Permanent Magnet Machine Model Considering Saturation Effects and Non-sinusoidal EMF

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Abstract — This paper proposes a permanent magnet machine (PMM) model accounting for saturation effects and non-sinusoidal EMF. The machine model has been developed by considering saturation and cross coupling effects incorporated into the equivalent circuit model enabling to accurately predict the machine performance. Embodying the developed model into the control strategy; proper actions for the converter operation can be obtained for maximum energy extraction in several applications such as wind generation. Developed model simulation results have been validated by experiments performed on a PMM prototype.

I. INTRODUCTION

Wind generators facilitate the spread use of the clean distributed generation presenting several advantages over the other renewable energy sources. Especially, small scale turbines are adopted for isolated operation necessitating to be reliable and to serve efficiently the continuous electrical energy needs. Being superior to the other machine types; permanent magnet machines (PMMs) are widely used providing power generation with high efficiency mainly owing to the non-existence of external excitation and copper losses in the rotor windings.

However, machine design optimization [1], [2] is not an adequate factor for capturing maximum energy. Therefore, in contemporary energy conversion systems maximum energy utilization can be achieved also through the contribution of the proper control implementation for maximum power point tracking (MPPT). In literature various MPPT algorithms exist imposing the reference output to the controller and forcing the power system to operate at the peak of the power versus angular velocity curve (P-ω). Such a control strategy is the predictive control technique, estimating the future behavior of the controlled variables and obtaining proper control actions. In order such techniques to be implemented require high precision in the PMM model representation.

During the procedure of the development of the equivalent circuit model, saturation and cross coupling effects have to be taken into consideration [3]-[5]. The reflection of the magnetic saturation and cross coupling effects to the machine model can be attained by expressing model parameters as dependent on the two axes currents [6]. Consequently, the derived inductances of the two axes are non-linear functions of the stator currents [7], [8] attempting to accurately simulate machine performance for operation especially at lower rotor speeds.

In the present paper the procedure of the model development of a permanent magnet generator accounting for saturation and cross coupling effects for a maximum energy extraction application is introduced. The basic d and q axes equivalent circuit model of a PMM is subject to modifications integrating data derived from finite elements analysis (FEA). The developed model can be implemented for each machine type incorporating properly configured parameters of a certain generator. The proposed methodology has been validated by comparing its results with experiments performed on a PMM prototype.

II. MODEL PARAMETER ESTIMATION METHODOLOGY

Saturation and cross coupling effects have to be taken into account during the model development procedure thus employing FEA; the elements of the two axes inductances (L_d, L_q) and the permanent magnet flux linkage (ψ_m) can be extracted by using:

$$\Psi = 2p \cdot l \cdot \sum_{j=1}^{N/2/p} \frac{1}{S_j} \cdot \int_{S_j} A_z \cdot dS_j \qquad (1)$$

$$L_d(I_d, I_q) = \frac{\partial \Psi_d(I_d, I_q)}{\partial I_d},\; L_q(I_d, I_q) = \frac{\partial \Psi_q(I_d, I_q)}{\partial I_q} \qquad (2)$$

where p is the number of pole pairs, l is the stator length, N is the total number of slots, S is the slot surface, and A_z is the vector potential in z-direction. Fig. 1 illustrates the flux density distribution for the three requisite procedure steps: open circuit and rotor field alignment with the d- or q- axis substituting the magnets with air.

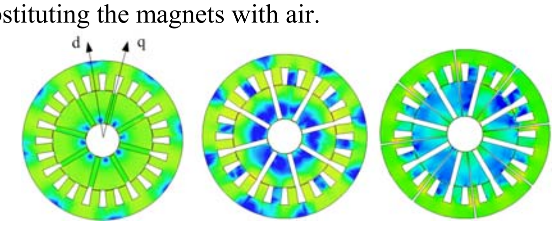

Fig. 1. Flux density distribution. (a) Open circuit. (b) Rotor field alignment with the d-axis. (c) Rotor field alignment with the q-axis.

Three dimensional FEA has been employed yielding more accurate results due to end connection and fringing effects involvement.

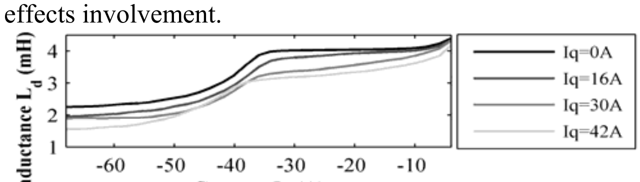

Fig. 2. d-axis inductance variation versus I_d as a function of I_q.

Figs 2 and 3 show that L_d decreases almost linearly when I_d increases, while L_q is more sensitive to I_q variations, owing to the fact that the q-axis flux linkage is affected strongly by the rotor and stator material B-H curve.

