Discrete Time Consensus of Leader Following BLDC Motor with Delay

Suhaib Masroor, Chen Peng, Zain Anwar Ali, and Jin Zhang

***Abstract*—In this paper, we address the leader following consensus of BLDC motor by considering the effect of delay in the network. Since BLDC motors are used in a variety of application such as Automobiles, Servo drives, UAV's, Aeronautics and other areas requiring higher efficiency and ease of control, therefore we think it is necessary to study the behavior of motor from the Multi-Agent point of view. We use RST pole placement control approach to design a system that controls the speed of BLDC motor and then elaborates the system from Multi-Agent prospective for consensus on speed by considering the effect of network delay. We assume that each agent communicates its data with neighbor via delay in a communication network. We use MATLAB Simulink to simulate the proposed model and results endorse the success of our approach.**

***Index Terms*—Leader following multi-agent system, consensus, brushless DC motor, RST controller, delay.**

I. INTRODUCTION

In the last two decades, multi-agent systems (MAS) has been one of the most leading and focused topics of research in control theory scientists, particularly consensus problem. Formation control of UAV's, robots, satellites, distributed sensor networks and time synchronization are some famous application areas that exhibit consensus problems. In MAS, the foremost challenge is how to propose control law that permits all agents to reach an agreement. A consensus algorithm is a communication law that postulates the information conversation among an agent and its adjoining agents on the network. Numerous results have been acquired with neighbor-based among which the leader-follower design was widely used by plentiful researchers.

In the leader-following situation, a consensus is achieved such that followers must be connected with the leader defining the desired trajectory. The main benefit of leader following approach is that reference trajectory is defined by leader whereas stability is governed by individual agents control protocol. Normally, leaders are at liberty to its followers but have an influence on followers so that governing the leader leads to accomplishing the anticipated task. In [1], it is proven that consensus is achieved as long as follower are kept connected with leader, as time goes on. In [2], Cyber Physical Energy System (CPES), is proposed in which leader following consensus protocol is applied for speed regulation of multiple Induction motors. Consensus problem with fixed and switching topologies with linear dynamics are addressed in [3]. In [4], Mahmoud address the consensus problem of fixed and switching topologies with disturbances by designing the output feedback controller.

A situation in which agents are required to follow the path is called tracking problem. In [5], a consensus problem of discrete time tracking of agents with fixed and switching topologies are studied such that leader velocity is unknown and to track the leader, follower's uses neighbors information and state estimation rule. For single and double integrator dynamics, tracking problem is addressed with situation of communication failure in [6], deriving a sufficiency condition under fixed topology thereby decreasing the tracking error.

In MAS, the delay has a significant effect on consensus protocol convergence. For MAS, delays can be classified as either communication delay or processing delay. When there is delay in information due to network such that agent receive delayed information from neighboring agent than it is case of communication delay but when there is delay due to processing of received information thereby causing delay in output than it is called processing delay, this eventually cause delayed input to neighboring agent, therefore, it is also called input delay. In network controlled actuator and controllers, input delays are common. In [7], average consensus problem for undirected fixed topology under communication delay is addressed by deriving a sufficiency conditions. In [8], the author explores the approach of [7] by considering the uniform delay and provide an upper bond to maximum allowable delay to achieve average consensus. Moreover, they also consider the case of non-uniform delay and proves average consensus problem. In [9], a leader following consensus problem under directed topology with time delay is considered. A sufficiency condition is obtained by using Lyapunov function to guarantee the stability of the system. In [10], a leader following consensus of second order system with nonlinear dynamics and time delay is presented and by using Lyapunov-Razumikhin function a sufficiency condition is derived to ensure stability.

