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Adaptive Voltage-based Control of Direct-drive Robots Driven by Permanent Magnet Synchronous Motors

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A B S T R A C T

Tracking control of the direct-drive robot manipulators in high-speed is a challenging problem. The Coriolis and centrifugal torques become dominant in the high-speed motion control. The dynamical model of the robotic system including the robot manipulator and actuators is highly nonlinear, heavily coupled, uncertain and computationally extensive in non-companion form. In order to overcome these problems, this paper presents a novel adaptive control for direct-drive robot manipulators driven by Permanent Magnet Synchronous Motors (PMSM) in tracking applications. The novelty of this paper is that the proposed adaptive law is free from manipulator dynamics by using the Voltage Control Strategy (VCS). Additionally, a state space model of the robotic system driven by PMSM is presented. The VCS differs from the commonly used control strategy for robot manipulators the so called torque control strategy. The position control of the PMSM is effectively used for the tracking control of the robot manipulator. This idea takes the control problem from the manipulator control to the motor control resulting in a simple yet efficient control design. Compared with the torque control, the control design is simpler, easier to implement with better tracking performance. The control method is verified by stability analysis. Simulation results show superiority of the proposed control to the torque control applied by field oriented control on the direct-drive robot driven by PMSM.

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1. INTRODUCTION

Torque Control Strategy (TCS) is a commonly used control strategy for robot manipulators. This strategy considers the joint torques as the control input, thereby pays attention to handling the dynamics of the robot manipulator. The dynamical model is nonlinear, multi-input/multi-output, uncertain and extensively computational. Many valuable robust and adaptive control approaches based on the TCS such as robust complaint control [1], sliding mode control [2], adaptive back stepping control [3], intelligent control [4] were proposed. To reduce the complexity of the TCS, the dynamics of actuators may be omitted. However, the control performance in high-speed tracking applications may be degraded. With considering the actuator dynamics, the control problem becomes more complex.

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To reduce the complexity of control design, the free-model control algorithms such as fuzzy [5] and neural control [6] were proposed. As an alternative to TCS, the Voltage Control Strategy (VCS) responds well to this enquiry by taking the control problem from the robot manipulator to the motor control [7]. The control inputs are the motor voltages instead of the joint torques. As a result, the control algorithm can be free from manipulator dynamics. Compared with the torque control, all mentioned control methods can be designed simpler and performs much better. Some control methods based on the VCS such as fuzzy control [8], robust control [9] and nonlinear control [10] were proposed for the robot driven by geared dc motors. The VCS was proposed on Permanent Magnet Synchronous Motors (PMSM), as well [11]. This paper presents a novel adaptive control for a direct-drive robot driven by PMSM for performing high speed tracking tasks. It shows superiority of the VCS to the TCS.

The PMSM are receiving increased attention in the recent years because of their high efficiency, large torque to volume ratio, and reliable operation [12]. So far, some control strategies namely the volts/Hertz control [13], Field Oriented Control (FOC) [14] and Direct Torque Control (DTC) [15] have been used for speed regulation of PMSM. Among them, the open-loop volts/Hertz control yields a poor torque regulation with a slow dynamic performance and significant limitations [16], thus more powerful control strategies such as FOC and DTC were proposed.

The rest of this paper is organized as follows: Section 2 presents modeling of the robotic system and develops the adaptive control. Section 3 presents stability analysis to verify the control method. Section 4 gives a comparative study. Section 5 presents the simulation results and finally Section 6 concludes the paper.

