Universal Low Cost Controller for Electric Motors with Programmable Characteristic Curves

J. Oehm, M. Gräfe, T. Kettner, and K. Schumacher

***Abstract*— The realization of a universal low-cost controller for electric motors in CMOS technology with programmable characteristic curves is presented. With regard to the required chip area of 2.7 mm^2 in a 1.6 μm, 40 nm technology, the general advantage in comparison to microcontroller-based solutions lies in the low factory costs. The analog dc power supply is generated directly from the 230 V ac power line. An on-chip functional unit controls the firing current for the off-chip motor driving triac. Features of this functional unit are torque control and overload protection, firing, and post firing control. A new method was used to implement programmable multidimensional characteristic curves which are temperature and technology insensitive. In the actual controller application for a drilling machine motor, the mask-programmed curve shapes have been generated with the help of fuzzy algorithms. An impression of the reproducibility of multidimensional characteristic curves in manufacturing, as well as the accuracy of their precalculation, is given by introducing simulated and measured statistics of the actual design.**

I. Introduction

In the last few years the fuzzy control idea has become very popular. The general advantage of a fuzzy controller is that its transfer function can be derived from a set of rules representing a human's expert knowledge. This potentially leads to a better control behavior in comparison with conventional methods. Many suggestions have been made as to how to implement an integrated analog fuzzy controller (e.g., [1], [2]) based on the structure given in Fig. 1. The main advantage of *analog* implementations (in comparison with *digital* solutions) lies in the fact that they require less chip area in the case of fixed rule sets. However, the area requirement increases drastically if high flexibility is provided.

A feature of fuzzy controllers is that they can be described completely by their multidimensional transfer functions. So it is possible to approximate their input–output behavior instead of processing the fuzzy algorithm itself. The multidimensional transfer function resulting from the fuzzy-rule-sets can be precalculated with the help of software tools (e.g., [3]). To approximate the transfer characteristics is sufficient for many applications and, using the proposed circuitry, requires less chip area than a conventional analog (or digital) fuzzy controller solution providing the same flexibility. Additionally, higher action-speed is obtainable with comparable accuracy. The proposed circuit also meets the demands on reproducibility in fabrication.

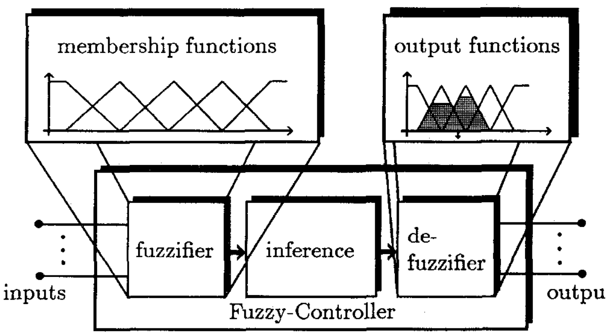

Fig. 1. Block diagram of a fuzzy-controller.

II. Synthesizing N-Dimensional Characteristic Curves

Fig. 2 illustrates the proposed architecture[1] required to synthesize N-dimensional transfer functions for two inputs ($I_{\text{in},x}$ and $I_{\text{in},y}$) and one output (I_{out}). It is a regular circuitry of 7 $\times$ 7 weight cells C_{ij} in current mode technique, each of which generates an output current like that shown in Fig. 3 (x and y are the normalized input currents $I_{\text{in},x}$ and $I_{\text{in},y}$, $g(x,y)$ is the normalized output of one cell). The superposition of all output currents leads to an approximation of the demanded transfer function. Each cell, except those in the left column and the bottom row, has two inputs driven by a ramp generator for each row and column. The ramp generators determine the "position" of the basic output shapes depicted in Fig. 3 while the "height" is stored in the cells.

