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Electrical Engineering

Elixir Elec. Engg. 64 (2013) 19324-19327

ISSN: 2229-712X

Performance Evaluation of BLDC Motor using Intelligent Hybrid Controllers for Position Control

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ARTICLE INFO

Article history:
Received: 20 September 2013;
Received in revised form:
3 November 2013;
Accepted: 11 November 2013;

Keywords
Fuzzy switching control,
MATLAB /Simulink environment,
Modified three-stage bang,
Bang control,
Motor drives.

ABSTRACT

This paper presents the development and implementation of a new and practical fuzzy switching position controller for process industry control. Compatible with the structure of a bang–bang controller, a two-input fuzzy switching position controller with five rules is proposed. The idea is based on constructing a fuzzy switching control law which is functionally analogous to a traditional bang–bang controller. Fuzzy logic rules are used to enable an improved version of the conventional bang–bang control. The objective is to replace the conventional bang–bang controller with the proposed fuzzy switching position controller. A modified three-stage bang–bang controller is also designed and implemented. This controller is tested under the same conditions as that of the proposed fuzzy switching position controller, and its performance is used as a basis of comparison by which both controllers are measured. Both controllers are developed using MATLAB using the position control of a brushless dc motor drive found in the majority of these new robotic devices. Simulation Results shows that the fuzzy switching position controller produces adequate control performance, particularly in handling nonlinearities and external disturbances. The efficacy of the fuzzy switching position controller is demonstrated by its positive results, practicality, and feasibility in the process industry sector, when compared with a modified traditional bang–bang controller.

Introduction

ELECTRIC motor drives have a wide range of applications such as automobiles, household appliances, railway, elevators [1], etc. In recent years, many efforts have been made to develop and improve variable speed drive technology which attempts to match motor speed with the optimum or desired operating point of the application being driven [2]. The bang–bang controller, also known as the on/off controller, is very useful in the control of nonlinear systems which make decisions based on target and threshold values and decides whether to turn the plant on or off. Owing to its simplicity, the bang–bang controller has many useful applications, such as motor switching control [3] or impact control in robots [4] and water tank system [5] and temperature control in a furnace or thermostat [6]. The relative effectiveness of bang–bang controllers versus linear controllers was investigated by comparison to human behavior in an experiment which investigated the tendency of human operators to behave in bang–bang fashion when controlling some high-order systems when a linear alternative was available [7]. It was concluded that, for the class of systems for which fine motor control about the reference is unnecessary, switching bang–bang control is more intuitive and can be performed without sacrificing performance. However, for those cases where fine motor control about a reference is required, bang–bang control may cause mechanical vibration, noise, and eventual machine wear and tear [8], [9]. This leads to lack of robustness and portability of bang–bang controllers. Chen *et al.* [10] propose a controller which integrates a bang–bang control methodology with proportional–integral–derivative (PID) control. The integrated controller switches between bang–bang and PID control based on deviation. The switching control is used when the deviation is large, and PID control is used when deviation is small. The concept of fuzzy logic in its current form was first proposed by Zadeh [11], after observing that conventional logic was insufficient to process data representing imprecise or vague ideas. Fuzzy logic, according to him, is an attempt at the formalization of the human ability to converse, reason, and make reasonable decisions when faced with imprecision, uncertainty, and conflicting information and the ability to perform many physical and mental tasks without any measurements or computations. The linguistic modeling of complex irregular systems constitutes the heart of many control and decision making systems, and fuzzy logic represents one of the most effective algorithms to build such linguistic models [12]. Thus, fuzzy logic control has emerged as one of the most successful nonlinear control techniques [13]. A fuzzy logic controller translates numeric input data into verbal or linguistic variables through membership functions, uses fuzzy rules to evaluate these variables, and, after a defuzzification process, outputs numeric output values [14]. A fuzzy bang–bang controller is proposed that possesses the advantages of bang–bang control while using friction damper enabling fine control without mechanical effects [15]. Sun [16] discusses pattern matching in a fuzzy rule-based control system. Pattern matching consists of a process which represents requirements and data which represent the real situation. Pattern matching in a rule-based system is the process whereby the antecedent of a rule is seen as the pattern which is matched against input signals, here treated as data.

