Online ISSN 1848-3380, Print ISSN 0005-1144
ATKAFF 56(4), 424–435(2015)

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# A Novel and Simple Hybrid Fuzzy/PI Controller for Brushless DC Motor Drives

DOI 10.7305/automatika.2016.01.1053
UDK 681.532.5.03.073-55:621.313.323

**Original scientific paper**

A novel speed controller for the trapezoidal three–phase Brushless DC (BLDC) Motor Drive is proposed using a hybrid fuzzy logic/proportional plus integral (PI) control. The structure of the fuzzy logic controller is different from conventional fuzzy logic implementations such that it only uses three simple rules based on speed error being either in the positive, negative or zero regions. The controller outputs a reference current, that is enforced through the motor phases by pulsewidth modulation (PWM) control. The proposed fuzzy logic controller can be used individually in applications requiring lower computation load and tolerating small steady state offset. For high performance applications requiring offset free tracking, a PI controller is augmented with the fuzzy logic controller and a simple switching scheme is devised based on error variance to select the active controller based on operating conditions. The response of the drive system under the proposed composite control structure is compared with the conventional PI based and the sliding mode controllers to demonstrate its improved performance. Simulations studies using detailed models in MATLAB/Simulink's SimPowerSystems toolbox are carried out to show the validity of proposed control.

**Key words:** BLDC Motor, Fuzzy Logic, Speed Control, Hybrid Control

**Nov i jednostavan hibridni neizraziti/PI regulator za istosmjerne motore bez četkica.** U ovome radu predlaže se nov regulator brzine za trapezoidalne trofazne istosmjerne motore bez četkica zasnovan na hibridnom regulatoru. Hibridni regulator sastoji se od dijela s neizrazitom logikom i proporcionano-integracijskog regulatora. Struktura neizrazitog regulatora razlikuje se od konvencionalnih implementacija neizrazitih regulatora po tome što koristi samo tri jednostavna pravila zasnovana na pogrešci brzine u pozitivnom, negativnom ili nultom području. Izlaz regulatora čini referentna struja, koja se šalje na faze motora pomoću širinsko-impulsne modulacije. Predloženi neizraziti regulator može se koristiti i zasebno u primjenama koje zahtijevaju manju računsku složenost i toleriraju malu pogrešku u stacionarnom stanju. Za slučajeve kada je potrebna visoka učinkovitost bez pogreške u stacionarnom stanju, s neizrazitim dijelom proširuje se PI regulator te je razvijen jednostavan postupak promijene regulatora zasnovan na varijanci pogreške. Odziv razmatranog sustava uspoređen je s konvencionalnim PI regulatorom i regulatorom u kliznom režimu rada kako bi se pokazala njegova učinkovitost. Izvršene su simulacije u Matlab/Simulinkovom SimPowerSystems alatu kako bi se pokazala ispravnost predloženog postupka.

**Ključne riječi:** istosmjerni motor bez četkica, neizrazita logika, upravljanje brzinom, hibridno upravljanje

## 1 INTRODUCTION

Variable frequency drives employing the brushless dc (BLDC) motors have gained high popularity among researchers and industry professionals, due to a wide variety of advantages offered by BLDC motors over brushed dc and induction motors. They include higher efficiency and torque–to–inertia ratios, lower inverter ratings requirement, lower losses, increased power output, lighter construction, smaller size, reduced control complexity and minimal maintenance [1–3]. Therefore, BLDC motor drives are seeing increased application in the automotive, aerospace, office automation, household appliance and robotics industries. Despite these advantages, there are a number of challenging issues that need to be solved before fully utilizing the potential of this technology. A significant amount of research effort is still going into various aspects of the BLDC motor drives such as miniaturization and integration, digitization, efficiency, design and performance improvement, speed control, harmonic and torque ripple reduction, and sensorless operation to name a few. In addition a variety of classical, modern, linear and non–linear control techniques are continuously being applied to enhance the dynamic performance of the BLDC motor drive.

In this paper, speed control of BLDC motor drive is addressed. In principal, the speed of a BLDC motor can be controlled either by controlling the duty cycle of the input voltage, or its magnitude. In the former, the current in the motor phases is controlled by applying a fixed magnitude voltage for a controlled amount of time to the phases. The duty cycle can be translated to inverter switching through a combination of rotor position information and either hysteresis band control or pulse width modulation (PWM) control. In the latter, the duty cycle of the applied voltage is kept fixed but its amplitude is changed according to the set–point speed requirements. The inverter switching is based entirely on rotor position obtained either from sensors or in a sensorless way. The advantages and disadvantages of these schemes are discussed in [4, 5] and are beyond the scope of this paper. The former technique, also termed as voltage source current controlled inverter topology, is more commonly employed [6] and supported by the available development tools [7, 8].

Due to low inertia and high torque producing capability, the BLDC motor can achieve a very fast dynamic speed response in comparison to its counterparts. Traditionally the proportional plus integral (PI) and the proportional plus integral plus derivative (PID) controllers have been employed to speed control of BLDC motors, due to their simplicity, good dynamic performance, robustness and offset free tracking. However, these controllers have their limitations. The PI controller may suffer from issues like large overshoot and slower response under the conditions of uncertainty in parameters and large disturbances [9–11]. Therefore, a variety of literature has been published to address the limitations of conventional controllers; either improving the existing conventional control scheme or replacing it altogether with a new one, thus improving the overall performance of the speed control system. A brief overview of the literature survey on speed control techniques is given here.

The works [2,12] give detailed mathematical modelling of the BLDC motor drive system and speed control using PI and PID controllers. The authors of [13] employed a fuzzy logic based controller that acted on the error between actual speed and its set–point to obtain current set–point; enforcing it through the phases through hysteresis control. In [14] the authors proposed a hybrid fuzzy/PI controller that switched between fuzzy and PI control structure based on oscillations, overshoot and large disturbances, and generated the output switching logic based on the control signal through pulsewidth modulation (PWM). In [15] a composite controller combining the classical PID and a fuzzy PID was proposed with online tunable parameters. The controller performance was demonstrated under load variations and set–point changes. Implementation of fuzzy logic based speed control was also demonstrated in literature [11], while subjecting the drive system to different operating conditions like change in speed reference, rotor inertia and load. Adaptive neuro–fuzzy inference system (ANFIS) based speed control of BLDC motor was reported in [9], where the authors also provided the details of the neural network training, fuzzy logic structure and comparative analysis of the proposed control with other techniques.

