PRACTICAL COMBINED PARAMETER IDENTIFICATION AND STATE ESTIMATION OF MACHINES

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ABSTRACT - High performance variable-speed drives usually incorporate a model for the system in either the controller or state estimation stages. The accuracy and general robustness of the drive is dependant on this model so it must accurately represent both the electrical and electromagnetic interactions within the machine and associated mechanical systems. This paper considers two motor forms; the separately excited dc machine and the ac induction machine. For both cases parameter identification methods are described which reduce the expense, or need, of the speed measurement. The Genetic Algorithm technique has been adapted in this work for use in the parameter identification stage. *Copyright© 2000 IFAC.*

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1. INTRODUCTION

To apply electrical machines in microprocessor-based control systems, or to simulate their behaviour on a computer, requires a mathematical model of the machine, together with a knowledge of the parameters in the model. Parameter values can be obtained by means of standard tests, but these are time-consuming, often inaccurate and generally cannot be run when the machine is in service. Each test will normally yield values for only one (at best, two) parameters. An alternative, which estimates all parameters jointly, is to use an optimisation technique to search for the parameter set which results in the behaviour predicted by the model most closely matching that measured. If all the state variables (or set of variables sufficient to define the system) can be measured the process is relatively straightforward. In other cases some of the states may be difficult or unacceptably expensive to measure – examples are the flux in an ac machine, or dynamic measurements of speed or torque in any machine – but even in these last cases solutions can be found. (Hart, et al., 2000)

The main area of interest for the authors is to enable control of speed without the expense of accurate dynamic speed sensors. This is achieved by means of a speed estimator, but that can be inaccurate if the parameters are poorly identified. The optimisation approach allows the parameters to be identified when running, and also partially compensates for errors in the model structure. Although identification of the full parameter set for a dc machine is only possible if speed is known, it is found that a simple and cheap measurement of steady state speed is sufficient.

2. SIMPLIFIED DC MACHINE MODEL

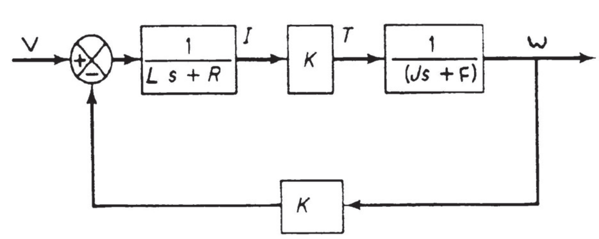

Fig. 1. The dc machine equivalent block diagrams.

Fig. 1 shows a simple model of a dc machine which is widely used and reported in many texts. It leads to the following equations:

$$V(t) = R(t)I + L(t)\dot{I} + K\omega(t) \tag{1}$$

$$T(t) = KI(t) = J\dot{\omega}(t) + F\omega(t) \tag{2}$$

V is the armature input voltage, I is the armature current and ω is the rotor speed. In these equations there are just five independent parameters, the electrical and mechanical circuit elements. It is convenient to rewrite the equations in terms of derived parameters, so:

$$\frac{I}{V}=\frac{D_1(S+D_2)}{(S+P_1)(S+P_2)} \quad (3), \qquad \frac{\omega}{V}=\frac{D_5}{(S+P_1)(S+P_2)} \quad (4)$$

$$(S+P_1)(S+P_2)=S^2+S\left[\frac{RJ+FL}{JL}\right]+\left[\frac{RF+K^2}{JL}\right]=S^2+S[2D_3]+\left[D_3^2+D_4^2\right]$$

and, $D_1=\frac{1}{L}$, $D_2=\frac{F}{J}$, $D_5=\frac{K}{JL}$.

The optimisation procedure will allow a set of four (derived) parameters to be found which give the best match between the variation of V/I against time, as predicted by eqn. (3), and that measured. From these it is possible to deduce only two of the original circuit parameters, L and R. To obtain a value for the fifth parameter requires that eqn. (4) be matched, but it is sufficient to do this at one point, which for convenience is the steady state (S=0). Once the fifth derived parameter is known the remaining circuit parameters can be easily calculated. Since speed need be measured only in the steady state a cheap and simple optical counter, requiring minimum modification to the machine, is sufficient.

3. OPTIMISATION

The optimiser used is based on Genetic Algorithms. As a result the "cost" is defined in such a way that the optimum corresponds to a maximum; specifically, here the global maximum will always be less than 1. The advantages of GAs, in contrast to conventional recursive schemes, are that they do not require the differential of the function, nor that it be linear, nor that it be continuous. GAs have been know for some time (see, for example, Goldberg (1989)) and the techniques employed here have been reported elsewhere by Hart et al. (2000). The specific values used in tuning the GA were: population size of 1000; for 500 generations; probability of cross-over = 0.8; probability of mutation = 0.001; number of cut chromosomes = 100 for pure simulation and 200 for practical noisy data.