More detailed parts of the circuitry depicted in Fig. 2 are shown in Fig. 4. Each ramp generator forms the difference between the reference current I_{ref} weighted with B_i or E_j and the input current $I_{\text{in},x}$ or $I_{\text{in},y}$. If this difference is positive, it is weighted with A_i^{-1} of D_j^{-1} and impressed into all cells of the corresponding row or column. In the cells, this current is subtracted from the reference current once again. If this difference is positive, it is weighted with C_{ij} and impressed into I_{add} or I_{sub} depending on whether a positive or negative slope is demanded—the total output current of the controller corresponds to the difference $I_{\text{add}} - I_{\text{sub}}$ generated by another current mirror. So the output current of the cell becomes

$$I_{\text{out},ij} = C_{ij}\max\{0; I_{\text{ref}} - A_i^{-1}\max\{0; B_iI_{\text{ref}} - I_{\text{in},x}\} - D_j^{-1}\max\{0; E_jI_{\text{ref}} - I_{\text{in},y}\}\}.$$

The factors B_i and E_j determine the position, A_i and D_j the slope and C_{ij} the height of the shape depicted in Fig. 3. Taking this into account, there are three possible states of each cell.

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[1] Patent applied for.

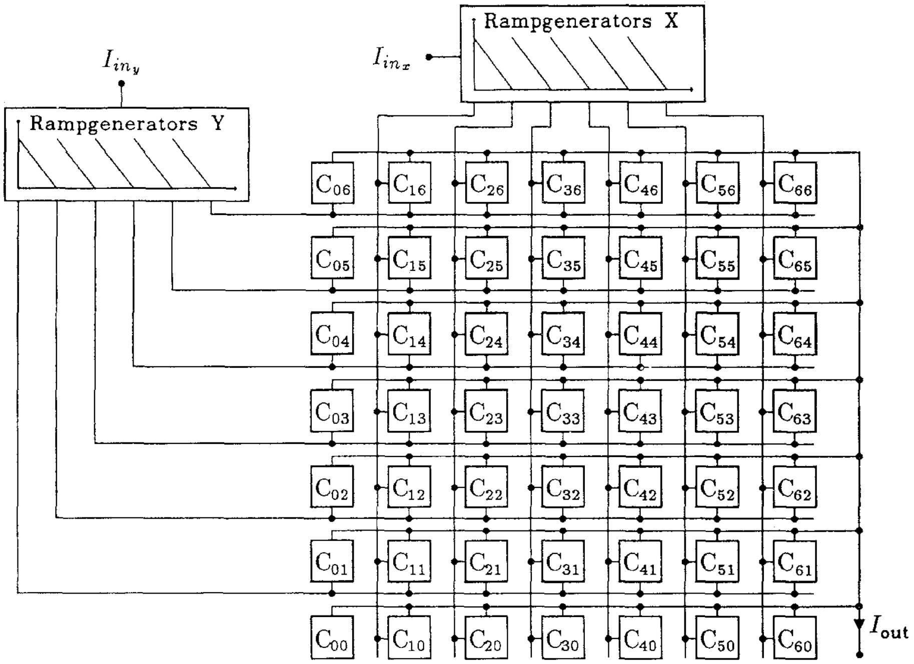

Fig. 2. Architecture for two-dimensional transfer function.

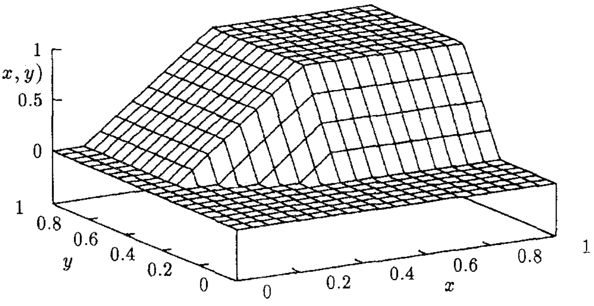

Fig. 3. Normalized transfer characteristic of a basic unit X_i, Y_j, C_{ij}.

1) The sum of the currents impressed into the cell by the corresponding ramp generators is greater than I_{ref}
   $\Rightarrow$ The output current of the cells is zero, the cell is *off*. This corresponds to small input currents $I_{\text{in},x}$ and $I_{\text{in},y}$.
2) The sum of the cell's input currents is between zero and I_{ref}
   $\Rightarrow$ The output current of the cells is
   $$I_{\text{out},ij} = I_{\text{ref}} \cdot \left(1 - \frac{B_i}{A_i} - \frac{E_j}{D_j}\right) - \frac{I_{\text{in},x}}{A_i} - \frac{I_{\text{in},y}}{D_j}.$$
   This means the cell is *active*.
3) The input currents $I_{\text{in},x}$ and $I_{\text{in},y}$ are greater than the weighted reference current so the input currents of the cell are zero. This leads to the maximum output current $C_{ij} \cdot I_{\text{ref}}$. The cell is now *saturated*.