2. MODELING AND CONTROL GOAL

a. Modeling Consider an electrical robot driven directly by PMSM. The dynamic equation of motion:

$$\mathbf{D}(\boldsymbol{\theta})\ddot{\boldsymbol{\theta}} + \mathbf{C}(\boldsymbol{\theta},\dot{\boldsymbol{\theta}})\dot{\boldsymbol{\theta}} + \mathbf{g}(\boldsymbol{\theta}) = \boldsymbol{\tau} \tag{1}$$

where, $\boldsymbol{\theta} \in R^n$ is the vector of joint positions, $\mathbf{D}(\boldsymbol{\theta})$ is the $n \times n$ matrix of manipulator inertia, $\mathbf{C}(\boldsymbol{\theta},\dot{\boldsymbol{\theta}})\dot{\boldsymbol{\theta}} \in R^n$ is the vector of centrifugal and Coriolis torques, $\mathbf{g}(\boldsymbol{\theta}) \in R^n$ denotes the vector of gravitational torques, and $\boldsymbol{\tau} \in R^n$ is the vector of joint torques. The electric motors provide the joint torques $\boldsymbol{\tau}$ by:

$$\mathbf{J}\ddot{\boldsymbol{\theta}} + \mathbf{B}\dot{\boldsymbol{\theta}} + \boldsymbol{\tau} = \boldsymbol{\tau}_{\mathbf{m}} \tag{2}$$

where, $\boldsymbol{\tau}_{\mathbf{m}} \in R^n$ is the motors electromagnetic torque vector and, $\mathbf{J}$ and $\mathbf{B}$ are the $n \times n$ diagonal matrices for inertia and damping of motors, respectively. Note that vectors and matrices are represented bold.

In order to obtain motor voltages as inputs of the system, consider the electrical equation of the ith PMSM [17] that drives the ith joint as:

$$v_{qi} = R_i I_{qi} + L_{qi}\dot{I}_{qi} + P_i(L_{di}I_{di} + \lambda_{afi})\dot{\theta}_i \tag{3}$$

$$v_{di} = R_i I_{di} + L_{di}\dot{I}_{di} - P_i L_{qi} I_{qi}\dot{\theta}_i \tag{4}$$

where, for the ith motor, v_{di} and v_{qi} are the d and q axis voltages, I_{di} and I_{qi} are the d and q axis currents. The coefficient matrices, L_{di} and L_{qi} are the d and q axis inductances, R_i is the resistance of stator windings, P_i is pole pairs and λ_{afi} is the amplitude of the flux induced by the permanent magnets of the rotor in the stator phases [18].

Motor torque vector, τ_{mi} as the input for dynamic Equation (2) is produced by the motor currents as:

$$\tau_{mi} = 3P_i[\lambda_{afi}I_{qi} + (L_{di} - L_{qi})I_{di}I_{qi}]/2 \tag{5}$$

The stator voltages of each motor are calculated from, v_{di} and v_{qi} of that motor by the Inverse Park Transformation (IPT) [19].

A state space model for the robotic system driven by PMSM can be obtained as follows:

The matrix equations from (3)-(5) is formed as:

$$\dot{\mathbf{I}}_{\mathbf{q}} = \mathbf{L_q}^{-1}\mathbf{v_q} - \mathbf{L_q}^{-1}\mathbf{R}\mathbf{I_q} - \mathbf{P}\mathbf{L_q}^{-1}\boldsymbol{\lambda}_{\mathbf{af}}\dot{\boldsymbol{\theta}} - \mathbf{P}\mathbf{L_q}^{-1}\mathbf{L_d}\boldsymbol{\eta} \tag{6}$$

$$\dot{\mathbf{I}}_{\mathbf{d}} = \mathbf{L_d}^{-1}\mathbf{v_d} + \mathbf{L_d}^{-1}\mathbf{P}\mathbf{L_q}\boldsymbol{\mu} - \mathbf{L_d}^{-1}\mathbf{R}\mathbf{I_d} \tag{7}$$

$$\boldsymbol{\tau}_{\mathbf{m}} = 1.5\mathbf{P}\boldsymbol{\lambda}_{\mathbf{af}}\mathbf{I_q} + 1.5\mathbf{P}(\mathbf{L_d} - \mathbf{L_q})\boldsymbol{\xi} \tag{8}$$

where, $\mathbf{L_q}$, $\mathbf{L_d}$, $\mathbf{R}$, $\boldsymbol{\lambda}_{\mathbf{af}}$, and $\mathbf{P}$ are $n \times n$ diagonal matrices formed by the ith element of their diagonal L_{qi}, L_{di}, R_i, λ_{afi}, and P_i, respectively. Vectors $\boldsymbol{\eta} \in R^n$, $\boldsymbol{\mu} \in R^n$ and $\boldsymbol{\xi} \in R^n$ are defined through their ith elements as:

$$\eta_i = I_{di}\dot{\theta}_i \tag{9}$$

$$\mu_i = \dot{\theta}_i I_{qi} \tag{10}$$

$$\xi_i = I_{di}I_{qi} \tag{11}$$

Substituting Equations (1) and (8) in Equation (2) yields:

$$\ddot{\boldsymbol{\theta}} = \left(\mathbf{D}(\boldsymbol{\theta}) + \mathbf{J}\right)^{-1} \times \cdots \\ \left(1.5\mathbf{P}\boldsymbol{\lambda}_{\mathbf{af}}\mathbf{I_q} + 1.5\mathbf{P}(\mathbf{L_d} - \mathbf{L_q})\boldsymbol{\xi} - \mathbf{C}(\boldsymbol{\theta},\dot{\boldsymbol{\theta}})\dot{\boldsymbol{\theta}} - \mathbf{g}(\boldsymbol{\theta}) - \mathbf{B}\dot{\boldsymbol{\theta}}\right) \tag{12}$$

By using, $\mathbf{z}_1 = \boldsymbol{\theta}$, $\mathbf{z}_2 = \dot{\boldsymbol{\theta}}$, $\mathbf{z}_3 = \mathbf{I_q}$ and $\mathbf{z}_4 = \mathbf{I_d}$ as system states, the state space model is then formed from Equations (12), (6) and (7) as:

$$\dot{\mathbf{z}} = \mathbf{f}(\mathbf{z}) + \mathbf{b}\mathbf{v} \tag{13}$$

Voltages of the motors denoted by $\mathbf{v_d}$ and $\mathbf{v_q}$ are considered as the inputs of the robotic system in Equation (13). The state space Equation (13) shows a highly coupled nonlinear large multivariable system. Complexity of the model opens a serious challenge in the literature of robot modeling and control. In (13),

$$\mathbf{f}(\mathbf{z}) = \begin{bmatrix} \mathbf{z}_2 \\ (\mathbf{D}(\mathbf{z}_1)+\mathbf{J})^{-1}\left(1.5\mathbf{P}\boldsymbol{\lambda}\mathbf{z}_3 + 1.5\mathbf{P}(\mathbf{L_d}-\mathbf{L_q})\boldsymbol{\xi}(\mathbf{z}_3,\mathbf{z}_4) - \mathbf{C}(\mathbf{z}_1,\mathbf{z}_2)\mathbf{z}_2 - \mathbf{g}(\mathbf{z}_1) - \mathbf{B}\mathbf{z}_2\right) \\ -\mathbf{L_q}^{-1}\mathbf{R}\mathbf{z}_3 - \mathbf{P}\mathbf{L_q}^{-1}\boldsymbol{\lambda}_{\mathbf{af}}\mathbf{z}_2 - \mathbf{P}\mathbf{L_q}^{-1}\mathbf{L_d}\boldsymbol{\eta}(\mathbf{z}_4,\mathbf{z}_2) \\ \mathbf{L_d}^{-1}\mathbf{P}\mathbf{L_q}\boldsymbol{\mu}(\mathbf{z}_2,\mathbf{z}_3) - \mathbf{L_d}^{-1}\mathbf{R}\mathbf{z}_4 \end{bmatrix}, \mathbf{v} = \begin{bmatrix} \mathbf{v_q} \\ \mathbf{v_d} \end{bmatrix}, \mathbf{b} = \begin{bmatrix} \mathbf{0}_{n\times n} & \mathbf{0}_{n\times n} \\ \mathbf{0}_{n\times n} & \mathbf{0}_{n\times n} \\ \mathbf{L_q}^{-1} & \mathbf{0}_{n\times n} \\ \mathbf{0}_{n\times n} & \mathbf{L_d}^{-1} \end{bmatrix}, \mathbf{z} = \begin{bmatrix} \mathbf{z}_1 \\ \mathbf{z}_2 \\ \mathbf{z}_3 \\ \mathbf{z}_4 \end{bmatrix} \quad (14)$$

b. Adaptive Control The VCS opens a new field of research in the control of electrically driven robots. This strategy emphasizes on the control of motors of robot for the control of a robot. Its main advantage over the TCS is that the control law becomes free from manipulator dynamics. In this section, we develop the VCS for the direct-drive robots driven by the PMSM.