In the case of pure simulated behaviour, free from noise and errors, convergence was to costs of 0.95 or better; with practical data the best costs were typically 0.022.

4. HARDWARE

Measurements were made on a dc machine test bench fitted with a 3kW separately-excited dc machine supplied by a commercial thyristor based converter. There are sensors for I, V and speed measurement and a computer with a data acquisition card to record the measured signals. Initially standard tests were performed to obtain estimates of the circuit elements in the standard model.

As a result of several runs the following were found:
L=49.6 mH, K=0.79 $V.s.rad^2$, R=1.3 Ω,
J=0.0204 $kg\,m^2$ and F=0.0068 $N.m.s.rad^{-1}$.

5. IDENTIFICATION USING REAL DATA

The preceding identification method was employed using current and voltage data read in from a file recorded as the real machine was accelerating, after having been given a voltage step input. The Range of costs and parameter distribution follow a normal distribution centred around the parameter set which produces the best cost, Hart (2000). The spread of parameter estimations is shown in table 1 below.

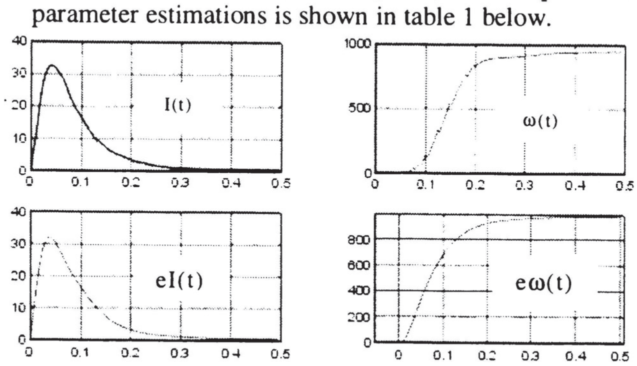

Fig. 3. Plot of I (X1) and ω (X2) against the estimated I(eX1) and ω (eX2) using the best optimised parameter set.

Table 1. Minimum and maximum estimated parameter values.

	L	R	K	J	F
Minimum	31.1mH	1.61Ω	0.78 N.m. A^{-1}	25.0mkg. m^2	3.29 mN.m.s.rad^{-1}
Maximum	40.0mH	1.97Ω	1.05 N.m. A^{-1}	33.8mkg. m^2	5.84 mN.m.s.rad^{-1}

6. RESULTS

Table 2. Cost results for the standard test, averaged optimised and best optimised parameters.

	L	R	K	J	F	Cost
Standard	49.6mH	1.3 Ω	0.79 N.m. A^{-1}	20.4mkg. m^2	6.8mN.m.s.rad^{-1}	0.0041
GA Average	34.6mH	1.72 Ω	0.91 Nm A^{-1}	29.2mkg m^2	4.8mN.m.s.rad^{-1}	0.0156
Best Cost	33mH	1.64 Ω	0.867 Nm A^{-1}	27.5mkg m^2	4.54mN.m.s.rad^{-1}	0.022

The behaviour of the system is quite different from that predicted using the conventionally obtained parameters and the circuit parameters obtained by the new method differ significantly from them, by much more than the measurement error. So, either employment of the conventionally measured parameters will lead to an incorrect prediction of performance, or physically incorrect parameters are required to allow a reasonably correct prediction of performance. For a successful estimator the latter is of more use. The low values of cost associated with the parameter sets are a measure of the structural error - a point which will be further refined.

As can be seen from the above costs the average of the parameters should not be used as, due to the cost function dependency the averaged parameter set, cost is worse than the best parameter set cost. This is due to the fact that a small error in one parameter can be reduce by moving the value for another, thus optimising, not averaging. So the parameter values which correspond to the set with the best cost should always be used. The average values are only used to normalise the results from the independent runs designed to test the robustness and repeatability of the method. The discrepancy between the estimated speed and the measured speed is increased by the large error in the speed measurement.

7. EFFECT OF STRUCTURAL ERRORS

It is thought that if the best cost value had approached that of the purely simulated case then structural accuracy would have been demonstrated. In the practical example the best cost is a great deal lower than 1.0, but no higher order or non-linear effects, such as brush loss and armature reactance, were incorporated into this model.

