Chapter 5

Results and Discussion

In the present work, multi-input FLCs and AIFLCs for the speed control of BLDC motor have been designed and developed. Similarly, PID and auto-tuned PID controllers were also designed and developed for the systematic comparison.

5.1 PID and Auto-Tuned PID Controllers:

The experimental transient response of the speed control system with conventional PID and auto-tuned PID are shown in figure(3.3). The settling time for conventional PID controller is 2.5 sec and for auto-tuned PID controller is 2.2 sec, with no overshoots/undershoots and with zero steady state error which is already mentioned in Chapter 3 (section).

In case of conventional PID controller, the PID parameters K_p, T_i, T_d were manually tuned to achieve the set point speed with no overshoots/undershoots and zero steady state error. Initially while tuning the PID parameters the transient response was observed. It showed large overshoots/undershoots and a large settling time. By varying the PID parameters, the overshoots/undershoots were eliminated using ultimate gain method and ensuring negative feedback. Fine-tuning of the PID parameters eliminated the transient completely and settling time is further reduced with zero steady state error. The fine tuned PID parameters are K_p=0.000081, T_i=0.18 and T_d=0.08. These fine tuned PID parameters were given to auto-tuned PID controller. The auto-tuned PID controller automatically tunes the PID controller. This results in adaptive controller for determining the PID parameters. The auto-tuning of conventional PID parameters resulted in further reduction in settling time (Fig 3.3) . With the variations in the ambient conditions and power supply, the armature current changes which results in variation of speed of DC motor. With negative feedback, these variations in speed are minimized by the auto tuned PID controller.If these variations are quite large,the auto tuned PID controller becomes ineffective,unstable and shows larger settling time/rise time and large steady state error.

5.2 Fuzzy Logic Controller (FLC) and Auto-tuned Integrated Fuzzy logic controllers (AIFLC):

The speed control of BLDC motor has been carried out using C2ISO and 3ISO FLC and AIFLC techniques. The C2ISO FLC has been implemented using three-number triangular membership functions, five-number triangular membership functions and seven-number triangular membership functions for fuzzification. The transient response with settling time of 2.2 sec for three-number triangular membership functions, 2.1 sec for five-number triangular membership functions and 1.9 sec for seven-number triangular membership functions for C2ISO FLC is observed. From these results it is concluded that seven-number triangular membership functions gives the best response for the speed control of the BLDC motor. This is because 7-membership function give higher accuracy and wider range for correction by FLC.

Similarly, the C2ISO FLC for the speed control of BLDC motor is carried out using COG, COM and MOM defuzzification methods. The settling time for

COG, COM and MOM is observed to be 1.9 sec, 2.0 sec and 2.15 sec respectively. Further, the time domain responses of various sampling times i.e., 1 msec, 1 sec and 0.1 sec for C2ISO FLC for the speed of BLDC motor were studied. For 0.1 sec of sampling time, the oscillations of ±12 rpm, for 1 sec of sampling time, the oscillations of ±25 rpm and for 1 msec the settling time of 1.9 sec were observed. From this study it is observed that as the sampling time increases, the response of the BLDC motor becomes sluggish, unstable and oscillatory at the set point (desired) speed of 1500 rpm. This is in accordance with the sample theorem. The higher the sampling frequency (or lower the sampling period) the better is the reconstruction of the control signal and hence better performance of the FLC.

With the above results, it can be concluded that the C2ISO FLC with seven-number triangular membership functions for fuzzification, COG method for defuzzification and 1 msec sampling time give optimum settling time for the speed control of BLDC motor.

Further, 3ISO FLC and AIFLC (for both C2ISO and 3ISO) were designed using above-mentioned optimized fuzzification, defuzzification and sampling time. The performance of speed control of BLDC motor for FLC and AIFLC (C2SIO and 3ISO) for desired (set point) speed, brake applications and load variations were observed.

Desired Speed:

Many applications demand a constant speed, irrespective of the motor being on no load or on load. 2ISO and 3ISO(FLC and AIFLC) have been implemented for the speed control of the BLDC motor for a set point of 1500 rpm. The experimental results are as follows: The settling time of the response of the speed control of the BLDC motor with 2ISO FLC is 1.9 sec, with 3ISO FLC it is 1.8 sec, with 2ISO AIFLC it is 1.75 sec and with 3ISO AIFLC it is 1.5 sec. In 3 ISO FLC the inputs are e (error), ce (change in error or velocity feed back) and cce (change in change in error or acceleration feed back). When error is maximum/minimum the second derivative cce is negative/positive respectively. Thus 3ISO FLC or AIFLC is able to do suitable corrections quickly and compared to the 2ISO FLC or AIFLC. This is the main reason for the improved transient response of 3ISO/AIFLC.

