CHAPTER 3

Q-AXIS FLUX MODELING USING REGRESSION MODELS

3.1 INTRODUCTION

The importance of measuring and modeling d-q axes saturated characteristics of synchronous machines has been recognized and analytical, experimental and certain modeling methods used for finding q-axis saturated characteristics are reported by many researchers. Four different analytical methods are explored for calculating q-axis saturated characteristics of salient pole synchronous machines from the measured d-axis characteristics by Ahmed El-Serafi and Kar (2003). Three possible experimental methods for measuring q-axis saturated characteristics of synchronous machines are also presented by Kar and Ahmed El-Serafi (2004, 2006). Four analytical methods for determining the intermediate axis saturated characteristics of Salient pole synchronous machines from the measured d-axis characteristics are proposed by Ahmed El-Serafi and Kar (2005). Kar et al (2000) have presented a new method to calculate the q-axis saturated characteristics of cylindrical rotor synchronous generator using readily available standard test data such as the d-axis saturation characteristics.

above papers have focused on any mathematical regression models to estimate q-axis flux in a synchronous machine from the d-axis flux and the field excitation.

In this chapter, two mathematical models are proposed for representing the q-axis magnetic flux in synchronous machines. The mathematical models use Multivariate Linear Regression (MVLR) and Multivariate Polynomial Regression (MVPR) to estimate the q-axis flux in projected pole synchronous machines. The experimental values of d-q axes flux measured in a Laboratory machine, whose data are given in Table 3.1, using Germanium diodes as flux sensors are used as one of the references in the proposed models. The q-axis magnetic flux calculated from the measured d-axis flux by Ahmed El-Serafi and Kar (2003) vide Method 2, for various Salient pole synchronous machines namely, a) Microalternator, b) Machine No. 1 and c) Machine No. 2, whose data are given in Table 3.1, are the other references employed in the development of the two models. The generalized models have been developed using these reference values and applying the models, the q-axis flux values have been calculated for the Salient pole synchronous machines at any value of field excitation.

Finally, the estimated q-axis flux values are compared with the available experimental and calculated values and the error investigated to verify the accuracy of the developed models. This chapter presents the development of two generalized models for estimating quadrature axis (q-axis) magnetic flux in salient pole synchronous machines.
Table 3.1  Data of the Salient pole synchronous machines used in the investigations

<table>
<thead>
<tr>
<th></th>
<th>Micro alternator</th>
<th>Machine No. 1</th>
<th>Machine No. 2</th>
<th>Laboratory machine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Capacity (VA)</td>
<td>3000</td>
<td>3000</td>
<td>4000</td>
<td>3000</td>
</tr>
<tr>
<td>Rated armature voltage (V)</td>
<td>220</td>
<td>220</td>
<td>208</td>
<td>415</td>
</tr>
<tr>
<td>Rated armature current (A)</td>
<td>7.87</td>
<td>7.87</td>
<td>11.1</td>
<td>4.2</td>
</tr>
<tr>
<td>Rated field current (A)</td>
<td>1.59</td>
<td>0.95</td>
<td>0.62</td>
<td>1.1</td>
</tr>
</tbody>
</table>

3.2  REGRESSION TECHNIQUES FOR FLUX MODELING

The available experimental values of d-axis flux ($\Phi_d$) and q-axis flux ($\Phi_q$), measured using Germanium diode flux sensors for the Laboratory machine and the calculated d-q axes flux in three Salient pole synchronous machines, namely Microalternator, Machine No. 1 and Machine No. 2 along with the respective field excitation (AT) are used in the development of generalized regression models using MATLAB. The four synchronous machines used in the investigations have different specifications. Even though the rated capacity is same, Microalternator and Laboratory machine differ from each other largely by rated armature voltage and rated armature current. Machine No. 1 and Machine No. 2 differ largely by rated capacity, armature current and field current.

For the purpose of modeling, various forms of mathematical techniques are available. Plenty of linear and non-linear regression techniques such as constant time, discrete time techniques, polynomial and exponential techniques are existing in MATLAB. For most of the statistical estimations
and for power quality solutions, researchers use linear and polynomial regression techniques. These two are simple methods and easy to use because DSP implementation of these equations in discrete time domain is much simpler. Hence the methods selected to model q-axis flux ($\Phi_q$) are:

i) Multivariate Linear Regression (MVLR) technique and  
ii) Multivariate Polynomial Regression (MVPR) technique.

It is observed that MVLR and MVPR techniques are widely used for modeling of different systems. For the given values of d-axis flux and field excitation, the selected MVLR and MVPR models are found to give better fit over the measured and calculated reference values. The models have been trained using the experimentally measured and calculated data of four different synchronous machines having different specifications (Table 3.1) viz., Microalternator, Machine No. 1, Machine No. 2 and Laboratory machine. Thus the models have the generalization capability to estimate the q-axis flux for any synchronous machine.

The usefulness of the proposed techniques is that, knowing the d-axis characteristics from the open circuit test conducted on a synchronous machine and if the d-axis flux and the corresponding field excitation values are given, the proposed models estimate the q-axis flux.

The models thus calculate the q-axis flux during field excitation change. The equation developed for $\Phi_q$ is in terms of $\Phi_d$ and AT. The estimation of q-axis flux by using MVLR and MVPR flux models is discussed and the design values of q-axis flux obtained by these models are presented in the subsequent sections. The models are verified with the experimental and calculated results.
3.2.1 Multivariate Linear Regression Technique

The q-axis magnetic flux ($\Phi_q$) is obtained as a function of d-axis flux ($\Phi_d$) and the field excitation (AT) as discussed in previous sections using the Multivariate Linear Regression Technique as below:

$$\Phi_q = \begin{cases} 0, & AT \text{ and } \Phi_d < 0 \\ -a AT + b \Phi_d - c, & AT \geq 0 \text{ and } \Phi_d > 0 \end{cases}$$  \hspace{1cm} (3.1)$$

where $a = 0.051779$, $b = 0.79213$, $c = 0.041672$.