For communication delay systems, consensus protocols are designed such that agent compares its current state with neighboring agent delayed ones. Invigorated by above results, we explore the consensus problem for BLDC motor connected in leader following manner under fixed topology with delay. Since BLDC motors exhibit linearity not only between current & torque but also voltage & rpm, they found a lot of applications in aerospace, automotive vehicles, different electronics gadgets and etc [11]. There are a

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number of reasons for BLDC to be preferred choice over brushed DC motors or Induction motors such as greater speed, efficiency and control, high speed, negligible noise operation, linearity between torque and speed. The dominant approach for controlling the speed of BLDC motor is by regulating the rotor voltage and current [12]. Mostly, the speed of BLDC motor is controlled by employing P, PI and PID controllers [13].

Practically, communication delay exists in every system that degrades its performance, therefore, the aim of this paper is to study the performance and stability of proposed BLDC motor leader following system in the scenario of communication delay using RST controller under fixed topology.

The rest of the paper is structured as follows. Basics of graph and consensus theory for multi agent system is provided in Section II. Section III elaborates the use of consensus protocol to the proposed system. BLDC motor model is presented in Section IV. In Section V, controller design with a motor model in IV is presented. Simulation results are provided in Section VI and as a final point conclusion is given.

II. PRELIMINARIES AND GRAPH THEORY

Communication among agents plays a significant role to achieve consensus thereby exchanging information with one another. Algebraic Graph theory play a crucial role to demonstrate the distribution of information among agents. A graph $G\ (V, E)$, is defined as the set of nodes and edges as $V = \{v_1, \ldots\ v_N\}$, and $E \subseteq V \times V$ respectively. Exchange of information between two nodes is described by an edge as (v_i, v_j) such that v_i is said to be the parent while v_j is child node. Every node is considered as an agent, so the neighbors of node v_i (or agent) is symbolized as N_i i-e Neighbors set $N_i = \{j{:}\, ij \in E\}$. The degree matrix is the number of neighbors of node v_i such that $\deg(v_i)\, if\ i = j$, otherwise 0 i-e $\Lambda = diag\{d_1, \ldots .\, d_N\}$. The adjacency of graph is defined by a matrix called adjacency matrix $\Pi = [\alpha_{ij}] \in \mathbb{R}^{N\times N}$ such that $\alpha_{ii} = 0$, α_{ij} is a positive value if there is an edge between two nodes otherwise $\alpha_{ij} = 0$. In the case of undirected graph $\alpha_{ij} = \alpha_{ji}$ for $i \neq j$. Moreover, Graph Laplacian is a matrix $[L_{ij}] \in \mathbb{R}^{N\times N}$ defined as $L = \Lambda - \Pi$ such that $L_{ii} = \sum_{j\neq i} \alpha_{ij}$ and $L_{ij} = -\alpha_{ij}, i \neq j$. An important property of Laplacian matrix is that, its row sum will always zero such that 0 will be the simplest eigenvalue with eigenvector of **1**.

Lemma 1. In [14], Laplacian of undirected connected graph has simple zero eigenvalue and smallest nonzero eigenvalue λ_2 satisfies $\min_{x\neq 0, 1^T x = 0} \frac{x^T L x}{x^T x}$

Lemma 2. In [14], Laplacian of strongly connected graph has a left eigenvector $r = [r_1, \ldots, r_N]^T$ with zero eigenvalue and $RL + L^T R \geq 0$, such that $R = diag(r_1, \ldots, r_N)$.

In Leader following scenario, the leader is not a neighbor of any agent but it exchange information with those agents which comes in its neighborhood. We restrict node 0 for the leader. So, now we have another graph $\tilde{G}$ representing the information distribution between leader and agents which are in its neighborhood. Agents in the neighborhood of leader is defined by a diagonal matrix $D = diag\ \{d_1, d_2, \ldots .\, d_N\}$ such that $d_i > 0$ if agent i is the neighbor otherwise $d_i = 0$. This shows that, d_i is positive if agent i has contact with leader and 0 otherwise. Now what we are trying to do is designing a controller $u_i, i = 1,2, \ldots ., N$ such that all the agents in the network must follow the leader.

Definition: Leader following consensus is assumed to be attained for agent $i \in \{1, \ldots ., N\}$, starting with any initial condition $x_i(0),\ i = 1, \ldots ., N$ as long as a feedback u_i of $\{x_j : j \in N_i\}$ exists such that $\lim_{t\to\infty} \|x_i(t) - x_o(t)\| = 0$, $i = 1, \ldots ., N$.