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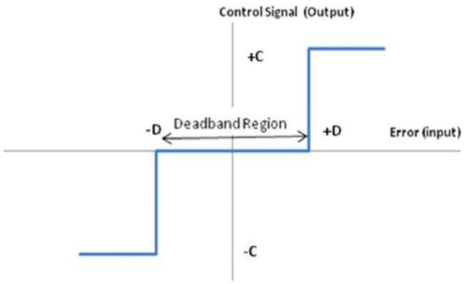

Fig. 1. Improved bang–bang controller

This paper presents a new systematic design of fuzzy switching position controller-based traditional bang–bang analysis and design for use in process industry control, in vibration control of building structure, in a flow control valve operated in bang–bang mode, and with human-interactive robotic devices. Simplicity is a key principle of this design methodology. A simple controller applying two variables and five rules is developed. The developed controller, having a simple structure to form a control law, is closely analogous to a conventional bang–bang controller. The control law was designed and implemented in real time which proved to be a self-contained, practical, and realistic controller for use in process industry division. The key advantage is the ease of the design and flexibility. The controller code has been generated directly from Simulink using IF–THEN rules and Real-Time Workshop. This paper also presents a hardware platform used during the implementation stage. The proposed controller shows promise for process industry control due to its ability to combine many control laws together in a simple intuitive manner.

Modified Three- Stage Bang–Bang Controller

A modified three-state bang–bang controller is designed and presented in this section. Fig. 1 displays the basic function of the modified bang–bang controller. Note that $uc(k)$ is the output of the controller; C is the magnitude of the output of the controller when the error lies outside of the dead-band setting, and D is the dead-band setting. The error is the difference between the desired reference signal and the rotor angular position. A model-free control law is introduced based on the following intuitive rules:

IF the ERROR $> D$,THEN $uc(k) = +C$
IF the ERROR $< -D$,THEN $uc(k) = -C$
IF the $|\text{ERROR}| < D$,THEN $uc(k) = 0$.

Rule 1) IF the ERROR is positive (lies outside the deadband setting), THEN the controller output is positive.

Rule 2) IF the ERROR is negative (less than the dead-band setting), THEN the controller output is negative.

Rule 3) IF the ERROR lies within the dead-band setting, THEN the controller output is zero.

The modified three-stage bang–bang controller was developed and implemented using MATLAB/Simulink environment. The Simulink model implementing the modified bang–bang controller is displayed in Fig. 2. The error signal is fed into the "If Block" and compared to the dead-band setting. Then, an "If Statement" compares the signals and activates the appropriate subsystem. The three-stage modified bang–bang controller generates the control signal as follows.

1) IF the ERROR is GREATER THAN the dead-band setting, THEN the "If Block" sends a signal to the "If Action Subsystem." Subsequently, the "If Action Subsystem" sends the control action $+uc(k)$ to Merge Block. The "Saturation Block" passes the control signal $u(k)$ up to the given saturation limits. Saturation is also used to limit the controller output $uc(k)$ as follows:

$u(k)$ =$u$max when $uc > u$max
uc when $u$min $\le uc \le u$max
$u$min when $uc < u$min

where uc is the input to the saturation block and $u$max and $u$min are the upper limit and the lower limit of the saturation block.

2) IF the ERROR is LESS THAN the negative dead-band setting, THEN the "If Block" sends the signal to the "If Action Subsystem" which sends the control action $uc(k)$ to Merge Block.

3) IF the ERROR is within the dead-band setting, THEN the control action is stopped. That is, the control action $uc(k)$ is 0.

Fuzzy Switching Position Controller

The structure built here is a two-input single-output controller. The inputs and outputs of the modified three-stage bang–bang system were translated into linguistic variables and fuzzy rules. The formation of these variables summarizes and compresses information through the use of granulation [6]. The corresponding structure is shown in Fig. 3. It consists of building blocks:

1) A fuzzification block that expresses quantitative action to qualitative action;

2) A fuzzy inference engine that generates the fuzzy rules; and

3) A defuzzification block that articulates qualitative action to quantitative action. The fuzzification section translates qualitative data into a qualitative description, the fuzzy inference engine generates the fuzzy rules, and the defuzzification section translates qualitative action into quantitative action. The inputs to the fuzzy switching position controller were the error and direction of the angular position. The output of the controller was the motor voltage. Each of these inputs and outputs corresponded to a fuzzy variable. The error variable consists of three fuzzy sets, the positive, negative, and OK, with Gaussian membership functions. The parameters of the members of the error set corresponded to the class of the modified three-stage bang–bang controllers. The normalized error falls within the range [−1, 1]. The direction of the angular position variable also consists of three fuzzy sets, the negative, middle, and positive, with Gaussian membership functions.

