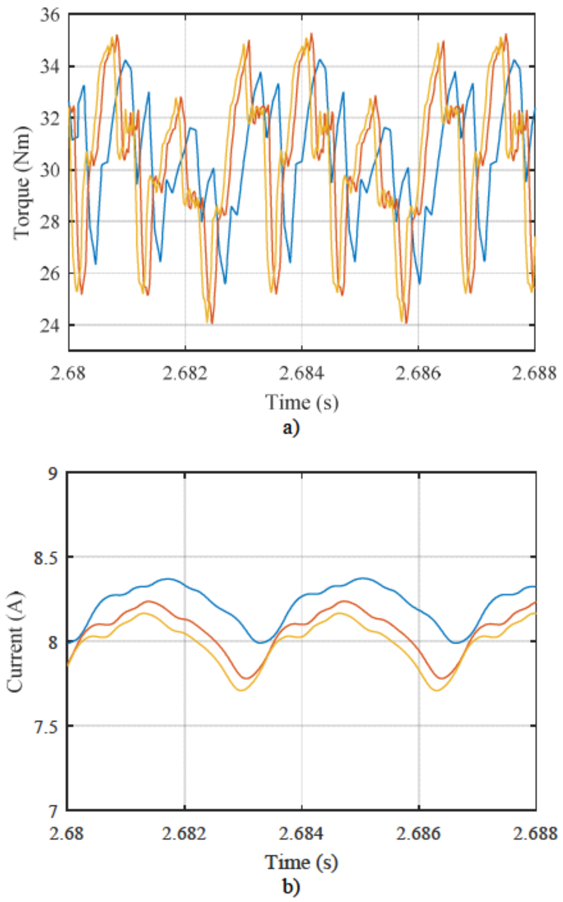

Fig. 6. a) Torque and b) i_q of the motor for the three different cases of magnetization. Healthy magnets in blue, 50% of demagnetization in red, 90% demagnetization in yellow.

difference in the magnetization of the magnets can affect the speed loop control. The main difference in appears during the starting of the machine, after the applying of the torque step the transient for healthy and both unbalanced cases have very similar behavior. Both unbalanced cases show similar behavior, this can be further explained in Fig. 6a), where it can be observed that the unbalanced cases show more ripple than the balanced one. In Fig.6b), the waveform of the current i_q is showed, where it can be seen that the difference in the ripple is not so evident. However, although both unbalanced cases exhibit similar behavior, there is a clear displacement in the phase of the waveforms.

For further analysis of the difference between the balanced and unbalanced cases, Fourier analysis of the three cases is carried out. The variables selected for the analysis are the speed, torque and currents, since this would be the variables measured in the real drive. The results are summarized in Fig. 7, where the spectrum for the cited variables is presented and compared between the three cases studied. Each harmonic component is expressed as a percentage of the DC value; given that they are variables of the synchronous reference frame. It can be observed that, although the torque ripple is greatly increased (almost a 3%), especially in the 900 Hz component, the speed spectra is not severely affected, due to the low-pass behavior of the rotor. Nevertheless, this increase in torque ripple will be the cause of noise and vibration on the system, which deteriorate the speed loop performance as it was shown in Fig. 5. Also, even if the i_q spectra is not so worsened, the increase in the ripple could affect the controllers' bandwidth.

On the other hand, in Fig. 8 the phase of the main harmonics is compared. As it was observed in the waveforms from Fig. 6, the phase lag is present in the main variables of the system. There is a dependence between the increase of the phase and the magnetization level of the magnets. This suggests that it can be employed for the diagnoses of partially demagnetized machines.

Conclusion

The following conclusions can be extracted from the work developed:

- The model proposed was developed and compared to the analytical one, giving correct and more accurate results. Moreover, this model opens the possibility of studying the machine under more realistic situations.
- The model developed has been employed in the analysis of a situation where the flux provided by the magnets have been decreased due to demagnetization. This effect has a negative impact on the performance of the drive, especially in the torque provided by the motor.
- The phase of the main harmonics in the drive is severely affected by the demagnetization of the magnets, which could provide with a diagnose procedure for detecting the fault.