Lemma 3. In [15], for undirected graph G and $\tilde{G}$, if graph $\tilde{G}$ is connected than $L + D$ is a symmetric positive definite matrix.

Lemma 4. In [16], for directed graph G and $\tilde{G}$, matrix $L + D$ is stable (real part of the eigenvalue is positive) if v_0 is reachable in $\tilde{G}$.

III. CONSENSUS PROTOCOL IN LEADER FOLLOWING SCENARIO WITH DELAY

This paper address the problem of leader following consensus for n agents (in this case BLDC motors) with a delay such that all the following agents come together at speed demarcated by leader ζ_{ref}. Additionally, information flow among leader and followers is supposed to be effectively organized and connected and to reach ζ_{ref} followers must retain connected with the leader. For following agent i, the control input is given as

$$u_i(k) = -\sum_{j\in N_i} (\zeta_i(k-\tau) - \zeta_k(k-\tau)) + d_i\big(\zeta_{ref}(k-\tau) - \zeta_i(k-\tau)\big) \tag{1}$$

IV. BLDC MOTOR MODEL

BLDC motor consists of a permanent magnet on rotor side and winding on stator side driven by a preset serial arrangement of DC power source called commutation. For a three phase stator winding, a six step inverter is used as shown in figure 1, there by generating a rotating magnetic field. In stator winding, back EMF is generated when rotating magnet interact with stator pole. The model of Y-connected BLDC motor is given in [11].

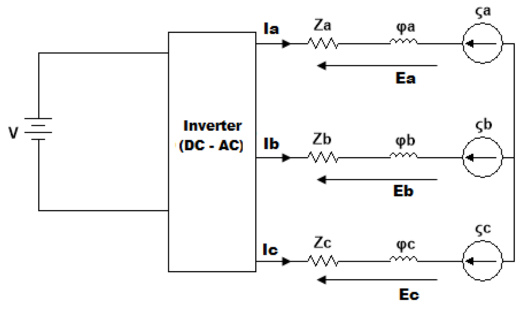


Fig. 1. BLDC motor model.

$$E_a = Z_a I_a + \varphi \frac{dI_a}{dt} + \varsigma_a \tag{2}$$

$$E_b = Z_b I_b + \varphi \frac{dI_b}{dt} + \varsigma_b \tag{3}$$

$$E_c = Z_c I_c + \varphi \frac{dI_c}{dt} + \varsigma_c \tag{4}$$

$$\begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} = \begin{bmatrix} Z_a & 0 & 0 \\ 0 & Z_b & 0 \\ 0 & 0 & Z_c \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + \begin{bmatrix} \varphi_a & \Psi_{ab} & \Psi_{ac} \\ \Psi_{ba} & \varphi_b & \Psi_{bc} \\ \Psi_{ca} & \Psi_{cb} & \varphi_c \end{bmatrix} \frac{d}{dt} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + \begin{bmatrix} \varsigma_a \\ \varsigma_b \\ \varsigma_c \end{bmatrix} \tag{5}$$

Let

$$Z_a = Z_b = Z_c = Z \tag{6}$$

$$\varphi_a = \varphi_b = \varphi_c = \varphi \tag{7}$$

$$\Psi_{ab} = \Psi_{ac} = \Psi_{ba} = \Psi_{bc} = \Psi_{ca} = \Psi_{cb} = \Psi = 0 \tag{8}$$