An overview of weight cell activity within the full system is shown in Fig. 5. Weight cells having active status belong to the same row or column controlling ramp generator. Their output currents depend linearly on the input currents.

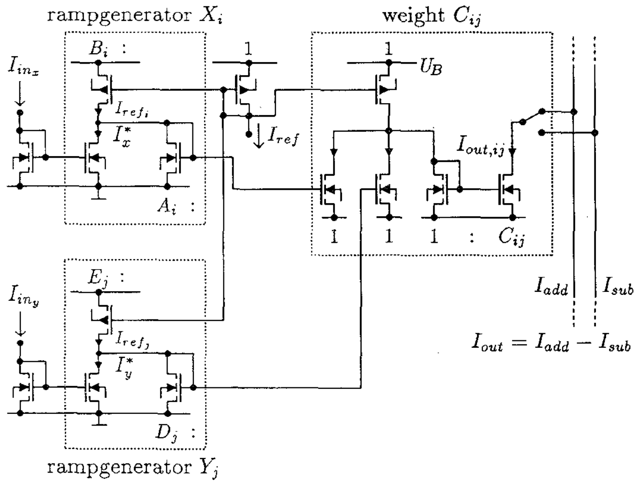

Fig. 4. Ramp generators X_i, Y_j, and weight cell C_{ij} in detail.

This behavior leads to a simple method to calculate the weights C_{ij} from the function $f(x,y)$ to be approximated

$$\begin{aligned} C_{00} &= f(0,0) \\ C_{i0} &= f(x_i,0) - f(x_{i-1},0) \\ C_{0j} &= f(0,y_j) - f(0,y_{j-1}) \\ C_{ij} &= f(x_i,y_j) - f(x_{i-1},y_j) - f(x_i,y_{j-1}) + f(x_{i-1},y_{j-1}). \end{aligned}$$

The weights calculated can subsequently be optimized. The transfer ratios of the current mirrors determining the height and the active range of each cell can be programmed with high precision by connecting transistors with equal design in parallel. The reproducibility of the transfer characteristics is mainly influenced by the effects of local mismatching between

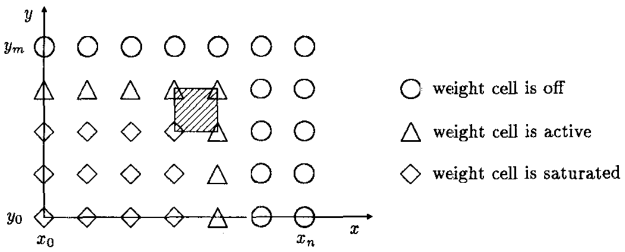

Fig. 5. Weight activity within full system.

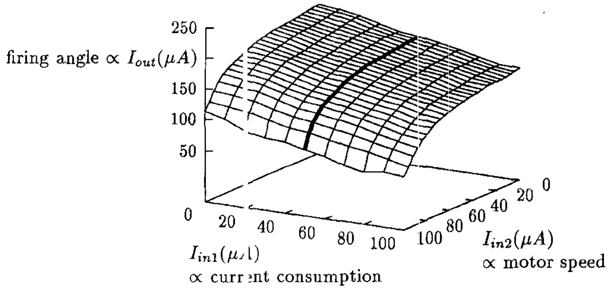

Fig. 6. Measurement of 2-D current transfer function implemented in a drilling machine application.

transistor parameters, however, these requirements can be controlled within the design phase [4]. Systematic errors can be kept small by using cascode configurations.