This paper proposes a simple and effective composite fuzzy logic/PI based speed control technique for the BLDC motor drive with a fast dynamic response and offset free tracking, both under normal operating conditions and in the presence of disturbances. The proposed scheme combines the desirable features of both the control structures namely fast dynamic response, no overshoot and offset free tracking, resulting in an improved composite control system. A supervisory switching strategy based on error variance is employed. It promptly shifts the control task to the appropriate controller according to the operating conditions, while avoiding frequent or unnecessary switching between them.

In the light of available literature on speed control of BLDC motor drives, the idea of hybrid control or the application of fuzzy logic to speed control is not new. Therefore, the aimed contributions of this paper must be highlighted. The key contribution of the proposed technique as compared to other fuzzy logic based implementations is its simplicity and fewer number of rules and membership functions. All of fuzzy based control structures [11,13–15] use at least nine or more decision making rules, whereas fuzzy logic in the proposed scheme uses only three rules. Fuzzy logic controller in the proposed scheme operates on the knowledge of speed error alone, as opposed to the conventional implementation using both error and change in error. The resultant simple structure is also computationally lighter and does not sacrifice the dynamic performance of the control system.

Another contribution is that the design rules of the simple fuzzy logic controller are described. Using these rules, a controller can be easily designed for a wide range of BLDC motor ratings with knowledge of only the rated currents. The flexibility of the method, ease of customization and minimal information required for design, set it apart from high complexity techniques. Results of the design are demonstrated for two motors having different ratings.

Finally, it is shown that the fuzzy logic controller can be employed in standalone without the composite PI structure where small steady state speed error can be tolerated, or reduced computational complexity is required.

The paper is organized is follows: Section 2 gives the mathematical modeling and operation of the BLDC motor drive. Section 3 gives the development details of the simple fuzzy logic controller and the composite fuzzy/PI control system. Section 4 presents the results of simulation test cases and discussion of results. Section 5 gives the final remarks and conclusion.

## 2 MODELING AND OPERATION OF BLDC MOTOR DRIVE

### 2.1 Mathematical model

The mathematical model of a three phase wye–connected bldc motor can be described by the following dynamic equations [2,4]:

$$\begin{aligned}\frac{di_a}{dt} &= \frac{1}{L_s}(-R_s i_a + v_{an} - e_{an}),\\ \frac{di_b}{dt} &= \frac{1}{L_s}(-R_s i_b + v_{bn} - e_{bn}),\\ \frac{di_c}{dt} &= \frac{1}{L_s}(-R_s i_c + v_{cn} - e_{cn}),\\ \frac{d\omega_m}{dt} &= \frac{1}{J}(T_e - T_{load} - B\omega_m),\\ \frac{d\theta_e}{dt} &= \frac{P}{2}\omega_m\end{aligned} \tag{1}$$

Here $v_{an}$, $v_{bn}$ and $v_{cn}$ stand for the phase to neutral voltages in $[V]$; $i_a$, $i_b$ and $i_c$ represent phase currents in $[A]$, and $e_{an}$, $e_{bn}$ and $e_{cn}$ represent the back–emf in $[V]$, of each of the phases $a$, $b$ and $c$ respectively. $J$ is the rotor inertia in $[kg.m^2]$, $B$ is the friction coefficient in $[N.m.s]$, $R_s$ is the stator resistance in $[\Omega]$, $L_s$ is the winding inductance in $[H]$, $T_e$ and $T_{load}$ are the electromagnetic torque and the load torque in $[N.m]$, respectively, $\omega_m$ is the rotor mechanical speed in $[\frac{rad}{s}]$, $\theta_e$ is the rotor angle in electrical radians, and $P$ is the number of machine poles. The back–emf of each of the phases, and the electromagnetic torque can be further expressed as:

$$\begin{aligned}e_{an} &= K_e\omega_m f_a(\theta_e),\\ e_{bn} &= K_e\omega_m f_b(\theta_e),\\ e_{cn} &= K_e\omega_m f_c(\theta_e),\\ T_e &= K_t(f_a(\theta_e)i_a + f_b(\theta_e)i_b + f_c(\theta_e)\end{aligned} \tag{2}$$

where $K_e$ and $K_t$ are the back–emf and torque constants, respectively. The electrical rotor angle $\theta_e$ is equal to the rotor angle $\theta_m$ times the number of pole–pairs $\frac{P}{2}$. Functions $f_a(\theta_e)$, $f_b(\theta_e)$ and $f_c(\theta_e)$ are the trapezoidal unit envelopes of the back–emf waveforms for phases $a$, $b$ and $c$ respectively. One full cycle of the $f_a(\theta_e)$ is given as:

$$f_a(\theta_e) = \begin{cases} 1, & 0 \le \theta_e \le \frac{2\pi}{3} \\ 1 - \frac{6}{\pi}(\theta_e - \frac{2\pi}{3}), & \frac{2\pi}{3} \le \theta_e \le \pi \\ -1, & \pi \le \theta_e \le \frac{5\pi}{3} \\ -1 + \frac{6}{\pi}(\theta_e - \frac{5\pi}{3}), & \frac{5\pi}{3} \le \theta_e \le 2\pi \end{cases} \tag{3}$$

The functions $f_b(\theta_e)$ and $f_c(\theta_e)$ in the fourth equation of (2) are given as:

$$\begin{aligned}f_b(\theta_e) &= f_a(\theta_e - \frac{2\pi}{3}),\\ f_b(\theta_e) &= f_a(\theta_e - \frac{4\pi}{3})\end{aligned} \tag{4}$$

### 2.2 Drive operation

A simplified schematic of the BLDC Motor drive is shown in figure 1:

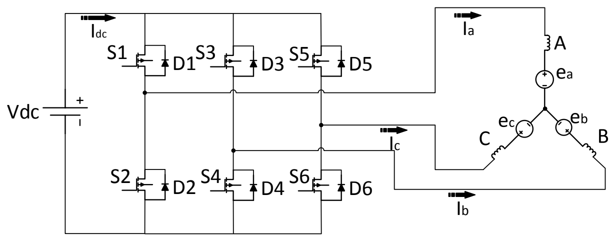



*Fig. 1. A simplified BLDC motor drive*

This three–phase topology is driven by energizing two phases at a time; the ones that will produce most amount of torque [4]. The gate signals are generated based on rotor position feedback according to the rules show in Table 1. In addition, the free–wheeling currents that flow through the diodes as a result of phase commutation must also be taken into account. The details of commutation transient processes are well discussed in references [1,4,16].