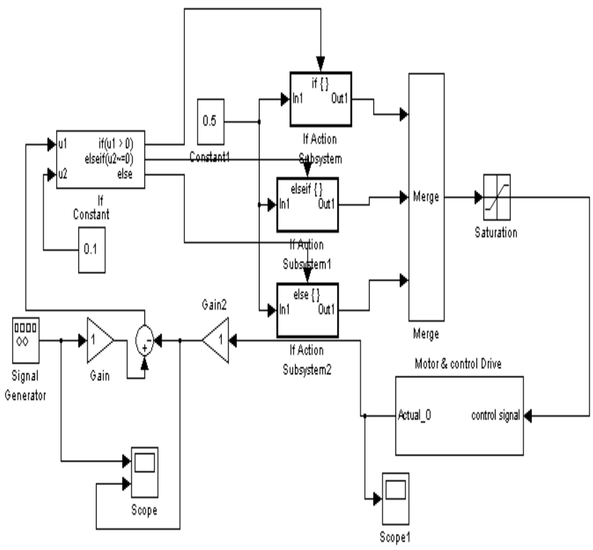

Fig. 2. Simulink model implementing the three-stage bang–bang controller

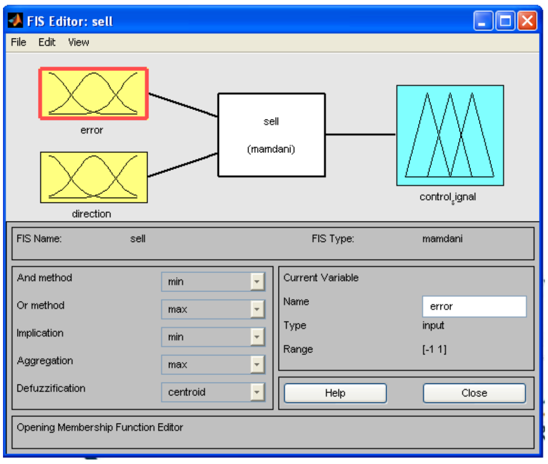

Fig. 3. Basic fuzzy structure

The scaling factors $\xi 1 = 1$ and $\xi 2 = 0.8$ were determined using experimental tests in such a way that the normalized inputs are well adapted to the universe of discourse $[-1, 1]$ for any operating point. The scaled input and output membership functions sets are shown in Fig. 4.There were two fuzzy input sets, each with three members. This implies a maximum of nine fuzzy rules. These nine rules were reduced to five that described the system dynamics. These rules are as follows.

IF ERROR is negative, THEN control signal is negative.

IF ERROR is positive, THEN control signal is positive.

IF ERROR is within dead-band setting AND direction of the angular position is positive, THEN control signal is positive.

IF ERROR is within dead-band setting AND direction of the angular position is negative, THEN control signal is negative.

IF ERROR is within dead-band setting AND direction of the angular position is zero, THEN control signal is no action.

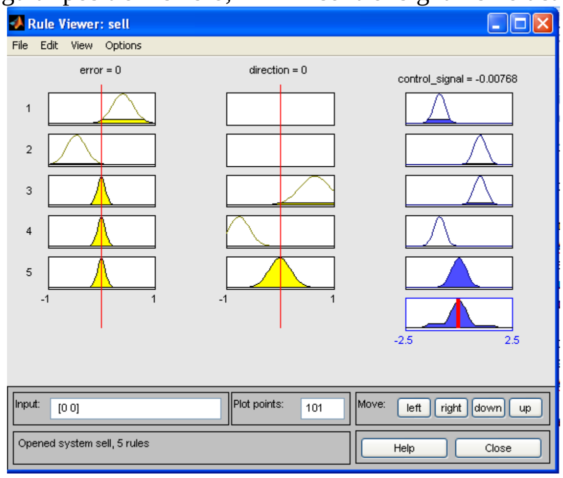

Fig. 4. Membership functions for position error.

Rule 1) This rule is similar to part of the definition of the modified three-stage bang–bang control

$u(k) = umax$ when $uc > umax$.

If the error signal is greater than the positive deadband limit, then the output is positive, regardless of the direction of the output.

Rule 2) This rule is similar to part of the definition of the modified three-stage bang–bang control

$u(k) = umin$ when $uc < umin$.

If the error signal lies within the negative dead-band limit, then the output is negative, regardless of the direction of the output.

Rule 3) If the error lies within limits and the angular position is increasing, then the output is positive so that the output can stay within the desired region with less oscillation or other movement about the reference.

Rule 4) This rule is complementary to Rule 3. If the error lies within limits and the plant output is decreasing, then the output is negative so that the output can stay within the desired region with less movement about the reference than would occur in a regular bang–bang control system.