In order to assess how the maximum cost can assist with the selection of the model structure a second model structure was proposed. This took the form below and represents an eight parameter non-linear model of the same machine.

$$V = IR + L\dot{I} + E = IR + L\dot{I} + (K+b)\omega + cI\omega \tag{5}$$

$$T = KI + cI^2 = J\dot{\omega} + F\omega + e\,. \tag{6}$$

The steady state and the transient forms of the model were initially considered separately. However, due to the nature of the parameter mapping a better solution is found by combining both models and measurements in one optimisation procedure. This led to the inclusion of a cost weighting routine within the genetic algorithm. As with the first method the procedure was tested first using a pure simulation case. The parameter values employed were;

L = 0.0496, K = 0.79, R = 1.3, J = 0.0204,
F = 0.0068, b = 0.05, c = 0.05 and e = 0.001.

The method performs as well as the first method in the pure simulation case. This is to be expected as the effect of noise errors is minimal. However, the effective cost function maximum given by optimisation of real data (0.043) is higher than that from the original method (0.022). Therefore we suppose that the second structure represented the actual system more accurately than the standard one. The problem associated with this complex method is the increase in optimisation time for the same optimisation variables. Both costs are much lower than 1.0, but there is still noise present on the measured signal.

Table 4. Cost results for the standard test, standard optimised model and complex optimised model.

Test	Standard tests @18°C	Best optimised standard model @18°C	Best optimised complex model @25°C
K	0.79	0.79	0.73
L	49.6m	33.0m	31.7m
R	1.30	1.64	1.61
J	20.4m	25.0m	27.3m
F	6.80m	5.10m	5.55m
b	-	-	5.92m
c	-	-	3.08m
e	-	-	146m
Cost	0.0041	0.022	0.043

Overall the complex non-linear model based method shows a tens time improvement in overall cost compared to the original parameters provided by the standard tests.

8. THE AC MACHINE

For the ac useful results can be obtained without optimising a dynamic response function. Unlike the dc machine, the dynamic elements, such as the inductance, still feature in the ac machine steady state function. For this paper a simple steady state model, defined by the equations below, was employed.

$$\bar{V}_s = (R_s + j\omega_s L_s)\bar{I}_s + j\omega_s L_m \bar{I}_r, \tag{7}$$

$$0 = \left(\frac{R_r}{Slip} + j\omega_s L_r\right)\bar{I}_r + j\omega_s L_m \bar{I}_s \cdot \tag{8}$$

9. THE FIRST AC MACHINE METHOD

The first ac induction machine method uses the stator voltages and currents together the steady state rotor speed to produce estimates for the four parameters required for dynamic speed-sensorless rotor field orientated vector control, (RFOC). The parameters are as follows:

$A1 = R_s$; the stator resistance,

$A2 = \dfrac{L_m^2}{R_r}$; the multiplying impedance ,

$A3 = \left(\dfrac{L_r}{R_r}\right)^2$; the square of the rotor time constant, and,

$A4 = L_s$; the stator inductance.

The four parameters can be used to control the machine within the RFOC scheme described below; (Derivations can be found in most text books such as Leonhard (1985), Novotny and Lipo (1996) and Vas (1998)).

In the stator reference frame:

$$\left[\frac{\psi_r^s}{L_m}\right] = I_{mr}^s = \left[\frac{\sqrt{A3}}{A2}\right]\left[\int\left[V_s^s - A1 I_s^s\right]dt - \left[A4 - \frac{A2}{\sqrt{A3}}\right]I_s^s\right], \tag{9}$$

In the rotor reference frame:

$$\omega_r = \omega_g - \frac{1}{\sqrt{A3}}\frac{I_{sT}}{I_{sF}}\left[S\sqrt{A3}+1\right] \tag{10}$$

$$\left[\frac{|\psi_r|}{L_m}\right] = \frac{I_{sF}}{\left[S\sqrt{A3}+1\right]}. \tag{11}$$

With the rotor current cancelled the stator input impedance becomes:

$$\frac{\bar{V}_s}{\bar{I}_s} = \frac{(R_s + j\omega_s L_s)(R_r + j\omega_s L_r Slip) + \omega_s^2 L_m^2 Slip}{(R_r + j\omega_s L_r Slip)}$$

Substituting the parameters defined above and separating the complex impedance into real and imaginary components yields:

$$\mathrm{Re}\left\{\frac{\bar{V}_s}{\bar{I}_s}\right\} = \frac{\omega_s^2 Slip[A2] + \omega_s^2 Slip^2[A3A1] + [A1]}{\left(1+\omega_s^2 Slip^2 A3\right)} \tag{12}$$

$$\mathrm{Im}\left\{\frac{\bar{V}_s}{\bar{I}_s}\right\} = \frac{\omega_s^3 Slip^2\left[A3A4 - A2\sqrt{A3}\right] + \omega[A4]}{\left(1+\omega_s^2 Slip^2 A3\right)} \tag{13}$$

where all of the four parameters are identifiable.