*Table 1. Gate switching sequence*

| Switching Interval | Sequence number | Switch closed | | Phase current A | B | C |
|---|---|---|---|---|---|---|
| 0°–60° | 0 | S1 | S6 | + | off | - |
| 60°–120° | 1 | S3 | S6 | off | + | - |
| 120°–180° | 2 | S3 | S2 | - | + | off |
| 180°–240° | 3 | S5 | S2 | - | off | + |
| 240°–300° | 4 | S5 | S4 | off | - | + |
| 300°–360° | 5 | S1 | S4 | + | - | off |

From Table 1 it can be seen that at any given time, two of the three phases will conduct while the third phase, after the settling down of commutation transients, will be off. Ideally, during a complete 360° electrical cycle, each of the three phases will conduct for a 120° interval, having positive and negative current during each half of this intervals. The phase will stays off outside of this interval. Under this 120° conduction mode, the BLDC motor model can be reduced to the following equivalent DC motor model [1,17]:

$$\begin{aligned}\frac{di}{dt} &= \frac{1}{L}(-Ri - K_e\omega_m + V_{dc}),\\ \frac{d\omega_m}{dt} &= \frac{1}{J}(K_t i - T_{load} - B\omega_m)\end{aligned} \tag{5}$$

Here, $R = 2R_s$, $L = 2L_s$ and $i$ represents the equivalent dc current flowing in the conducting phases during any instant (other quantities are defined as before). This simplified model has been utilized in model based controller design in [10, 17–19].

## 3 PROPOSED COMPOSITE FUZZY/PI CONTROL

The original idea of fuzzy sets was introduced by Zadeh in [20]. Since its inception, the concept of fuzzy logic has been applied to numerous applications and engineering systems like subways, washing machines, biomedical systems and finance applications [11]. It emulates the behavior of an intuitive expert to best control a system with high amount of nonlinearities and uncertainties. With knowledge and understanding of the general behavior of the system, it enables the designer to specify controller's actions based on linguistic rules comprising of a number of '*if-else* 'statements; much similar to the reasoning ability of humans. This property makes the control algorithm easy to understand. Design process of a fuzzy logic based control system can be described in the following steps [11, 21]:

1. *Identify inputs and outputs, define universe of discourse*
   A collection of all available information on the problem is called the universe of discourse. This is the first step where the inputs and outputs are identified, and their ranges are specified, thus defining the universe.

2. *Fuzzification*
   The process of converting a crisp quantity into fuzzy is called fuzzification. A set of membership functions are defined that quantify the degree of membership of crisp inputs to fuzzy sets. This degree of membership is mapped on to the unit interval {0,1}.

3. *Fuzzy Rules Definition*
   The fuzzy information is linguistically represented through a set of '*if-else* 'statements, establishing a relationship between inputs and outputs. This representation is also called *if–then rule–based form* or the *deductive form*. These rules form the core of the fuzzy inference process.

4. *Defuzzification*
   Since the actual system's inputs and outputs are crisp values, output of the fuzzy process needs to be converted from fuzzy to crisp, or in other words, defuzzified. The method for defuzzification can be chosen from a wide variety of methods reported in the literature, including *max membership principle*, *centroid method*, *weighted average* and *mean max principle*.

### 3.1 Fuzzy logic design guidelines

For this design problem, Mamdani system structure was chosen, that is most common in practice [21]. The key guidelines that were employed in the design of fuzzy logic controller are listed as follows:

1. *If the speed error is large, then output a high valued current reference*

2. *If the speed error is small, then output a low valued current reference*

3. *If the speed error is in the middle, output a current reference value in between high and low*

This rule–base outputs a reference current proportional to the speed error. The terms *'large error'* and *'high current'* are subjective choices of the designer. A certain threshold for speed error can be defined, above which the error can be considered large. The low error can be defined as zero. The *high current* can be selected anywhere between the rated current and its higher multiples depending upon performance requirements and equipment ratings. If the drive system can withstand high orders of magnitude of the rated current for a limited time, it can be selected as higher multiples of rated current, resulting in a fast dynamic response. Otherwise, if equipment safety is a concern, it can be selected as the actual rated current, resulting in a slower dynamic response. The *low current* can be set close to zero. A corresponding threshold for reference current can be chosen forcing it to a specific value when the speed error threshold is reached or exceeded.

The application of these guidelines to the design of a fuzzy controller for given specifications is explained in the following section.

### 3.2 Fuzzy logic controller design

The structure of fuzzy logic controller designed for the BLDC motor drive is shown in Fig. 2. The controller was designed for two motors M1 (rated 1 $kW$, 3000 $rpm$, 3 $N.m$), and M2 (rated 0.75 $kW$, 3000 $rpm$, 1.91 $N.m$). The motor parameters are given in Table 5 in APPENDIX A. The design details for motor M1 are discussed.

As the first step, input to the fuzzy logic controller was chosen as the speed error $e_\omega$ defined as $\omega_r - \omega$, with $\omega_r$ and $\omega$ denoting speed set–point and actual speed, respectively. The output was taken as the current command $I^*$ to be applied to the PWM controller. Based on ratings of the motor M1, the universe of discourse of input was chosen to be between $-3200$ $rpm$ to 3200 $rpm$ while for the output was chosen as $-11$ $A$ to 11 $A$.

Next, membership functions were defined for the process of fuzzification. Three linguistic terms were defined