Than

$$\begin{bmatrix} \mathrm{E}_a \\ \mathrm{E}_b \\ \mathrm{E}_c \end{bmatrix} = \begin{bmatrix} \mathrm{Z} & 0 & 0 \\ 0 & \mathrm{Z} & 0 \\ 0 & 0 & \mathrm{Z} \end{bmatrix} \begin{bmatrix} \mathrm{I}_a \\ \mathrm{I}_b \\ \mathrm{I}_c \end{bmatrix} + \begin{bmatrix} \mathrm{\varphi} & 0 & 0 \\ 0 & \mathrm{\varphi} & 0 \\ 0 & 0 & \mathrm{\varphi} \end{bmatrix} \frac{d}{dt} \begin{bmatrix} \mathrm{I}_a \\ \mathrm{I}_b \\ \mathrm{I}_c \end{bmatrix} + \begin{bmatrix} \varsigma_a \\ \varsigma_b \\ \varsigma_c \end{bmatrix} \tag{9}$$

$$\begin{bmatrix} \mathrm{E}_a \\ \mathrm{E}_b \\ \mathrm{E}_c \end{bmatrix} = \mathrm{Z} \begin{bmatrix} \mathrm{I}_a \\ \mathrm{I}_b \\ \mathrm{I}_c \end{bmatrix} + \mathrm{\varphi} \frac{d}{dt} \begin{bmatrix} \mathrm{I}_a \\ \mathrm{I}_b \\ \mathrm{I}_c \end{bmatrix} + \begin{bmatrix} \varsigma_a \\ \varsigma_b \\ \varsigma_c \end{bmatrix} \tag{10}$$

Equation (11-13) gives back EMF of the motor

$$\varsigma_a = \zeta_r . \Gamma_r f(\Theta_r) \tag{11}$$

$$\varsigma_b = \zeta_r . \Gamma_r f(\Theta_r - \tfrac{2\pi}{3}) \tag{12}$$

$$\varsigma_c = \zeta_r . \Gamma_r f(\Theta_r + \tfrac{2\pi}{3}) \tag{13}$$

where $\zeta_r, \Theta_r, \Gamma_r$ are angular rotor velocity, rotor position and rotor magnetic flux constant respectively. Generated torque is given as

$$\mathcal{T}_e = \frac{\varsigma_a \mathrm{I}_a + \varsigma_b \mathrm{I}_b + \varsigma_c \mathrm{I}_c}{\zeta_r} \tag{14}$$

In terms of machine parameters, torque is defined as

$$\mathcal{T}_e = \mathcal{T}_L + J \frac{d\zeta_r}{dt} + \xi \zeta_r \tag{15}$$

where ξ, J, $\mathcal{T}_L$ are friction co-efficient, inertia and loaded torque respectively.

Now let's think via multi-agent system point of view consisting of N agents and a leader. Every agent has following dynamics

$$\dot{x}_i = Ax_i + Bu_i \tag{16}$$

where $x_i \in \mathbb{R}^n$ is the state of agent i and $u_i \in \mathbb{R}^n$ is its input which uses local information from neighboring agents. The matrix B is of appropriate dimensions. The leader i-e $i = 0$, has linear dynamics as

$$\dot{x}_o = Ax_o \tag{17}$$

$$\begin{bmatrix} \dot{I}_a \\ \dot{I}_b \\ \dot{I}_c \\ \dot{\zeta}_r \\ \dot{\Theta}_r \end{bmatrix} = \begin{bmatrix} {-Z}/{\varphi} & 0 & 0 & {(\Gamma_r f(\Theta_r))}/{J} & 0 \\ 0 & {-Z}/{\varphi} & 0 & {(\Gamma_r f\left(\Theta_r - \frac{2\pi}{3}\right))}/{J} & 0 \\ 0 & 0 & {-Z}/{\varphi} & {\left(\Gamma_r f\left(\Theta_r + \frac{2\pi}{3}\right)\right)}/{J} & 0 \\ {(\Gamma_r f(\Theta_r))}/{J} & {(\Gamma_r f\left(\Theta_r - \frac{2\pi}{3}\right))}/{J} & {\left(\Gamma_r f\left(\Theta_r + \frac{2\pi}{3}\right)\right)}/{J} & {-\xi}/{J} & 0 \\ 0 & 0 & 0 & {P}/{2} & 0 \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \\ \zeta_r \\ \Theta_r \end{bmatrix} + \begin{bmatrix} {1}/{\varphi} & 0 & 0 & 0 \\ 0 & {1}/{\varphi} & 0 & 0 \\ 0 & 0 & {1}/{\varphi} & 0 \\ 0 & 0 & 0 & {-1}/{J} \end{bmatrix} \begin{bmatrix} E_a \\ E_b \\ E_c \\ \mathcal{T}_L \end{bmatrix} \tag{18}$$