Rule 5) If the error lies within limits and the plant outputis not increasing or decreasing much, then the control signal should be zero. This is similar to the bang–bang rule

$u(k) = uc$ when $umin \le uc \le umax.$

Fig. 5 Illustrates the normalized output of the controller as a function of the error and the direction of the rotor position .A fuzzy inference engine uses fuzzified measurements to evaluate the control rules stored in the rule base. This evaluation yields a fuzzy output to each rule. The fuzzy centroid method is used to defuzzify the output and determine the resulting control signal. The output is dependent on the set of outputs *Oij* and their corresponding rule strengths *wij output.*

$$= \frac{w1,_{o1} ,_{+w2,1} , o2,1 + w2,2, o2,2 + w2,3, o2,3 + w3,\_, o3,\_}{w1, +w2,1 + w2,2 + w2,3 + w3}$$

The output of the controller can be written in compact form

$uc = \Sigma wijoij \Sigma wi.$

Saturation is also incorporated in the controller structure. Thus, the final output of the fuzzy switching bang–bang controller is

$u(k) = umax(k),\ uC(k) > umax(k),$

$uC(k)\ umin(k) \le uC(k) \le umax(k)$

$umin(k)\ uC(k) < umin(k)$

where *umin* and *umax* are the permitted minimum and maximum inputs to the brushless drive system.

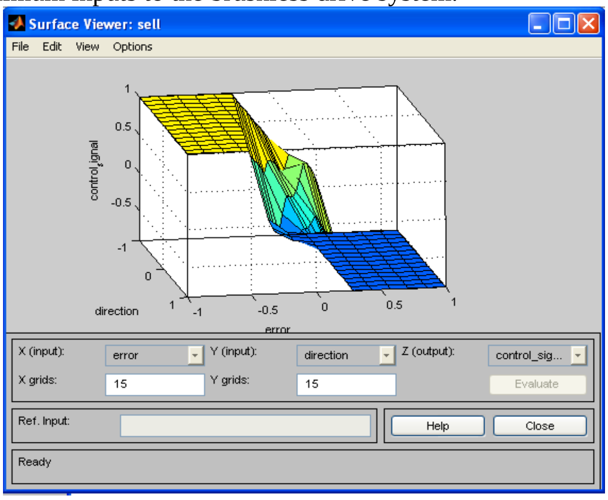

Fig. 5 Illustrates the normalized output of the controller as a function of the error and the direction of the rotor position

Clearly, Fig. 5 displays the nonlinear characteristics of the proposed control structure. The Simulink implementation of the fuzzy switching position controller is displayed in Fig. 6. It is assumed that the controller always has access to complete information about each of the inputs. In the situation where this condition is not met, the firing strength will be zero, and the rule will not be triggered.

Experimental Results

Several test cases were completed under different operational conditions. In all cases, the actual position is superimposed on the desired reference position in order to compare the tracking accuracy. Fuzzy switching position control results are compared to the modified three-stage bang–bang controller.

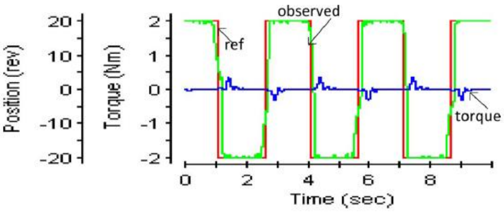

Fig. 6. Position control using fuzzy switching position controller

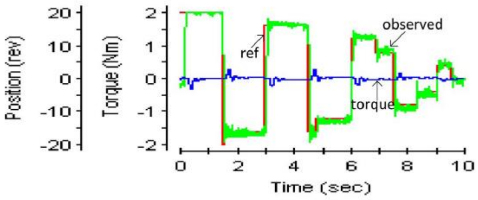

Fig. 7. Position control using fuzzy switching position controller under variation of reference signal

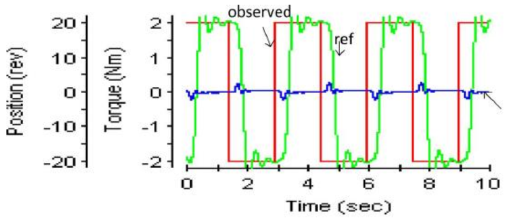

Fig. 8. Three-stage bang–bang tracking position for baseline condition

Conclusion

In this paper, a fuzzy switching position controller-based theoretical bang–bang controller was designed and implemented. Effects of saturation block using fuzzy switching bang–bang control. Effects of saturation block using three-stage bang–bang control. The key advantage is the ease of the design and flexibility. A modified three-stage bang–bang control was also developed and implemented under the same loading conditions is shown in Fig 8. The fuzzy switching position controller was compared to the modified three-stage bang–bang controller, and its performance was evaluated based on this comparison. The ability of the fuzzy position controller to achieve the tracking process with a high degree of accuracy, even in the presence of external disturbance, was illustrated. The sensitivity of the proposed controller to rapid load changes in the external load was also verified, and very promising results were observed. This good performance is coupled with relatively simple and easily implemented designs which can be operated by a human with little knowledge of the drive system being controlled. The authors believe that the proposed fuzzy switching position controller shows clear promise for switching motor control and holds great promise for the future process industry control.

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