III. EXPERIMENTAL RESULTS WITH SYNTHESIZING CHARACTERISTIC CURVES

In our implementation we used a matrix of 7 × 7 weight cells, each of which is programmable with 3 b plus sign. Fig. 6 illustrates the measured input–output-behavior of the controller itself as the superposition of all weight cells output currents. The transfer function was programmed in the controller for a drilling machine application. The current value on the X-axis represents the current consumption of the motor, the current value on the Y-axis stands for the user-given nominal value of the motor speed, the Z-axis value is a measure for the firing angle to get a specific motor action. The depiction in Fig. 7 shows for the marked shape in Fig. 6 the simulated statistics of reproducibility in comparison to the statistics of 40 samples fabricated in two different CMOS-technologies. Simulated and measured statistics are in good agreement. The reproducibility of N-dimensional characteristic curves is only limited by the local mismatching in the parameters of the MOS-transistors. No dependence on temperature or other parameters is given. In Fig. 8, the step response of the two-dimensional (2-D) current transfer function is shown. The step response time of the actual design is 1 μs. Further investigations in the field of high speed applications indicated that shorter step response times are possible with a modified design and circuitry, with the drawback that the accuracy is reduced.

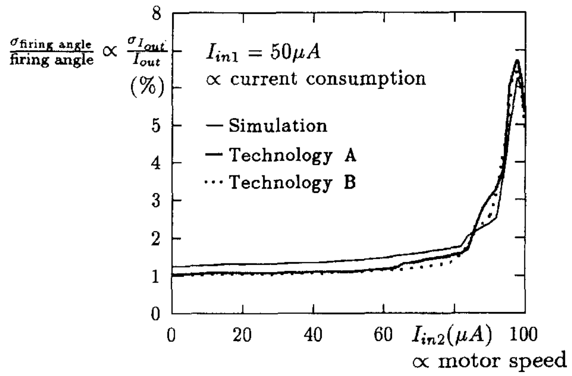

Fig. 7. Reproducibility of a shape.

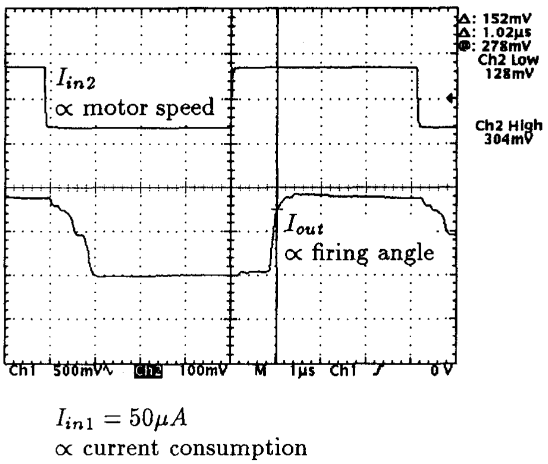

Fig. 8. Step response.

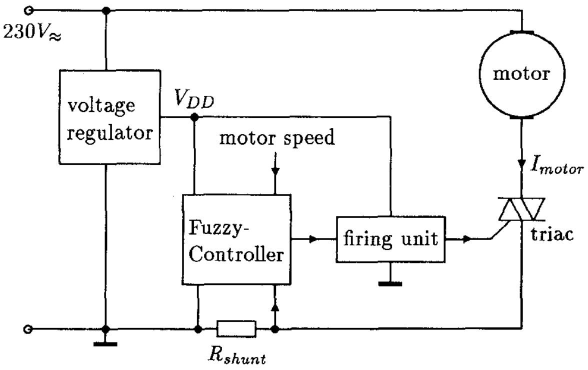

Fig. 9. Low-cost controller concept for electric motors including a fuzzy controller.

IV. CONTROLLER FOR ELECTRIC MOTORS

The basic concept of a low cost controller for electric motors including a fuzzy controller is depicted in Fig. 9. The current flow through the motor is determined by the firing angle at which the triac is turned on. The current flow is measured with the help of R_{shunt}. The voltage drop over R_{shunt} and the user-given value for the engine speed are the two input values for the fuzzy controller. The output value of the fuzzy controller determines the angle of firing impulses relative to the zero crossing of the line voltage. The voltage regulator generates the supply voltage for the fuzzy controller and the