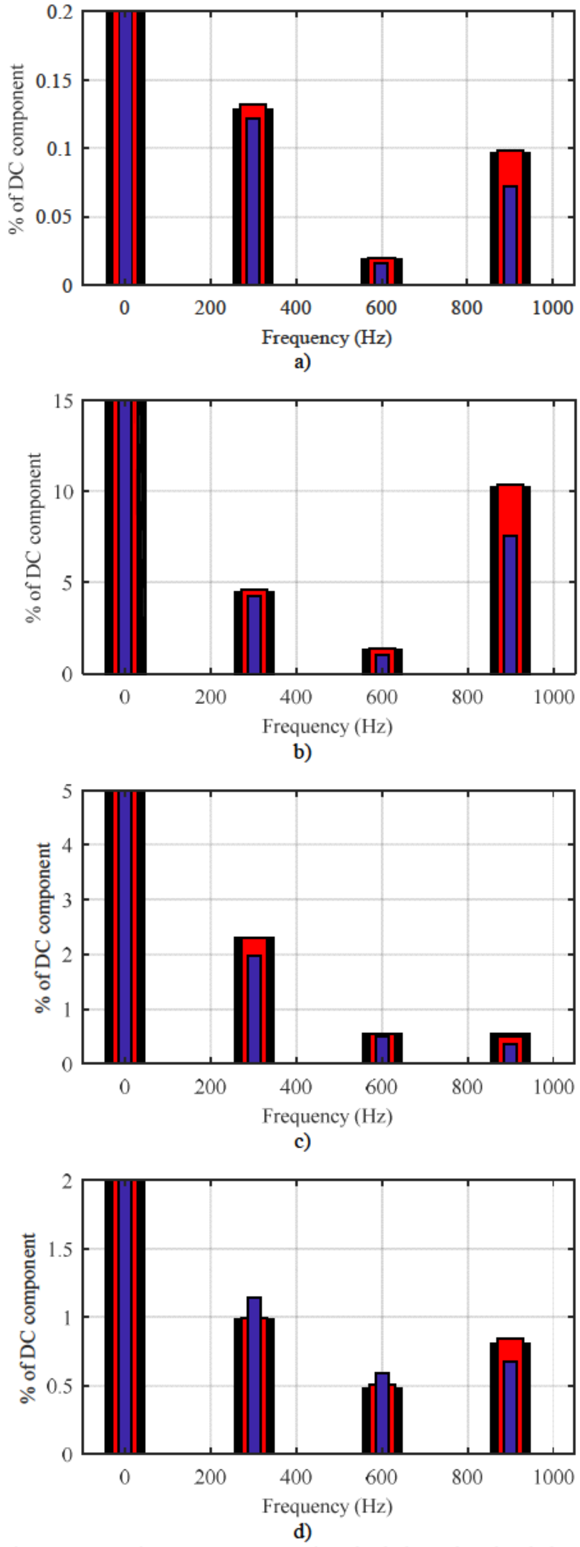

Fig. 7. Harmonic spectrum comparing the balanced and unbalanced cases. All components are relative to the fundamental component. Healthy magnets in purple, 50% demagnetization in red and 90% demagnetization in black. a) Speed spectra. b) Torque spectra. c) i_q spectra. d) i_d spectra.

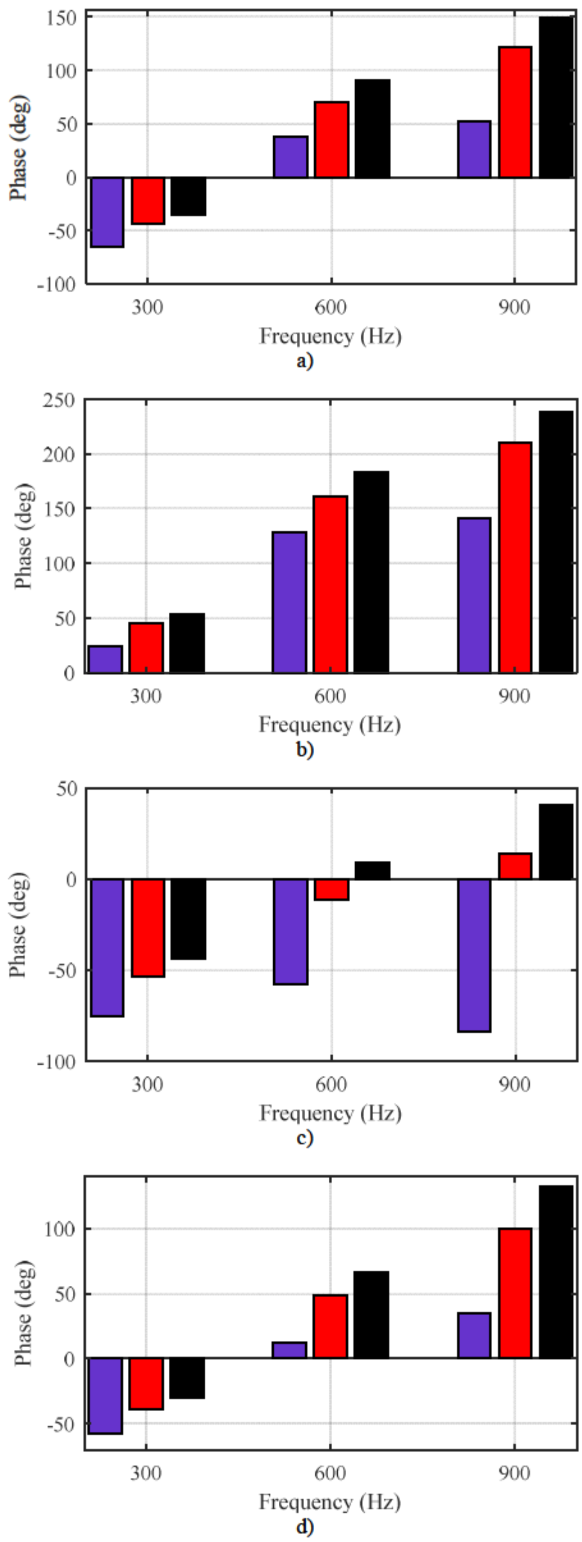

Fig. 8. Phase of the main harmonics. Healthy magnets in purple, 50% demagnetization in red and 90% demagnetization in black. a) Speed spectra. b) Torque spectra. c) i_q spectra. d) i_d spectra.

- As shown in [15] model-based direct flux vector control could be successfully applied for PMaSynRM control, with no need for regulators tuning.

For future studies, more operation points should be studied to guarantee the model effectivity in the whole speed and torque range. Also, different distributions of damaged magnets should be introduced to study how they affect the main variables.

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