Brake Applications:

In many applications, it may be necessary to apply sudden brake to the motor, when it is running. Electronic brake is used in the present work and when the motor is running at 1500 rpm, the brake is applied by means of a switch connected at the brake terminal of the IC UCC 3626. Figure shows experimental transient response for brake application for FLCs and AIFLCs (C2ISO and 3ISO). When brake is applied, speed of BLDC motors starts decreasing. When the speed becomes 1250 rpm, the brake is released. The speed starts increasing to reach the set point. The settling time of the response of the speed control system is 8.5 secs for C2ISO FLC, with an overshoot of 20 rpm. Similarly, for a C3ISO FLC a settling time of 7.5 secs, for C2ISO AIFLC a settling time of 5.5 sec and for C3ISO AIFLC a setting time of 4 sec is observed. From these observations, it was concluded that performance of 3ISO AIFLC is the best among the proposed controllers with the braking conditions. Brake applications is like step response of a linear time invariant system resulting in oscillator transient response. Application of brake results in the variation of speed and hence requires revised values of the K_p, T_i and T_d. The system is unable to supply the optimal values quickly as it has to search for the parameters smoothly in the iterative manner. This results in increasing in settling (rise) time and considerable steady state error. Hence 3ISO FLC/AIFLC still perform better as compared to 2ISO FLC/AIFLC

Load Variations

Three aluminum discs of different sizes and weights were employed for load variations. The diameters of these discs are 2.3 cm, 2.60 cm and 3.5 cm and of thickness 0.10 cm and with different moments of inertia. Figure (a-c) shows response of BLDC motor speed control using FLC and AIFLC (C2ISO and C3ISO) methods. For the 2.3 cm diameter load (smallest of the three), the settling time with C2ISO FLC is 24.5 sec, with C3ISO FLC it is 22.5 sec, with C2ISO AIFLC it is 13.5sec and with C3ISO AIFLC it is 8.5 sec. For the load of 2.6 cm diameter disc, settling time with C2ISO FLC is 25.5 sec, with 3CISO FLC it is 23.5 sec, with 2CISO AIFLC it is 18.5 sec and with C3ISO AIFLC it is 11.5 sec. For the load of 3.5 cm diameter disc, the settling time for 2ISO FLC is 29.5 sec, with 3ISO FLC it is 28 sec, with 2ISO AIFLC it is 25 sec and with 3ISO AIFLC it is 14.5 sec. It is observed that settling time is increasing with increasing load for any method under consideration.

Discussions:

The C2ISO FLC has been successfully implemented for the real time speed control of BLDC motor for a rated speed 1500 rpm. First, C2ISO FLC has been carried out using three-number, five-number and seven-number triangular membership functions for fuzzification. Most of the physical processes statistically obey Guassian distribution. The triangular membership functions are similar to Gaussian shape. Therefore, triangular membership functions operate in a similar manner as Gaussian function. The rule base is designed based on the number of input variables. For C2SIO FLC, three-number triangular membership functions contains 3x3=9 rules, whereas seven-number triangular membership functions consists 7x7=49 rules. Hence, precision in firing the rules from the rule-based editor of 2 input seven-number triangular membership functions is best. This is because the rule base of the one with seven-number membership functions contains more number of rules. Hence, seven-number triangular membership functions give lesser settling time with zero steady state error and with no overshoots/undershoots, even though the computational time is more in arriving at correct rule to the fired form 343 rules available. The rules and defuzzification methods were chosen using rule base editor in the design VI option of fuzzy logic tool kit. FLC is based on linguistic model (rule base and the defined membership functions) instead of a mathematical model as is the case with PID controller. In the fuzzy systems, more than one rule may be fired at the same time, but with varying strengths, which leads to a crisp control action through the process of defuzzification. We have 7X7 =49 rules in a C2ISO FLC. Even with the firing of more than one rule, the strength of control action will be less accurate. With the addition of one more input that is (cce(k)), the accuracy of firing rules is increased because, the number of rules are increased 7X7X7=343 rules. The introduction of cce (k) in the present strategy is the first report in the literature to the best of our knowledge.

The e(k) and ce(k) are appreciable (negative/positive) at the overshoots and undershoots. The addition of cce(k) as another input along with the e(k) and ce(k) to the FLC, greatly reduces the settling time and steady state error. cce(k) is substantial at the overshoots/undershoots and is essential for accurate and better speed control of BLDC motor. The control signal in this type of controller gives faster convergence to e(k), that ensures lesser settling time ,smaller rise time with no overshoots/undershoots and zero steady state error.