The method was tested first by pure simulation. As with the dc machine this allowed the optimiser to be tuned and the general robustness of the method to be examined. Like the dc machine methods the ac method theoretically requires only a small number of test points, but with fewer points the method is more sensitive to measurement errors. The optimiser converged with a "cost" of 0.999 after 100 generations of a population of 500, all the parameters then being within a fifth of a percent of their true values.

Standard no-load, locked rotor, dc resistance and mechanical time constant tests where performed to produce the first estimate of the parameter set, the results of which are given in table 5 .

Six steady state points were then recorded from the real machine and the optimiser produced the parameter set below:

Table 5. The standard and new parameter sets.

Parameter	Standard Tests	First Method
D1	7.2	8.3
D2	0.17582	0.25362
D3	0.0945	0.160
D4	0.615	0.680
Cost	0.002177	0.068335

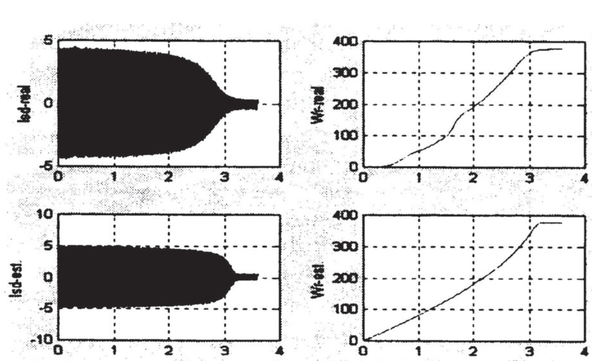

Fig. 4. Plots of estimated and real Isd and ω_r at 100V, 60Hz using first method parameters.

The state estimations from the first method were compared with real data. This included the off-line dynamic estimation of flux and speed for each of the test point conditions, the results of which are given in table 6.

Table 6. Rise times for different input conditions.

Volts.	Freq.	Practical Data	Standard Tests	First Method
120	40	0.8	1.2	0.8
120	50	1.2	1.5	1.2
120	60	2.2	2.5	2.1
100	40	1.2	1.1	1.1
100	50	1.7	2.3	1.8
100	60	3.3	3.6	3.2

Table 6 shows the speed rise times for each parameter set. It can be seen that the new parameter set produces more accurate dynamic speed responses than the standard test produced set. As the method aims to reduce the steady state error the slip error is negligible at all the test points.

The method suffers due to a high sensitivity to measurement error, but this can be remedied if, as in the dc method, more test points are employed. Unfortunately this increases the update time when the method is used on-line.

10. REDUCED MODEL OPERATING RANGE

The ac method shows a high structural error when used across a wide operating region. To increase the accuracy of the state estimation either a more complex model is required or the parameters in the simple model structure must be tuned more rapidly. In order to analyse the latter situation test points were generated from the machine at a constant voltage level with synchronous frequencies between 45 and 55 Hertz.

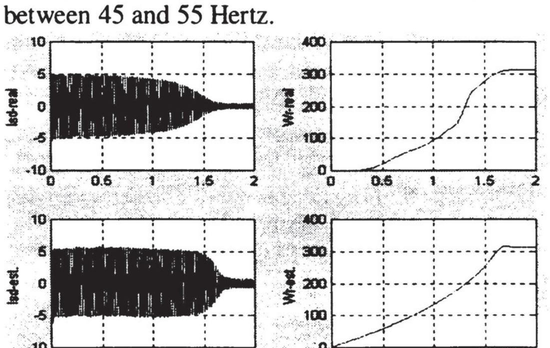

Fig. 5. Plots of estimated and real Isd and ω_r at 50Hz input frequency.

Table 7. Parameter sets from the eleven points taken from a reduced operating range.