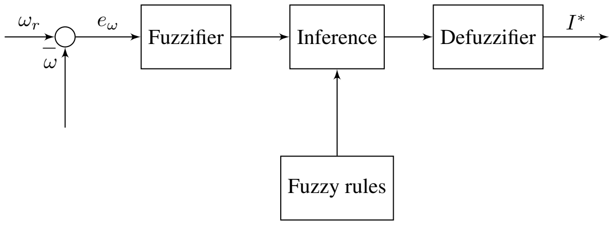



*Fig. 2. Fuzzy controller block diagram*

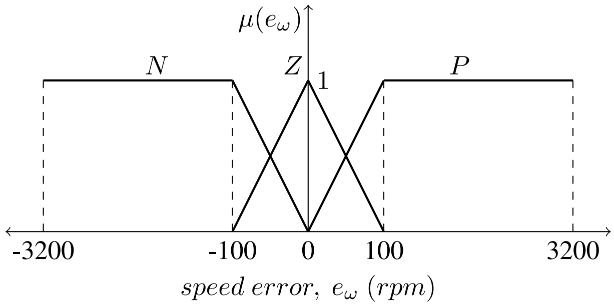



*Fig. 3. Input $e_\omega$ membership functions, motor M1*

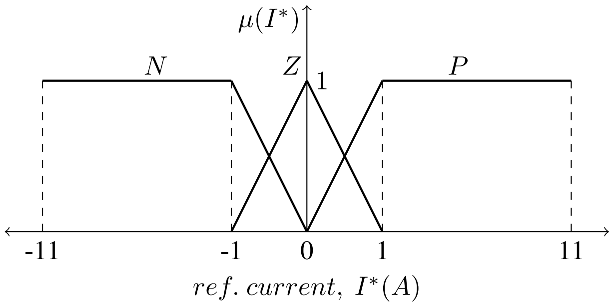



*Fig. 4. Output $I^*$ membership functions motor M1*

for the fuzzy variable $e_\omega$ namely *Negative (N)*, *Zero (Z)* and *Positive (P)*. The linguistic terms for output were defined the same way. The threshold above which the speed error was considered to be high, was chosen as $\pm 100\ rpm$. The corresponding current threshold was chosen to be $\pm 1\ A$. Triangular and trapezoidal membership functions were chosen for both $e_\omega$ and $I^*$, depicted in Fig. 3 and 4, where $\mu(e_\omega)$ and $\mu(I^*)$ represent the degree of membership of the speed error $e_\omega$ and reference current $I^*$ in their corresponding fuzzy sets.

In the next step, decision making rules in the form of '*if-then*'statements were defined to specify the control action. A total of three rules were defined as follows:

1. If $e_\omega$ is negative then $I^*$ is negative
2. If $e_\omega$ is zero then $I^*$ is zero
3. If $e_\omega$ is positive then $I^*$ is positive

Similar design rules were followed in the design of fuzzy controller for motor M2. The membership function ranges were adjusted according to M2 ratings. They are depicted in figures 5 and 6.

With the chosen membership functions and rules, the following input–output relationship was obtained:

$$\begin{aligned} &I^* \cong 2I_r, && if\ \ e_\omega \geq 100\ rpm \\ &I^* \cong -2I_r, && if\ \ e_\omega \leq -100\ rpm \\ &-2I_r \leq I^* \leq 2I_r, && if\ \ 0 \leq |e_\omega| \leq 100\ rpm \end{aligned} \tag{6}$$

Here $I_r$ stands for the motor's continuous rated current. Although the motor under consideration could withstand up to $4I_r$ for a short time, here the maximum current output of the controller was limited for safety. The rated value of current required by M1 under full load to maintain rated speed was $3.3\ A$ while for M2 it was $4.4\ A$.

The fuzzy output of the membership functions for each input must be combined corresponding to the rules. With the chosen rule–base, each input's degree of membership corresponding to a fuzzy number, was directly mapped on to the output fuzzy set called the consequent, through the process of implication. Finally, the resultant fuzzy set was

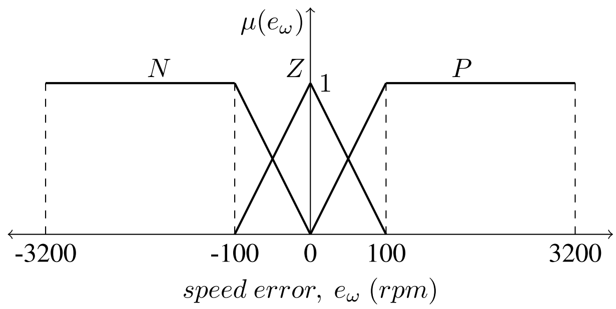



*Fig. 5. Input $e_\omega$ membership functions, motor M2*

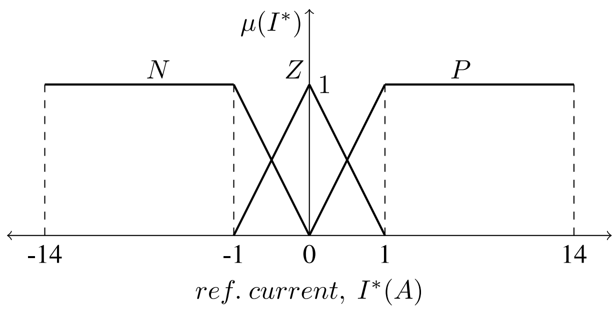



*Fig. 6. Output $I^*$ membership functions motor M2*

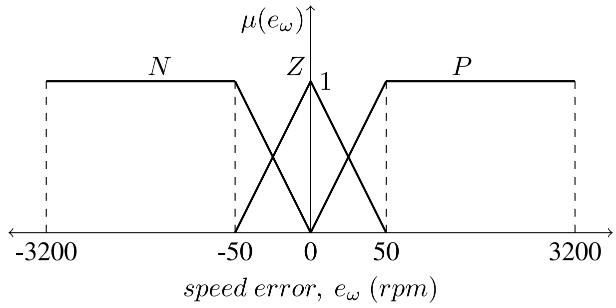



*Fig. 7. Modified Input $e_\omega$ membership functions, motor M1 with increased slopes*

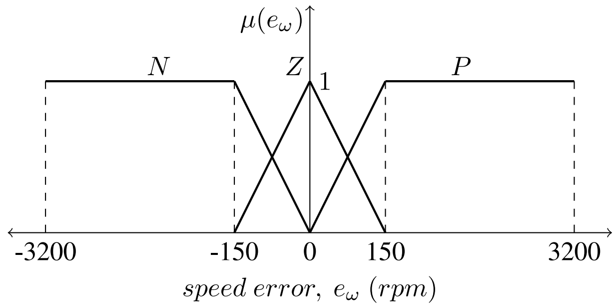



*Fig. 8. Modified Input $e_\omega$ membership functions, motor M1 with reduced slopes*

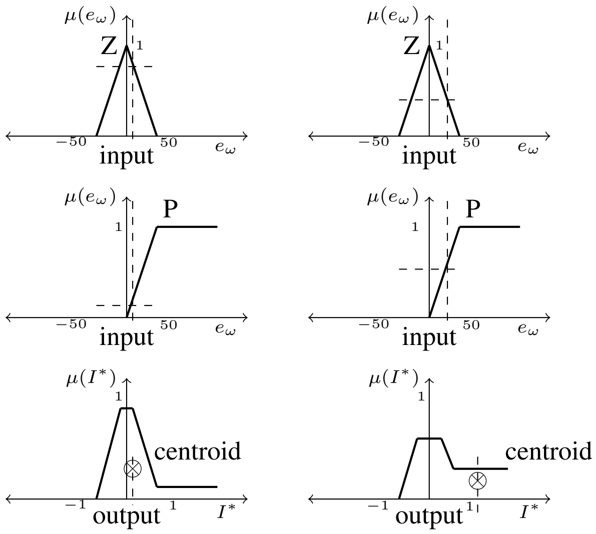
defuzzified. The truncation and centroid methods were used for implication and defuzzification, respectively [22].