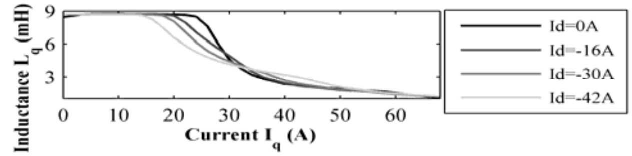

Fig. 3. q-axis inductance variation versus I_q as a function of I_d.

From Fig. 3 cross magnetization effect is intense as d and q axes currents increase having significant impact on the inductance value. Incorporating these inductances variations into the machine equivalent circuit model enables the model to predict accurately machine performance.

III. RESULTS AND DISCUSSION

Output voltage at the generator terminals is unconventionally non-sinusoidal because PM structure generates a large portion of harmonics. The n-order harmonic components have to be regenerated in the back electromotive force. Thus using superposition principle, independent circuits are examined with the suitable parameter values. Simulation results shown in Fig. 4 and in Table I, are in good correlation with the experimental ones for the fundamental frequency and lower saturation levels, however high order harmonic components saturate non-uniformly stator and rotor materials.

Due to the non-linear behavior of the machine further improvement can be attained by applying approximation methods combined with measurements carried out in a prototype manufacture; the corresponding output voltage with tuned parameters is marked with an asterisk (*).

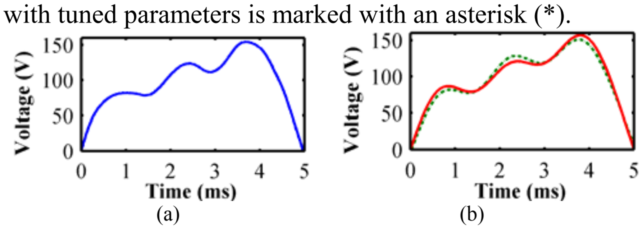

Fig. 4. Comparison of the output voltages for the same loading. (a) Measured voltage. (b) Simulated voltages (solid line for the tuned parameters).

Moreover, in IPMMs the output voltage waveform changes considerably with loading and approaches sinusoidal shape under nominal operating conditions eliminating harmonic components. Power quality issues may arise in the cases of isolated operation; hence control scheme have to account for the output voltage distortion regulating appropriately the machine loading.

TABLE I
FOURIER ANALYSIS OF THE MEASURED AND SIMULATED VOLTAGES

Order	*Measured Voltage (V)*		*Simulated Voltage (V)*			
	No load	*12 A*	*Simulated*	*%*	*Simulated**	*%*
1st	*165.6*	*143.5*	*143.5*	*0*	*143.5*	*0*
3rd	*56.32*	*37.08*	*30.72*	*-17*	*38.20*	*3.2*
5th	*41.46*	*16.73*	*14.97*	*-10*	*16.27*	*2.7*

Controller schemes based on the predictive technique demand the knowledge of the accurate machine model in order to be capable of predicting future system behavior at time *k+1*. System equations involving the inductance variations can be expressed in discrete form:

$$\psi_{d(k+1)} = \left[v_{d(k)} - R_s i_{d(k)} + \omega L_q i_{q(k)} \right] T_s + \psi_{d(k)} \quad (3)$$

$$\psi_{q(k+1)} = \left[v_{q(k)} - R_s i_{q(k)} - \omega L_d i_{d(k)} - \omega \psi_m \right] T_s + \psi_{q(k)} \quad (4)$$

The three phase currents transformed in dq reference frame are designated as inputs to the controller. Then, according to the measured current values; the evaluation of the model parameters follows as shown in Fig. 5.

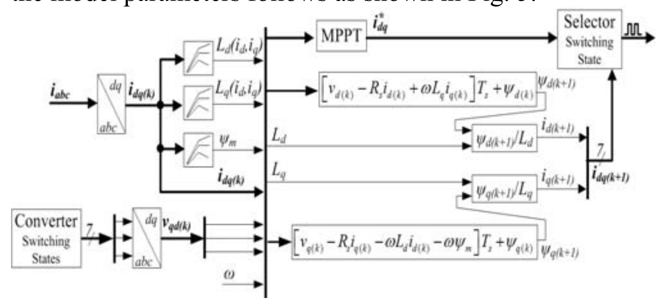

Fig. 5. Schematic of the permanent magnet generator simulation model.

Voltages v_d and v_q at the present time k are given by evaluating machine model examining all possible converter switching states. The selector block inputs the MPPT reference output appropriate for maximum energy exploitation and also the model two axes currents evaluated for the converter switching states and finally determines which converter state satisfies the applied criteria. From the aforementioned, system performance dependence on the prediction of the machine model behavior is strong.

IV. CONCLUSIONS

In this paper permanent magnet generator model enabling magnet saturation and cross-coupling effects for a maximum energy extraction application has been developed. The experimental validation has shown that the developed model predicts accurately the IPMM prototype performance thus facilitating the control schemes to operate efficiently.

V. REFERENCES

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