Knowing the values of $\Phi_d$ and AT, the corresponding q-axis magnetic flux, $\Phi_q$ of synchronous machine are estimated using Equation (3.1).

3.2.2 Multivariate Polynomial Regression Technique

Using the Multivariate Polynomial Regression Technique, the q-axis magnetic flux ($\Phi_q$) is modeled as a function of d-axis flux ($\Phi_d$) and the field excitation (AT) as shown in Equation (3.2).

$$\Phi_q = \begin{cases} 0, & AT \text{ and } \Phi_d < 0 \\ a AT^2 - b AT \Phi_d + c \Phi_d^2 + d AT + e \Phi_d - f, & AT \geq 0 \text{ and } \Phi_d > 0 \end{cases}$$  \hspace{1cm} (3.2)$$

where $a = 0.1727$, $b = 0.8873$, $c = 0.9945$, $d = 0.2973$, $e = 0.12564$, $f = 0.007137$.

Given the values of $\Phi_d$ and AT, the MVPR model thus estimates the q-axis magnetic flux, $\Phi_q$ of synchronous machines.
3.3 FLUX OBTAINED BY MVLR AND MVPR MODELS

3.3.1 Flux obtained for four salient pole synchronous machines by MVLR

The modeled values of q-axis flux, $\Phi_q$ using Equation (3.1) employing Multivariate Linear Regression Technique for the Microalternator, Machine No. 1, Machine No. 2 and Laboratory synchronous machine are plotted in Figures 3.1, 3.2, 3.3 and 3.4 respectively for various field excitations (ampere-turns). The calculated and measured d-q axes flux for these machines are also drawn.

![Figure 3.1 Calculated d-q axes flux characteristics and q-axis flux modeled by MVLR for Microalternator](image)
Figure 3.2 Calculated d-q axes flux characteristics and q-axis flux modeled by MVLR for Machine No. 1

Figure 3.3 Calculated d-q axes flux characteristics and q-axis flux modeled by MVLR for Machine No. 2
Figure 3.4  Measured d-q axes flux characteristics and q-axis flux modeled by MVLR for Laboratory machine

3.3.2 Flux obtained for four salient pole synchronous machines by MVPR

Modeled values of q-axis flux for the four synchronous machines used in the present study using the Equation (3.2) by MVPR technique are plotted in Figures 3.5, 3.6, 3.7 and 3.8.

Curves of calculated flux and measured flux using Germanium diode flux sensors in both the axes are also given in the same plot against the respective field ampere-turns.
Figure 3.5  Calculated d-q axes flux characteristics and q-axis flux modeled by MVPR for Microalternator

Figure 3.6  Calculated d-q axes flux characteristics and q-axis flux modeled by MVPR for Machine No. 1
Figure 3.7 Calculated d-q axes flux characteristics and q-axis flux modeled by MVPR for Machine No. 2

Figure 3.8 Measured d-q axes flux characteristics and q-axis flux modeled by MVPR for Laboratory machine
3.3.3 Comparison of flux characteristics obtained by MVLR and MVPR models

The accuracy of MVLR and MVPR models has been verified by comparing the estimated q-axis flux values obtained using the models with those available results of Ahmed El-Serafi and Kar (2003) for the three synchronous machines namely, Microalternator, Machine No. 1 and Machine No. 2 and the experimental results of q-axis flux measured in a Laboratory machine. Error is computed on comparing available reference q-axis flux values and modeled q-axis flux values. Figures 3.9, 3.10, 3.11 and 3.12 compare the various reference flux characteristics along with the q-axis flux characteristics obtained by MVLR and MVPR models respectively for the four synchronous machines viz., Microalternator, Machine No. 1, Machine No. 2 and Laboratory synchronous machine.

From the comparison between the modeled and reference flux values, it is found that the MVPR model is found to be more accurate than the MVLR model for Machine No. 1 and No. 2. However, MVLR model suits well for the Microalternator and Laboratory machine. Further, the estimation of error in these models, when comparing with modeled and reference values and root mean square error (RMSE) calculation are discussed in Chapter 5.

![Figure 3.9 Estimated flux obtained by both MVLR and MVPR models - A comparison for Microalternator](image-url)
Figure 3.10 Estimated flux obtained by both MVLR and MVPR models
-A comparison: for Machine No. 1

Figure 3.11 Estimated flux obtained by both MVLR and MVPR models
- A comparison: for Machine No. 2
3.4 SUMMARY

Two mathematical regression models called Multivariate Linear Regression (MVLR) model and Multivariate Polynomial Regression (MVPR) model are introduced and the performance of the models is discussed. The aim of this work is to estimate q-axis flux of synchronous machines using generalized mathematical models. Available experimental flux values on a laboratory machine in d-axis and q-axis measured using Germanium diode Flux sensors and the calculated flux values of three different synchronous machines namely, Microalternator, Machine No. 1, Machine No. 2 are used in the present work for the development of two mathematical models employing MVLR and MVPR.

The models are designed such that knowing the d-axis flux and the field excitation, q-axis flux of the synchronous machines can be estimated. The estimation of q-axis flux is carried out for synchronous machines and the results of the models are plotted.