where $x_o \in \mathbb{R}^n$ the leader state and its dynamics is independent of others. The state space model of BLDC motor is presented in equation (18). All the matrices of leader and the following agents are taken to be identical, this is because the system is inspired by multi agent system in the real world such as birds group, fish school etc.

V. CONTROLLER DESIGN

RST digital controller is a worthy alternative to PI controller having two degrees of freedom, and by pole placement methodology, it is conceivable to enforce poles in a close loop. The preferred regulation performance is accomplished by designing the polynomials R and S while T is designed subsequently to achieve desired tracking performance.

In [17], several methods related to the design of PI, PD, PID and 2DOF PID controller are surveyed. They not only present the selection of control parameters but also their inter-transformation and tuning approaches.

When dealing with electro-hydraulic systems, it is difficult to model them due to varying hydraulic properties, delays and dead zone. Trajectory tracking is difficult for fuzzy feedback control in the presence of dead zone and delays in hydraulic systems. In [18], a 2 DOF fuzzy controller is proposed for foot trajectory tracking of hexapod robot having a prefilter, designed by genetic algorithm (GA), in feed forward loop to overcome delay caused by dead zone thereby improving tracking whereas feedback controller ensure stability. In [19], Takagi-Sugeno and Mamdani fuzzy model are used to design PI-Fuzzy controller for servo based integral plant. They tune PI controller by the extended symmetrical optimum method to ensure robust stability in the presence of disturbances in the plant. In [20], a 2 DOF control algorithm based on Takagi-Sugeno model having feed forward and a backward controller is designed for SISO systems such that feed forward controller converges the system to the reference signal while feedback controller performs reference tracking by using error model predictive control obtained from TS fuzzy model.

The designing of a controller using the approach of Pole placement is straightforward by tuning R, S & T polynomials. System response (in this case it is BLDC motor), is defined as ${}^{B}\!/_{A}$ whereas desired system response is ${}^{B_m}\!/_{A_m}$.

The RST controlled close loop system configuration is given in Fig. 2 while transfer functions are presented in equation (19) and (20) respectively [21].

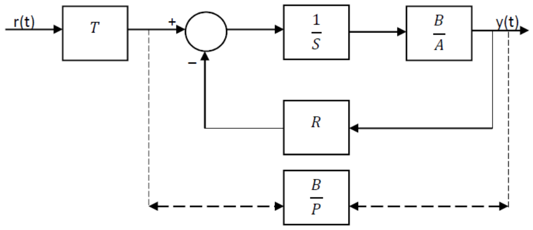


Fig. 2. Pole placement with RST controller.

$$H_{ol} = \frac{BR}{AS} \tag{19}$$

$$H_{cl} = \frac{B}{P} \tag{20}$$

From equation (20), we deduce that polynomial P define close loop poles which can be decomposed into P_D and P_F i-e desired dominant poles and auxiliary poles of the closed loop respectively.

$$P = P_D + P_F \tag{21}$$

Fig. 3 shows the canonical architecture of the RST digital controller having two degrees of freedom such that anticipated regulation is achieved by proper designing of R and S filters while T provide tracking.