Parameter	Standard Tests	First Method
D1	7.2	6.0
D2	0.1758	0.1903
D3	0.0945	0.144
D4	0.615	0.634
Cost	0.00248	0.00263

It can be seen from the parameter sets in table 7 that the difference between each set, and between the "costs", has reduced. The "cost" for the standard test produced parameters has also increased from the value achieved from the broader range of six test points, even with the inherent decrease of cost usually associated with an increase in the number of test points. This shows, as expected, that the simple model is too simplistic to fully describe the system over large operating ranges. The standard tests were performed at 50Hz, which should also increase the accuracy of the parameters under these conditions. The first new method does, however, show the reduction in cost due to an increased number of test points. The parameters identified by the new method show more resemblance to the those from the standard tests, which is to be expected.

11. SECOND "SPEED SENSOR-LESS" METHOD

Unlike the dc machine case, where all the information regarding electrical and mechanical systems was used, so far for the ac machine no use of the mechanical system has been made. The following section shows how this additional information can be employed to reduce the number of require measured states in the steady state.

This second method produces an estimate of steady state rotor speed, or slip, using stator current and synchronous speed by way of equating the steady state torque equation in a mechanical system containing a single friction. Using this method in conjunction with the RFO parameter estimator a complete identifier can be constructed that produces estimates for the four parameters required for RFOC and also the total friction of the machine and load. In this paper only preliminary results are given as much work is still to be done.

Defining torque in terms of stator current, slip and synchronous frequency;

$$Tem_{ss} = \frac{3}{2}(pp)\frac{L_m^2 \bar{I}_s^2 \omega_s R_r Slip}{R_r^2 + \omega_s^2 L_r^2 Slip^2},$$

substituting $Tem_{ss} = \frac{F\omega_r}{(pp)}$, and $Slip = \frac{\omega_s - \omega_r}{\omega_s}$

gives a cubic for the steady state rotor speed in terms of stator current and synchronous speed:

$$\begin{aligned} &\omega_r^3 + \omega_r^2[-2\omega_s] \\ &+ \omega_r \left[\frac{FR_r^2 + FL_r^2\omega_s^2 + \frac{3}{2}(pp)^2 L_m^2 R_r \bar{I}_s^2}{FL_r^2} \right] \\ &+ \left[-\frac{\frac{3}{2}(pp)^2 L_m^2 R_r \bar{I}_s^2 \omega_s}{FL_r^2} \right] = 0 \end{aligned} \tag{14}$$

The slip can then be calculated and placed into the original speed measured steady state parameter estimator. As the cubic produces three roots all three of the subsequent slip values are individually used by the original method and the correct root selected as that which produces the smallest error in the original method.

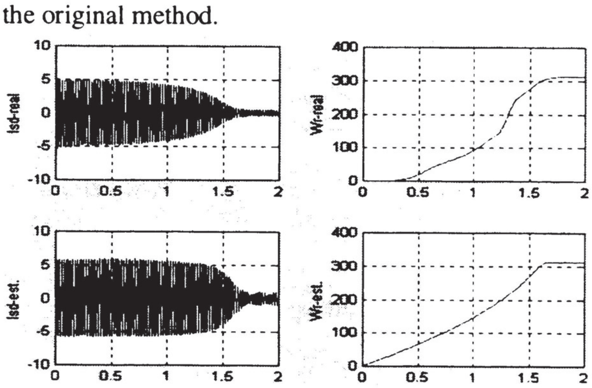

Fig. 6. Plots of estimated and real Isd and ω_r at 100V 50Hz using second method parameters.

Table 8. Parameter sets from the original six points.

Parameter	Standard Tests	First Method	Second Method
D1	7.2	8.3	8.1
D2	0.1758	0.2536	0.2545
D3	0.0945	0.160	0.158
D4	0.615	0.680	0.671
D5	0.00057	-	0.00051
Cost	0.002177	0.068335	0.05139

The second method produces a better cost and rise time error than the original standard tests produced, but a lower cost than the first method. This can be explained; the reduction in measured states and the increase in complexity makes the second method more sensitive to measurement error in the variables it employs. It would then be expected that at some point the second method would become more accurate than the first as the number of test points is increased.

12.CONCLUSION

The optimisation method of jointly estimating parameters and states has been shown to be repeatable and robust to noise and structural errors, using practical data. The method can produce a worst case error index for each circuit element which can be used to tune the optimiser. The ultimate test of the method is the comparison between the practical and estimated current and speed responses.

The standard dc model based method proposed offers considerably improved predictions of performance when compared to data from standard tests based on circuit measurements. The complex dc model based method shows even greater improvement. Both methods can also be used for on-line parameter tuning.

Preliminary results show that both ac methods produce parameter estimates that, when used in the standard model, produce more accurate dynamic speed estimation then those obtained by standard tests and, moreover, can be performed on-line.

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