In this study, assume that variables required to implement the control law are available through proper sensors in the system. Control law is d and q axis voltages so makes joint robot position lead to desired position trajectory.

Considering Equations (3) and (4), we propose control laws of the form:

$$v_{qi} = R_i I_{qi} + L_{qi}\dot{I}_{qi} + P_i L_{di} I_{di}\dot{\theta}_i + \cdots + P_i\lambda_{afi}\left(\dot{\theta}_{di} + \beta_i(t)(\theta_{di} - \theta_i)\right) \quad (15)$$

$$v_{di} = -P_i L_{qi} I_{qi}\dot{\theta}_i \quad (16)$$

where, scalar $\beta_i(t) > 0$ is a control design parameter. Substituting Equations (15) and (16) into Equations (3) and (4), respectively, yields:

$$\dot{e}_i + \beta_i(t) e_i = 0 \quad (17)$$

$$R_i I_{di} + L_{di}\dot{I}_{di} = 0 \quad (18)$$

where, the tracking error e_i is expressed as:

$$\theta_{di} - \theta_i = e_i \quad (19)$$

where, θ_{di} is a desired position. As a result, for $t \ge 0$:

$$e_i(t) = e_i(0).\exp\left(-\int_0^t \beta_i(t)dt\right) \quad (20)$$

$$I_{di}(t) = I_{di}(0).\exp\left(-R_i t / L_{di}\right) \quad (21)$$

Thus, $e_i \to 0$ and $I_{di} \to 0$ as $t \to \infty$. The tracking error vanishes and the current I_{di} will become zero to obtain the maximum torque. The proposed control laws have an important advantage of being free from manipulator dynamics. Instead, they require the model of motors that are much simpler and less computational than the model of robot manipulator. However, the control performance may be degraded in the case of parametric uncertainty. Therefore, adaptive control law is proposed as:

$$v_{qi} = \hat{R}_i I_{qi} + \hat{L}_{qi}\dot{I}_{qi} + P_i\hat{L}_{di} I_{di}\dot{\theta}_i + \cdots + P_i\hat{\lambda}_{afi}\left(\dot{\theta}_{di} + \beta_i(t)(\theta_{di} - \theta_i)\right) \quad (22)$$

$$v_{di} = -P_i\hat{L}_{qi} I_{qi}\dot{\theta}_i \quad (23)$$

where, $\hat{R}_i$, $\hat{L}_{qi}$ and $\hat{\lambda}_{afi}$ are estimations of R_i, L_{qi} and λ_{afi}, respectively. The estimated parameters are regulated using an updating law such that is the tracking error converges. The required feedbacks are the motor currents, the angle and speed of motors that can be measured conveniently.

Substituting Equation (22) in Equation (3) yields:

$$P_i\hat{\lambda}_{afi}\left(\dot{e}_i + \beta_i(t)e_i\right) = \left(\mathbf{w}_i - \hat{\mathbf{w}}_i\right)^T \mathbf{y}_i \quad (24)$$

where, $\mathbf{w}_i$ is the parameters vector, $\hat{\mathbf{w}}_i$ is its estimation and $\mathbf{y}_i$ is the variables vector defined as:

$$\mathbf{w}_i^T = [R_i \quad L_{qi} \quad P_i L_{di} \quad P_i\lambda_{afi}] \quad (25)$$

$$\hat{\mathbf{w}}_i^T = [\hat{R}_i \quad \hat{L}_{qi} \quad P_i\hat{L}_{di} \quad P_i\hat{\lambda}_{afi}] \quad (26)$$

$$\mathbf{y}_i^T = [I_{qi} \quad \dot{I}_{qi} \quad I_{di}\dot{\theta}_i \quad \dot{\theta}_i] \quad (27)$$