The 3ISO FLC is superior in comparison with C2ISO FLC. Using these two controllers i.e., 2ISO FLC, 3ISO FLC and auto-tuned PID controller, C2ISO/3 ISO AIFLC (Auto Integrated Fuzzy Logic Controllers) were constructed. This further improves the performance of the existing control system. The control action of AIFLC depends mainly on change in output signal from FLC. For the design of AIFLC, we do not have to redesign the system completely and with slight modifications i.e. value of cce(k) of FLC, over all gain of the controller can be adjusted.

5.3 Gaussian white Noise:

5.3.1 C2ISO FLC:

Gaussian white noise of 10 mV to 50 mV are introduced in the C2ISO FLC for the speed control of BLDC motor. The transient response of system was observed to be oscillatory (Fig and table).

5.3.2 3ISO FLC:

Gaussian white noise of 10 mV to 50 mV is introduced in the 3ISO FLC for the speed control of BLDC motor. The settling time of **transient response of** the speed control of BLDC motor using 3ISO FLC for 10 mV is 10.5 secs with an over shoot of 30 rpm. When the noise is increased to 20 mV, with +/- 20 rpm oscillations, the system is settling at 17.5 secs. When the amplitude of the noise is increased further, there is further increase in settling time. When a noise of 50 mV is introduced, the system is settling at a 35 sec and the system is showing oscillation in the beginning with +/- 40 rpm. Therefore, the response with 3ISO FLC is superior to C2ISO FLC.

5.3.3 C2ISO AIFLC:

Gaussian white noise of 10 mV to 50 mV is introduced in the C2ISO AIFLC for the speed control of BLDC motor. When a Gaussian white noise of 10 mV is introduced in the system, the settling time is 9.5 sec. With noise of 20 mV, the settling time is increased further 13.5 sec. With the increase of noise amplitude ,the settling time is increased further to 24sec, 26sec and 33sec respectively, for Gaussian noise of amplitues 30mV, 40mV and 50mV.

5.3.4 3ISO AIFLC:

Gaussian white noise of 10 mV to 50 mV is introduced in the C3ISO AIFLC for the speed control of BLDC motor. When a Gaussian white noise of 10 mV is introduced in the system, the system reaches the set point in slightly larger time without any oscillations(overshoots/ undershoots) and with zero steady state error. The response was slightly oscillatory with a noise of 30 mV and above.The settling time of transient response of speed control of BLDC motor using C3ISO AIFLC is 24 sec, 26 sec and 33 sec with 30mV, 40 mV and 50mV respectively and a steady state error of 10 rpm was observed with noise of 50mV.

With these readings, it was observed that, the effect of Gaussian white noise on 2ISO FLC is more. When the noise amplitude is increased to 30 mV or above, system undergoes oscillations whose amplitude increases with increasing noise amplitude. Effect of noise on 3ISO FLC is less, compared to 2ISO FLC. Even for noise of amplitude of 30 mV the system is settling at 21.5 sec with no oscillations. Effect of noise is in decreasing order from 2ISOFLC, 3ISO FLC, 2ISO AIFLC and 3ISO AIFLC.

5.8 IIR Filter:

A filter may be introduced for suppressing the Gaussian white noise in all the proposed controllers. In the present work, an IIR chebyshev filter of 30^{th} order was used which has shown remarkable improvement in the system performance with FLC and AIFLC (C2ISO and 3ISO). But in case of C2SIO FLC, oscillations of ±25 rpm in the transient response are observed.

In case of 3ISO FLC, the settling time is decreased with no oscillations even though slight oscillations were observed with noise and without filter. Even in the case of C2ISO AIFLC, system response is improved with no oscillations and the settling time is decreased. In case of 3ISO AIFLC, the system response has no oscillations with much decreased settling time. When noise of 50 mV is introduced, the system response is showing oscillations with a steady state error of 10 rpm, but the addition of filter has remarkably improved the response with zero steady state error and decreased settling time.

These observations indicate that the FLC or AIFLC can reject white noise of smaller amplitude but succumbs to the white Gaussian noise at higher amplitude. Use of IIR filter partially removes noise. It has finite bandwidth whereas the bandwidth of white Gaussian noise is infinite. Hence white Gaussian noise of higher amplitude cannot be completely eliminated. However noise suppression performance of 3ISO FLC/AIFLC is better than 2ISO FLC/AIFLC for obvious reasons.