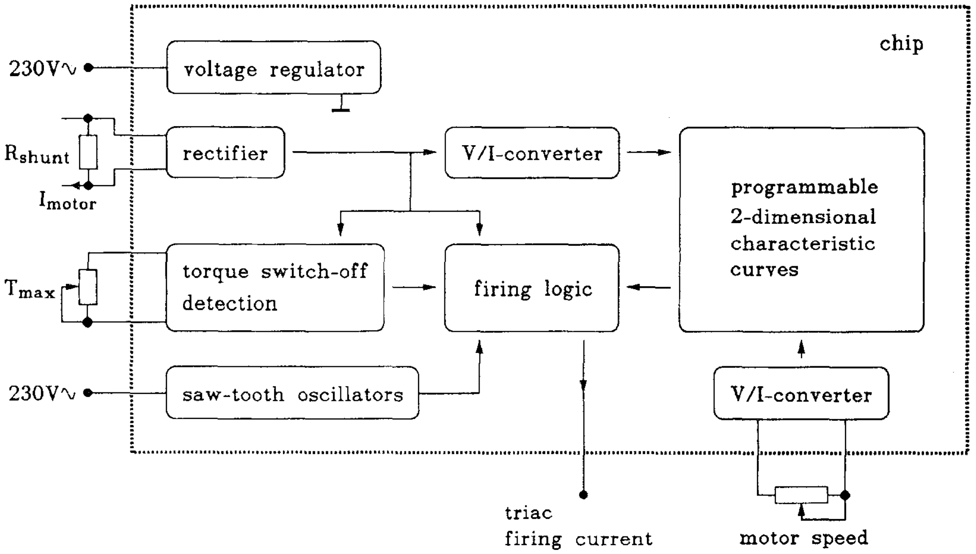

Fig. 10. Low-cost controller concept for electric motors including programmable characteristic curves.

firing unit. To keep costs low, the engine speed is not measured directly. It can be only calculated indirectly from the actual current flow and the user-given value for the engine speed. The nonlinear characteristics between the input values and the firing angle for specific motor characteristics are generated with the help of a fuzzy controller, which generates them from a set of (programmed) fuzzy rules, representing a human's expert knowledge.

As explained previously, it is more cost effective to adapt the transfer characteristics of the programmed fuzzy controller with the proposed programmable regular circuitry. Fig. 10 shows the final architecture of the implemented low cost controller for electric motors with programmable 2-D characteristic curves in place of the fuzzy controller. In this concept, the controlling characteristics are, for example, first calculated from fuzzy rule sets externally by a personal computer. Next, these results are transformed into the programming of the proposed programmable regular circuitry, which approximates the transfer characteristics of the fuzzy controller (Fig. 6). In general, there is no need to derive the (nonlinear) controlling characteristics with the help of fuzzy rules. They can be also found experimentally. However, the user-given value for the engine speed is converted into a current. This current value represents the first input of the 2-D programmable current transfer function. The actual current consumption of the engine is detected with a shunt-resistor. In general, the current consumption is nonlinear dependent on the motor speed. The ohmic drop in potential is amplified and rectified next. After this, the root-mean-square value is calculated and converted into a current which builds the second input value of the 2-D current transfer function. The output current depending on the two input currents and the programming of the transfer function is a measure of the time delay of the triac firing current relative to the zero crossing of the line voltage. The time delay signal itself is generated from a current controlled sawtooth oscillator, reset to zero at the zero crossing line voltage. If the output of the sawtooth oscillator becomes equal to a reference value, a starting signal for the triac firing current is sent to the firing logic. Features of the firing logic are torque control and overload protection, firing, and post firing control.

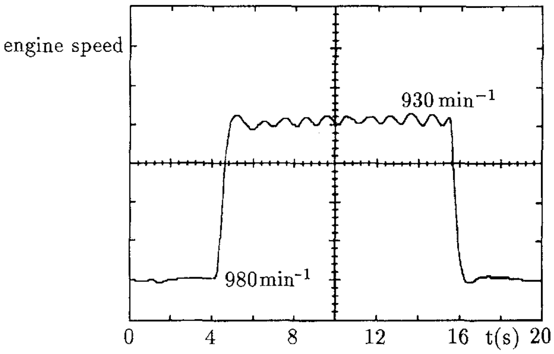

Fig. 11. Oscillation in the step response of the complete control loop with 8 b quantization of the characteristic curves.