A positive definite function is suggested to establish convergence of the error:

$$V_i(\mathbf{x}) = 0.5 P_i\hat{\lambda}_{afi} e_i^2 + 0.5(\mathbf{w}_i - \hat{\mathbf{w}}_i)^T(\mathbf{w}_i - \hat{\mathbf{w}}_i)/\gamma_i \quad (28)$$

where, $\mathbf{x}^T = \left[e_i \quad (\mathbf{w}_i - \hat{\mathbf{w}}_i)^T\right]$ and $\gamma_i > 0$ is a constant gain. Under condition $\hat{\lambda}_{afi} > 0$, $V_i(\mathbf{x})$ is positive definite since $V_i(\mathbf{0}) = 0$ and $V_i(\mathbf{x}) > 0$ if $\mathbf{x} \ne 0$. The time derivative of V_i is calculated as:

$$\dot{V}_i(\mathbf{x}) = 0.5 P_i\dot{\hat{\lambda}}_{afi} e_i^2 + P_i\hat{\lambda}_{afi} e_i\dot{e}_i - (\mathbf{w}_i - \hat{\mathbf{w}}_i)^T\dot{\hat{\mathbf{w}}}_i/\gamma_i \quad (29)$$

From Equation (24), we have $P_i\hat{\lambda}_{afi}\left(\dot{e}_i + \beta_i(t)e_i\right) = \left(\mathbf{w}_i - \hat{\mathbf{w}}_i\right)^T \mathbf{y}_i$:

$$P_i\hat{\lambda}_{afi}\dot{e}_i = -P_i\hat{\lambda}_{afi}\beta_i(t)e_i + \left(\mathbf{w}_i - \hat{\mathbf{w}}_i\right)^T \mathbf{y}_i \quad (30)$$

Substituting (30) into (29) yields:

$$\dot{V}_i(\mathbf{x}) = \frac{P_i e_i^2}{2}\left(\dot{\hat{\lambda}}_{afi} - 2\hat{\lambda}_{afi}\beta_i(t)\right) + \left(\mathbf{w}_i - \hat{\mathbf{w}}_i\right)^T\left(\mathbf{y}_i e_i - \frac{\dot{\hat{\mathbf{w}}}_i}{\gamma_i}\right) \quad (31)$$

An updating law is proposed to establish the convergence as:

$$\dot{\hat{\mathbf{w}}}_i = \gamma_i e_i \mathbf{y}_i \quad (32)$$

$$\beta_i(t) = 0.5(\dot{\hat{\lambda}}_{afi} + \lambda_i) / \hat{\lambda}_{afi} \quad (33)$$

where, λ_i is a positive gain. Substituting Equations (32) and (33) in Equation (31) yields:

$$\dot{V}_i(\mathbf{x}) = -0.5\lambda_i P_i e_i^2 \quad (34)$$

This result implies that $\dot{V}_i(\mathbf{x}) < 0$ if $e_i \neq 0$. Therefore, e_i converges to zero. If e_i holds zero, then $\dot{\hat{\mathbf{w}}}_i = 0$. This means that the parameters converge to constant values. Using Equations (25) and (32), we obtain:

$$\dot{\hat{\lambda}}_{afi} = \gamma_i e_i \dot{\theta}_i / P_i \quad (35)$$

Substituting Equation (35) in Equation (33) one obtains an updating law for $\beta_i(t)$ as:

$$\beta_i(t) = 0.5(\gamma_i e_i \dot{\theta}_i + \lambda_i P_i) / (P_i \hat{\lambda}_{afi}) \quad (36)$$

The updating law (32) implies that:

$$\hat{\mathbf{w}}_i = \gamma_i \int_0^t e_i \mathbf{y}_i dt + \hat{\mathbf{w}}_i(0) \quad (37)$$