From (6), it can be seen that the control law leads to an equivalent of a proportional type controller with saturation. Within the saturation limits, the fuzzy logic controller would behave like an 'aggressive' proportional controller. Therefore, a finite steady state error is to be expected under this type of control, an inherent feature of proportional type controllers. Increasing the slopes of membership functions as shown in Fig. 7 for M1, is equivalent to increasing the proportional gain. This would increase the rate of transient response and reduce steady state error. However, it would also increase the amount of steady state torque and speed ripples. On the other hand, decreasing the slopes of membership functions as shown in Fig. 8 would cause lesser steady state torque and speed ripple, but slow down the response and increase steady state error.

For instance, for M1 to maintain rated speed at rated load, using the membership functions of Fig. 7 would give the required current of $3.3\ A$ at a speed error of $e_\omega = 5\ rpm$, if the same output membership functions of Fig. 4 were used. If those in Fig. 8 were used, the required current would be output at $e_\omega = 15\ rpm$. Hence, the average steady state errors under rated conditions using membership functions of Fig. 7 and 8 would be close to $5\ rpm$ and $15\ rpm$, respectively. Their respective 'aggressive' and 'gentle' slopes would lead to a higher and lower amount of steady state torque and speed ripples in the response.

The input–output calculation process of the fuzzy logic controller under no–load and load conditions is depicted in figure 9. The third fuzzy input set *Negative(N)* is not shown since its membership value was zero and did not contribute to the output fuzzy set.

This fuzzy control scheme alone can be employed in applications where lower computational complexity is required and small steady state error is acceptable. The simulation results and discussion of drive performance under the fuzzy logic controller alone are discussed and compared in Section 4.




(a) No Load (b) Full Load

*Fig. 9. Input fuzzy sets (top and middle rows), output fuzzy sets (bottom row) and centroid locations under no–load and full load at rated speed*

### 3.3 Hybrid control and supervisory switching scheme

A composite control scheme is proposed combining the fuzzy logic and PI controllers to fully utilize their merits while overcoming their demerits. A supervisory control was employed to switch between controllers, based on the error variance. The block diagram of drive system under the composite control scheme is shown in Fig. 10.

The fuzzy controller outperformed the PI controller under transient conditions and offered a faster response, free from overshoot and oscillations. However, unlike the PI controller, it could not eliminate steady state error due to

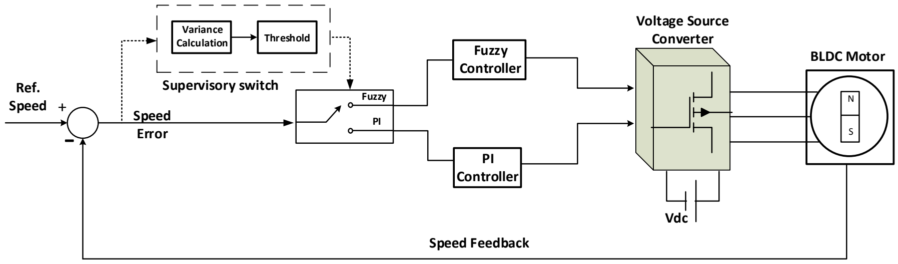



*Fig. 10. Simplified block diagram of the drive system under proposed control*

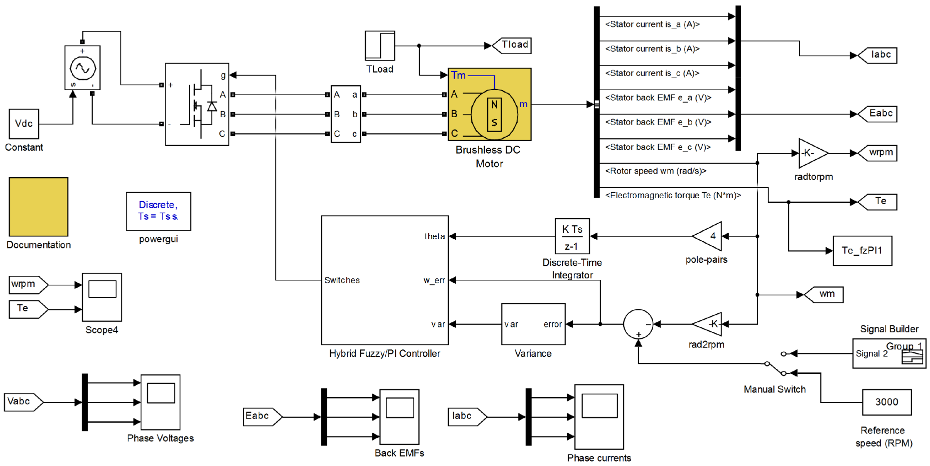



*Fig. 11. Simulink model of the hybrid Fuzzy/PI speed control system*

reasons already explained in section 3.2. Thus, it could not be used alone to achieve high performance control. A highly effective control scheme could be achieved if the fuzzy logic controller was to be used under transient conditions and the PI controller under steady state. In order to select a controller best suited for the operating conditions, the present state of the system had to be characterized. This was done using speed error's variance. For convenience, we defined *'transient state'* as the state of the system when the error was either increasing or decreasing rapidly. Conditions like startup from zero speed, step change in speed set–point and sudden application of load torque, were all categorized by this state. We defined *'steady state'* as the condition when error was constant. Accordingly, in *transient* state the error variance would be non–zero, while in the steady state under constant error, the error variance would ideally be zero. Once the state of the system was determined, the supervisory scheme could select which controller to use based on error variance. The switching rule is described as:

$$Control = \begin{cases} Fuzzy, & e_v > threshold\ (transient\ state) \\ PI, & e_v <= threshold\ (steady\ state) \end{cases} \tag{7}$$

where $e_v$ denotes error variance, and the threshold values are given in Table 2 in APPENDIX A. This switching law ensured that the extreme operating conditions like sudden set–point change, load disturbance, etc. were handled by the fuzzy logic controller, achieving a fast dynamic response and error stabilization. The PI controller was active only in the steady state to drive the offset to zero.

## 4 SIMULATION RESULTS AND DISCUSSION

The drive's performance under the proposed fuzzy logic and hybrid fuzzy/PI controllers was analyzed through extensive simulations on BLDC motors M1 and M2. Simulation studies were carried out using MATLAB/Simulink's SimPowerSystems toolbox and Fuzzy Logic toolbox. The simulation model is shown in Fig. 11.