V. Experimental Results with the Controller for Electric Motors

For experimental purposes the 2-D transfer function characteristics of the controller for electric motors has been alternatively carried out with the help of a personal computer interfaced by A/D- and D/A-converters. For a very large quantization of the 2-D transfer function characteristic, it was found that stability problems can occur. As an example, in Fig. 11 the step response of the complete control loop including a digital generation of the 2-D transfer function characteristics with a resolution of 8 b is shown. The motor speed of a controlled drilling machine oscillates. The oscillation stops if the quantization resolution is set to a resolution of at least 10 b. Since the demand for chip-area for 10-b A/D- and D/A-converters is very large, the advantage of the analog solution

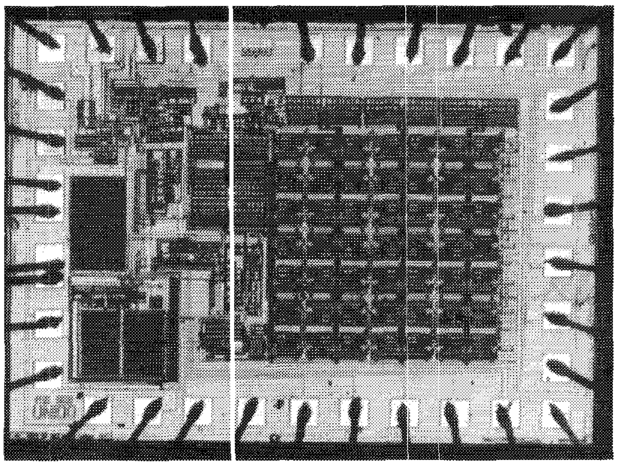

Fig. 12. Chip photo of the controller for electric motors with programmable characteristic curves.

becomes obviously. Only 4 mm^2 including connection pads are needed. The chip photo of the controller is shown in Fig. 12. The number of connection pads to the externals is 16 (the rest of the connection pads are for the testability of the functional blocks), the number of transistors is about 1600. In the regular region, the programmable 2-D current transfer network is placed. Fig. 13 depicts the measured characteristics between the brake voltage connected to the eddy-current brake, engine speed, and user-given value for the engine speed. The measured characteristics are in good agreement with the given specifications of a drilling machine manufacturer for a good drilling behavior of an electronic controlled machine. The engine speed should not remain constant with increasing load to avoid thermal overload and to give the user an impression of the actual load by acoustic feedback. In Fig. 14 the step response of the complete system—controller for electric motors, drilling machine, eddy-current brake—is shown. After a step in the load by changing the brake voltage, the current I_{motor} increases within a settling time of 750 ms. The settling time is mainly determined by the frequency of the power line. No instability has been observed within the whole operating range.

VI. CONCLUSION

A low-cost single chip controller for electric motors in CMOS technology with programmable characteristic curves has been introduced. Nonlinear motor-characteristics can be converted to the aspired behavior by changing the characteristic curves. Further features of the completely analog solution are small chip area, good reproducibility of control action in manufacturing, few chip-external components, and easy external alignment. Features of the introduced method to implement programmable multidimensional characteristic curves are insensitivity to variations in temperature and technology parameters.

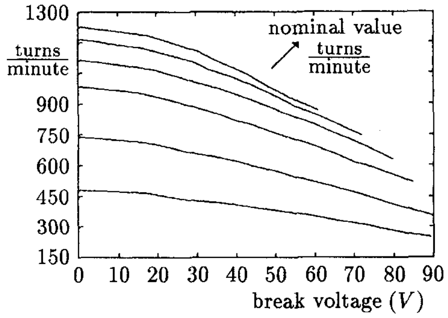

Fig. 13. Measured electronic controlled drilling machine characteristics.

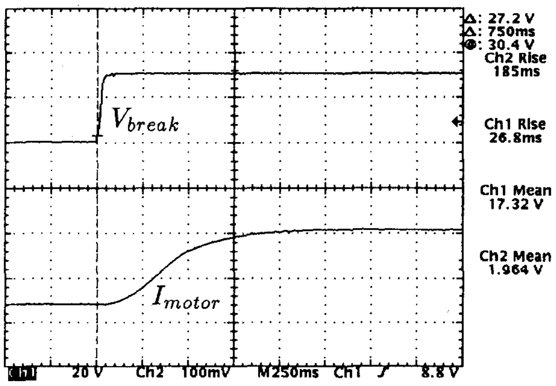

Fig. 14. Step response controller, drilling machine, Eddy-current brake.

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