Now, at this stage Diophantine equation comes into consideration to determine R and S as given below

$$P = AS + BR \tag{22}$$

Putting Equation (22) into (20) yields

$$H_{cl} = \frac{B}{AS+BR} \tag{23}$$

Nonetheless, R and S comprise preset fixed parts demarcated by the performance stipulations, which can be expressed as

$$R = H_R\, R' \tag{24}$$

$$S = H_S\, S' \tag{25}$$

Putting $S = H_S\, S'$ and $R = H_R\, R'$ in equation (22) gives

$$P = A\, H_S\, S' + B\, H_R\, R' \tag{26}$$

Equation (26) is used to solve S and R, ensuring desired close loop poles. So, if n is the degree of polynomial A, than

$$deg(S) = deg(A) + 1 \tag{27}$$

$$deg(R) = deg(A) \tag{28}$$

$$deg(P) = 2n + 1 \tag{29}$$

Let's introduce polynomial T in our system, so the close loop system response is given as

$$H_{cl} = \frac{TB}{AS+BR} \tag{30}$$

Now, we introduce a reference system model to be tracked, given as

$$H_m = \frac{B_m}{A_m} \tag{31}$$

And reference trajectory (i-e desired response of BLDC motor), is defined as

$$y^* = \frac{B_m}{A_m}\, r(t) \tag{32}$$

The complete RST system response is given as

$$u(t) = \frac{T}{S} y^* - \frac{R}{S}\, y(t) \tag{33}$$

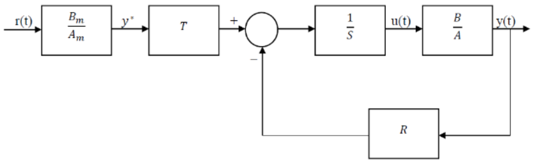


Fig. 3. Pole placement, tracking and regulation.

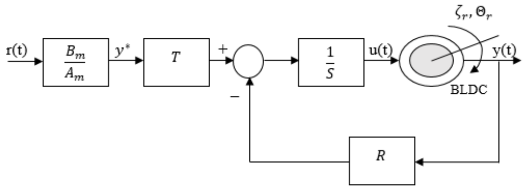


Fig. 4. BLDC speed control model.

Now what we are trying to do is using RST pole placement approach designing a system which is use to control the speed of BLDC motor, furthermore, we extend this system as leader following multi-agent system in which consensus is said to be achieved when the followers converge to the same speed as that of leader with the assumption of network induced delay. The model of proposed system is given in Fig. 4.

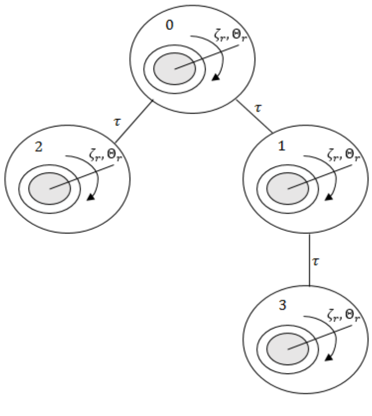


Fig. 5. Agent's communication topology with delay.

VI. RESULTS

In this section, we give simulation results to demonstrate our theoretical results derived in above sections. Consider a system consists of three agents and one leader such that interaction topology is fixed as shown in Fig. 5. Then the Laplacian and the matrix D are given as follows endorsing Lemma 3 and 4.

$$L = \begin{bmatrix} 1 & 0 & -1 \\ 0 & 0 & 0 \\ -1 & 0 & 1 \end{bmatrix}, D = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

The simulation results are given in Fig. 6 and Fig. 7 validates the effectiveness of discussion in above sections.