### 4.1 Fuzzy Logic Controller Performance and Comparison with Proposed Controller

Speed regulation response of the fuzzy logic controller under rated load for motors M1 and M2 is shown in Fig. 12. For comparison, the plot of speed regulation under proposed control is shown in Fig. 13. Error plots under speed regulation and zoomed view of speed regulation responses under rated conditions are shown in Fig. 14 and 15. For this test case, a setpoint speed of 3000 $rpm$ was selected while rated loads of 3 $N.m$ and 1.91 $N.m$ were applied to the motors M1 and M2 respectively at $t = 0.25$ $s$.

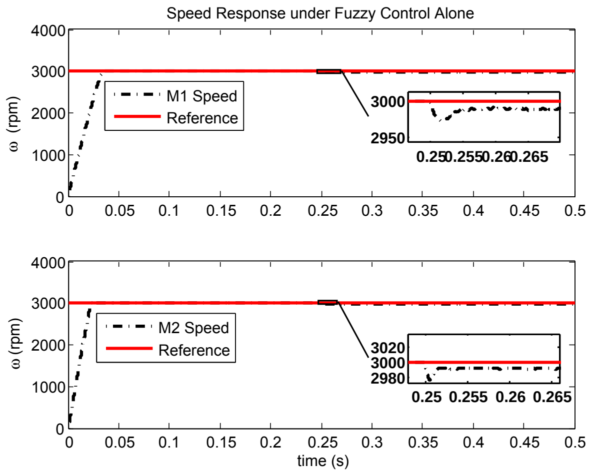



*Fig. 12. Speed regulation response with fuzzy logic controller alone for M1 and M2 under $\omega_r = 3000$ $rpm$ and rated load*

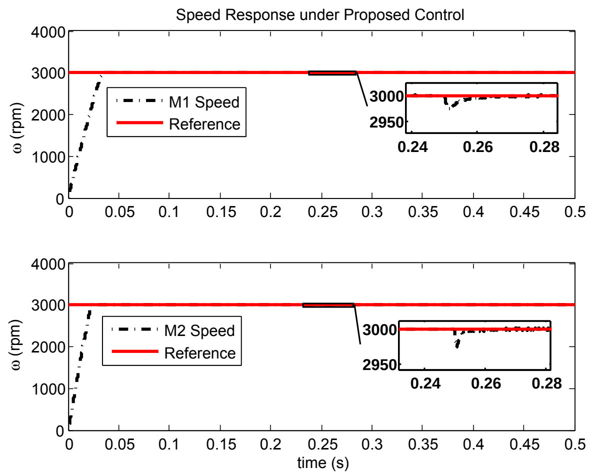



*Fig. 13. Speed regulation response with proposed controller for M1 and M2 under $\omega_r = 3000$ $rpm$ and rated load*

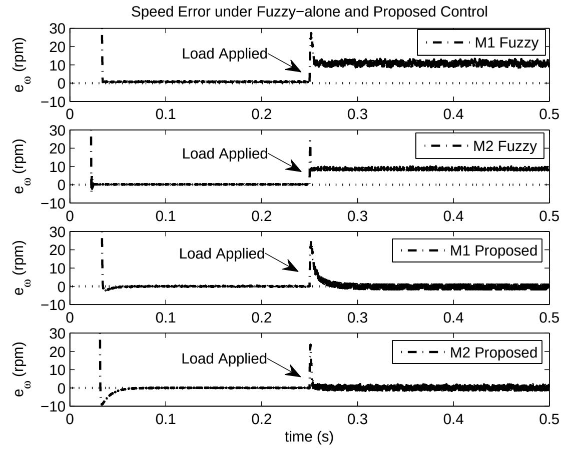



*Fig. 14. Speed regulation error comparison between fuzzy and proposed controllers under $\omega_r = 3000$ $rpm$ and rated load*

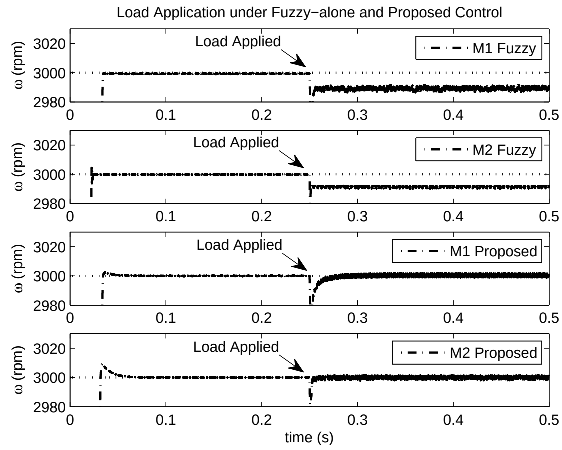



*Fig. 15. Speed regulation comparison (zoomed view) between fuzzy and proposed controllers under $\omega_r = 3000$ $rpm$ and rated load*

Speed tracking responses of the fuzzy and proposed controllers under fixed load are shown in Fig. 16 and 17. The speed error comparison plots are shown in Fig. 18. For this test case, speed reference was changed periodically in steps from rated to fractions of rated speed under constant loading. The speed set–point was sequentially changed as 3000 $rpm$, 500 $rpm$, 2000 $rpm$, 2500 $rpm$ and 1000 $rpm$ at regular intervals. The load for M1 and M2 was kept constant at 1.5 $N.m$ and 1 $N.m$ respectively.

From the speed regulation responses in Fig. 12 and 13 it can be observed that the speed reached its set–point within 0.035 $s$ for M1 and 0.025 $s$ for M2, with no overshoot. However, in case of fuzzy controller alone, there was finite

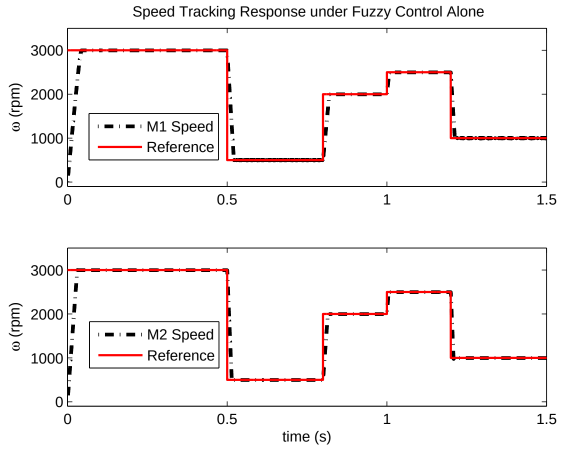



Fig. 16. *Speed tracking response of fuzzy logic controller alone, for M1 and M2 under constant load*