That is:

$$\begin{aligned} &\hat{R}_i = \gamma_i \int_0^t e_i I_{qi} dt + \hat{R}_i(0) \\ &\hat{L}_{qi} = \gamma_i \int_0^t e_i \dot{I}_{qi} dt + \hat{L}_{qi}(0) \\ &\hat{L}_{qi} = (\gamma_i / P)\int_0^t e_i I_{di}\dot{\theta}_i dt + \hat{L}_{qi}(0) \\ &\hat{\lambda}_{afi} = (\gamma_i / P)\int_0^t e_i \dot{\theta}_i dt + \hat{\lambda}_{afi}(0) \end{aligned} \quad (38)$$

The nominal parameters are already known and given as the initial values of the estimations. If the initial values of the parameters are selected close to the real values, the tracking error convergences fast. Thus:

$$\hat{\mathbf{w}}_i(0) = \bar{\mathbf{w}}_i \quad (39)$$

where, $\bar{\mathbf{w}}_i(0)$ is the nominal value for the parameter vector $\mathbf{w}_i$. There are differences between the real values and the nominal values due to the parametric errors, which should be compensated using the online parameter estimation. Performance of control system depends on the values of estimations. Therefore, the constraints are given to the estimations in Equation (38) as:

$$\begin{aligned} &\hat{R}_i = \gamma_i \int_0^t e_i I_{qi} dt + \hat{R}_i(0) \quad \text{if} \quad 0.8\bar{R}_i < \hat{R}_i < 1.2\bar{R}_i \\ &\hat{L}_{qi} = \gamma_i \int_0^t e_i \dot{I}_{qi} dt + \hat{L}_{qi}(0) \quad \text{if} \quad 0.8\bar{L}_{qi} < \hat{L}_{qi} < 1.2\bar{L}_{qi} \\ &\hat{L}_{di} = \frac{\gamma_i}{P}\int_0^t e_i I_{di}\dot{\theta}_i dt + \hat{L}_{di}(0) \quad \text{if} \quad 0.8\bar{L}_{di} < \hat{L}_{di} < 1.2\bar{L}_{di} \\ &\hat{\lambda}_{afi} = \frac{\gamma_i}{P}\int_0^t e_i \dot{\theta}_i dt + \hat{\lambda}_{afi}(0) \quad \text{if} \quad 0.8\bar{\lambda}_{afi} < \hat{\lambda}_{afi} < 1.2\bar{\lambda}_{afi} \end{aligned} \quad (40)$$

where $\bar{R}_i$, $\bar{L}_{qi}$, $\bar{L}_{di}$ and $\bar{\lambda}_{afi}$ are the nominal values for R_i, L_{qi}, L_{di} and λ_{afi}. The nominal values are given as known values. It is assumed that the real values are close to the nominal values. Therefore, we consider the parametric uncertainty stated by constraints in Equation (40). If the estimate values are beyond the given limits, they are set to the given limits. When the estimated values are located on the limits. At the limits $\dot{\hat{\mathbf{w}}}_\mathbf{i} = \mathbf{0}$. Thus, from Equation (31):

$$\dot{V}_i(\mathbf{x}) = \left(\mathbf{w}_i - \hat{\mathbf{w}}_i\right)^T \mathbf{y}_i e_i - P_i e_i^2 \hat{\lambda}_{afi}\beta_i(t) \quad (41)$$

To satisfy $\dot{V}_i < 0$, it is required that:

$$(\mathbf{w}_i - \hat{\mathbf{w}}_i)^T \mathbf{y}_i e_i / P_i \hat{\lambda}_{afi} < \beta_i(t) e_i^2 \quad (42)$$

Assume that:

$$\left|(\mathbf{w}_i - \hat{\mathbf{w}}_i)^T \mathbf{y}_i / P_i \hat{\lambda}_{afi}\right| < \rho_i \quad (43)$$

In order to define ρ_i, assume that:

$$\left\|(\mathbf{w}_i - \hat{\mathbf{w}}_i)^T\right\| \le \alpha_i \quad (44)$$

where, α_i is a constant which is known in advance with some knowledge about the worst case of parametric uncertainty of parameters stated by $\mathbf{w}_i$ in Equation (25). Thus:

$$\left|(\mathbf{w}_i - \hat{\mathbf{w}}_i)^T \mathbf{y}_\mathbf{i}\right| \le \alpha_i \|\mathbf{y}_i\| = \rho_i \quad (45)$$