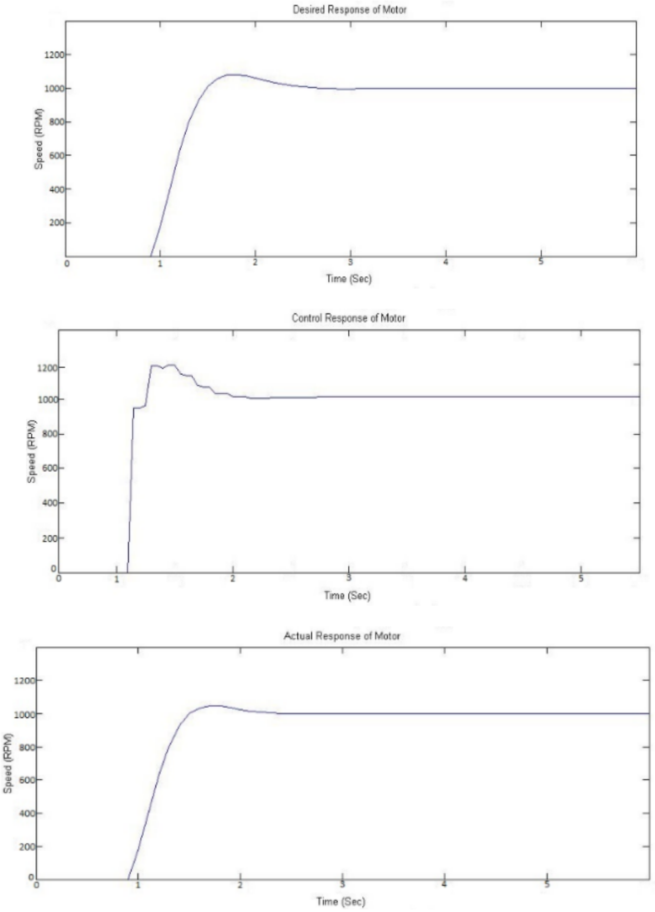
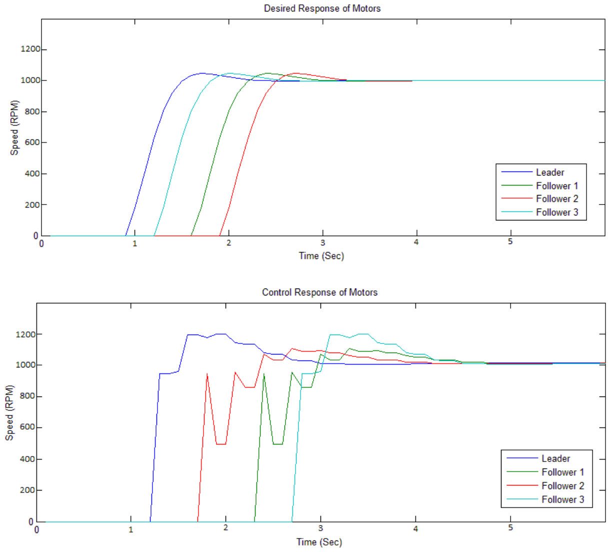


Fig. 6. (a) Desired response for BLDC motor (b) Response of individual controller (c) Actual response of BLDC motor.



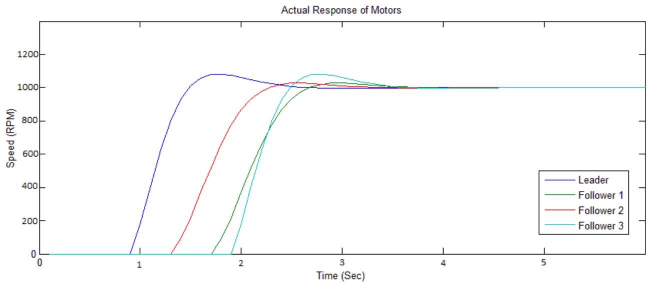


Fig. 7. (a) Desired response for leader following BLDC motor with delay (b) Response of individual agent controller w.r.t delay (c) Actual response of leader and follower with delay, having T = 0.667, S = 0.547 & R = 0.556 respectively.

In Fig. 6, we see the stand alone response of the system in which we can easily observe that the system stabilizes at constant speed after some transient behavior while Fig. 7 shows the responses in leader following scenario in which the following agents converge to same speed as that of leader with some delay in the system.

VII. CONCLUSION

In this paper, we have studied consensus of BLDC motor speed in leader following arrangement by assuming delay. Using pole placement RST controller, it is shown that consensus is achieved in discrete time case under network induced delay. The RST based leader following consensus bring robust approach in industrial sector applications and there are a lot of enhancement opportunities exists in this model and more efforts are needed in future to explore in this direction.

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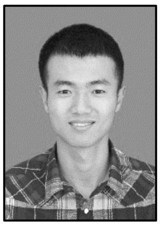

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