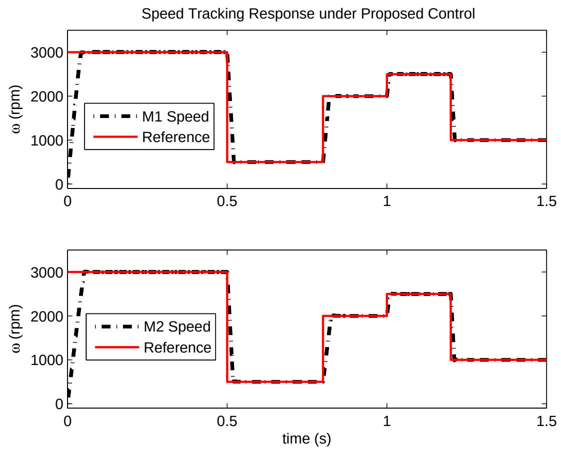



Fig. 17. *Speed tracking response of proposed controller, for M1 and M2 under constant load*

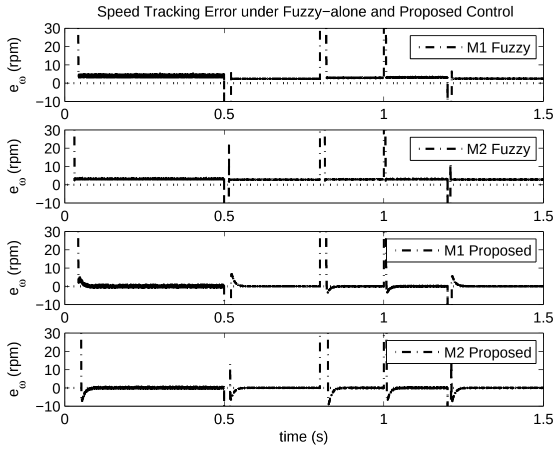



Fig. 18. *Speed tracking error comparison between fuzzy and proposed controllers for M1 and M2 under constant load*

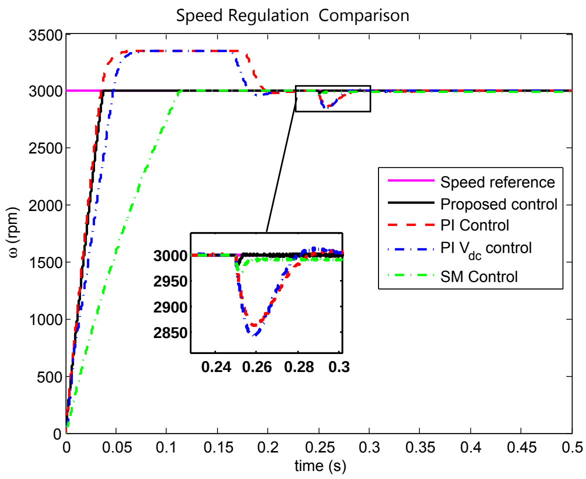



Fig. 19. *Speed regulation comparison of the proposed, PI and SM controllers at* $\omega_r = 3000\ rpm$, $T_{load} = 3\ N.m$ *applied at* $0.25\ s$, *motor M1*

steady state error under rated load as expected, shown in Fig. 14 and 15. It was approximately 10 $rpm$ for M1 and 9 $rpm$ for M2. This was the worst case steady state error that occurred under rated conditions, and was less than 1% for both M1 and M2.

From the speed tracking response in Fig. 16, similar results were observed. The fuzzy logic controller quickly responded to a changing speed reference both under no load and load conditions with no overshoot, but with a finite steady state error under loading.

### 4.2 Proposed Controller Performance and Comparison with Other Controllers

Speed regulation and tracking performance for M1 under the proposed hybrid controller was compared with three other benchmark controllers namely (1) a simple PI controller, (2) PI based variable dc–link voltage controller and (3) a sliding mode (SM) variable dc–link voltage controller for motor M1. Gains for the PI based controllers were designed by trial and error to achieve the best trade-off between transient response, overshoot and oscillations. These gains are given in Table 3 in APPENDIX A. The sliding mode controller was designed using the model of (5) and choosing a sliding surface $\mathcal{S}$ as:

$$\mathcal{S} = c_1 z_1 + z_2 \tag{8}$$

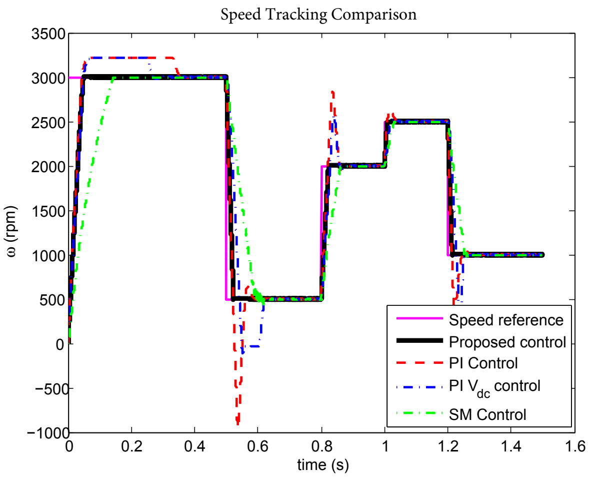



Fig. 20. Speed tracking comparison of the proposed, PI and SM controllers under constant $T_{load} = 1.5\ N.m$, motor M1

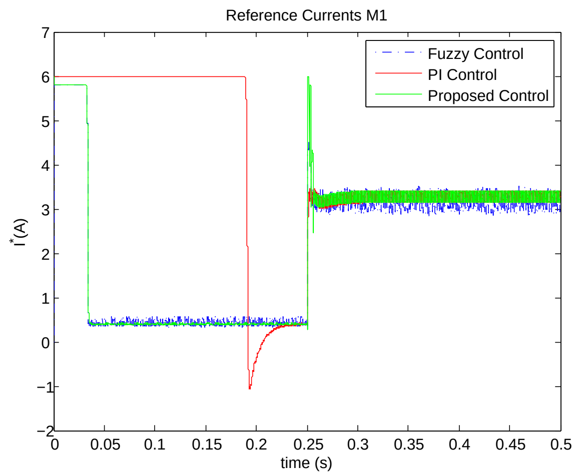



Fig. 21. Reference current $I^*$ for M1 under the fuzzy alone, PI and the proposed control schemes at a set–point speed of $3000\ rpm$ and $T_{load} = 3\ N.m$ applied at $0.25\ s$

where $z_1 = \omega_r - \omega$, $z_2 = \dot{z}_1$, and $c_1$ is a weight chosen by design (see APPENDIX A, Table 4). A control law was derived satisfying the reachability $\mathcal{S}\dot{\mathcal{S}}$ and stability conditions [23]. Plots comparing the speed regulation performance are shown in Fig. 19. Speed tracking comparison plots are shown in Fig. 20. Rated loading was applied for regulation test case at $0.25\ s$ while constant loading of $1.5\ N.m$ was applied for the tracking case. A step changing speed set–point was applied in tracking test case and sequentially changed as $3000\ rpm$, $500\ rpm$, $2000\ rpm$, $2500\ rpm$ and $1000\ rpm$ at regular intervals. Figures 21

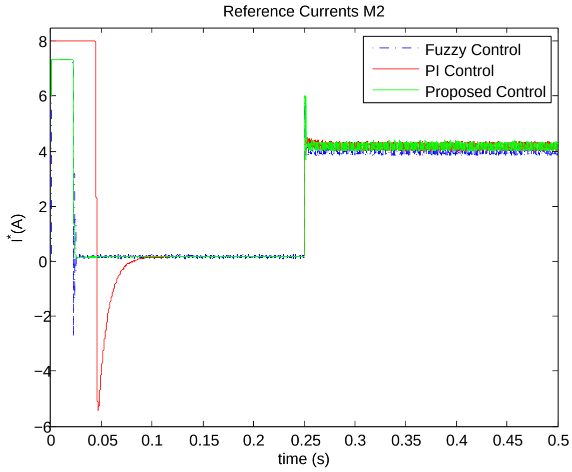



Fig. 22. Reference current $I^*$ for M2 under the fuzzy alone, PI and the proposed control schemes at a set–point speed of $3000\ rpm$ and $T_{load} = 1.91\ N.m$ applied at $0.25\ s$

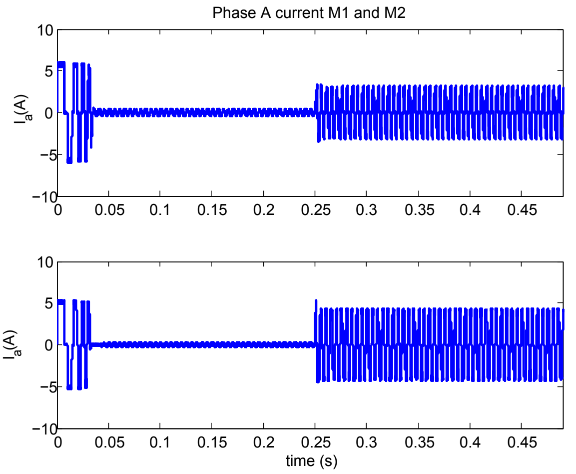



Fig. 23. Phase A currents of M1 and M2 under proposed scheme for a set–point speed of $3000\ rpm$, $T_{load} = 3\ N.m$ for M1 and $T_{load} = 1.91\ N.m$ for M2 applied at $0.25\ s$

and 22 show the reference current outputs of the fuzzy alone, PI and hybrid controllers for motor M1 and M2. Figure 23 shows the phase A currents of M1 and M2 for proposed controller under speed regulation.

From the speed regulation response in Fig. 19, it can be seen that the proposed hybrid controller exhibited better speed regulation response than the PI and SM controllers. It allowed the least amount of dip in the actual speed with sudden application of rated load at $t = 0.25\ s$, and quickly restored the speed to its set–point with no steady state error. In comparison, the responses of PI based controllers showed high amount of overshoot and speed dips under sudden load application. The response of SM based controller was slower and had finite steady state error. From the speed tracking response in Fig. 20 it can be seen that the proposed hybrid controller provided a fast, overshoot and offset free tracking for a step changing speed command under constant loading. The quick dynamic response of the drive system under transients (speed set–point changes, sudden loading, etc.) was achieved by the fuzzy logic controller through fast reference current generation, driving the speed error to a small steady value. At this point, the supervisory switching control activated the PI controller, which drove the steady state offset to zero. The flat top responses in the overshoot region for simple PI based controllers in Fig. 19 and Fig. 20 were due to rate limitation enforced to keep the motor current within safety limit. The higher amount of ripple apparent in the reference current response of the fuzzy controller alone, especially under loaded conditions, can be seen from Fig. 21 and 22. This caused a higher steady torque ripple due to reasons discussed in Subsection 3.2.

## 5 CONCLUSION

A novel fuzzy logic controller was proposed for speed control of a BLDC motor drive employing fewer design rules than the conventional fuzzy logic based implementations. The key features of the control scheme were simple structure, fewer decision making rules and ease of design. It was demonstrated that the proposed fuzzy logic control worked well alone and gave a fast dynamic response with a small steady state error. A hybrid speed control structure was presented, combining fuzzy logic and PI control to achieve offset free tracking. A supervisory switching mechanism based on speed error variance was employed to select the appropriate controller best suited to the operating conditions. The proposed controller yielded a faster dynamic response, minimal overshoot and offset free command tracking for motors of different ratings. The effectiveness of the proposed control was demonstrated through comparison with some commonly employed control methods, through an extensive set of simulations using MATLAB/Simulink SimPowerSystems toolbox. The results of the simulations demonstrated the improved performance achieved by the proposed control scheme under a wide range of operating conditions.

## APPENDIX A

*Table 2. Error Variance Threshold Values*

| Variance Threshold | Value |
|---|---|
| Motor M1 | 0.015 |
| Motor M2 | 0.050 |

*Table 3. PI Controller parameters*

| Parameter | Value |
|---|---|
| Proportional Gain (PWM based), $K_p$[a] | 0.1 |
| Integral Gain (PWM based), $K_i$[a] | 10 |
| Proportional Gain (Variable $V_{dc}$), $K_p$ | 0.013 |
| Integral Gain (Variable $V_{dc}$), $K_i$ | 16.61 |

[a] Same for both M1 and M2 in both PI–alone and Hybrid modes

*Table 4. Sliding-mode Controller Parameter*

| Parameter | Value |
|---|---|
| Surface weight $c_1$ | 1000 |

*Table 5. Parameters of the motors*

| Parameter | Motor M1 | Motor M2 | Units |
|---|---|---|---|
| $V_{rated,LL}$ | 500 | 320 | $V$ |
| $I_{rated}$ | 3.3 | 4.4 | $A$ |
| $R_s$ | 2.875 | 3.16 | $\Omega$ |
| $L_s$ | 0.0085 | 0.0064 | $H$ |
| $J$ | 0.0008 | 0.000259 | $kg.m^2$ |
| $B$ | 0.001 | 0.00002865 | $N.m.s$ |
| $K_e$ | 1.4 | 0.5162 | $\frac{V.s}{rad}$ |
| $P$ | 4 | 4 | − |

## ACKNOWLEDGMENT

The authors acknowledge the support of King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia for this work.

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Received: 2014-10-13
Accepted: 2015-07-25