The upper bound, ρ_i, is known since the variable vector $\mathbf{y}_i$ can be measured in real time. Since:

$$\frac{(\mathbf{w}_i - \hat{\mathbf{w}}_i)^T e_i \mathbf{y}_i}{P_i \hat{\lambda}_{afi}} \le \frac{1}{P_i \hat{\lambda}_{afi}} \left\|(\mathbf{w}_i - \hat{\mathbf{w}}_i)^T \mathbf{y}_i\right\| |e_i| \quad (46)$$

and parameters $\hat{\lambda}_{afi} > 0$ and $P_i > 0$, using Equation (45) in Equation (46) results in:

$$(\mathbf{w}_i - \hat{\mathbf{w}}_i)^T e_i \mathbf{y}_i / P_i \hat{\lambda}_{afi} \le |e_i| \rho_i / P_i \hat{\lambda}_{afi} \quad (47)$$

Using inequality Equation (47), to satisfy Equation (42) it is sufficient that:

$$|e_i|\rho_i / P_i\hat{\lambda}_{afi} = \beta_i(t)e_i^2 \tag{48}$$

Which yields:

$$\rho_i / P_i\hat{\lambda}_{afi}|e_i| = \beta_i(t) \tag{49}$$

It can be concluded that if $\rho_i / (P_i\hat{\lambda}_{afi}|e_i|) = \beta_i(t)$, then $\dot{V}_i < 0$. Control law Equation (22) is formed by Equation (49) as:

$$\begin{aligned} v_{qi} &= \hat{R}_i I_{qi} + \hat{L}_{qi}\dot{I}_{qi} + P_i\hat{L}_{di}I_{di}\dot{\theta}_i + \cdots \\ &+ P_i\hat{\lambda}_{afi}\dot{\theta}_{di} + \rho_i\, sign(e_i) \end{aligned} \tag{50}$$

where, $sign(e_i) = e_i / |e_i|$ defined as $sign(e_i) = 1$ if $e_i > 0$, $sign(e_i) = -1$ if $e_i < 0$ and $sign(e_i) = 0$ if $e_i = 0$. Since $\beta_i(t) = \rho_i / |e_i| > 0$, control law (50) can be applied for case 1 as well. It can be concluded that control law (50) guarantees $\dot{V}_i < 0$ for both cases. As a result, the boundedness of both motor tracking error and the parameter estimation error are guaranteed using Equation (33) and control laws (50) and (23). Since the control law (50) is discontinuous, the chattering problem occurs. To eliminate chattering phenomenon, the saturation function should be used in replace of the sign function in Equation (50):

$$\begin{aligned} v_{qi} &= \hat{R}_i I_{qi} + \hat{L}_{qi}\dot{I}_{qi} + P_i\hat{L}_{di}I_{di}\dot{\theta}_i + \cdots \\ &+ P_i\hat{\lambda}_{afi}\left(\dot{\theta}_{di} + \rho_i\, sat(e_i / \varepsilon)\right) \end{aligned} \tag{51}$$

where, ε is a small positive constant and the saturation function is expressed as:

$$sat(x) = \begin{cases} 1 & x \ge 1 \\ x & |x| < 1 \\ -1 & x \le -1 \end{cases} \tag{52}$$

The motors should be protected from over voltages. Thus, we make the following assumption:

Assumption 1: The motor voltages in qd frame is bounded as

$$\begin{aligned} |v_{qi}| &\le v_{mqi} \\ |v_{di}| &\le v_{mdi} \end{aligned} \tag{53}$$

To ensure this assumption, we modify the control law (50) and (23) as

$$v_{qi} = v_{mqi}\, sat(u_{qi} / v_{mqi}) \tag{54}$$

$$v_{di} = v_{mdi}\, sat(u_{di} / v_{mdi}) \tag{55}$$

where, $sat(.)$ was defined in Equation (52), v_{mqi} and v_{mdi} are the maximum values of q and d axes, and u_{qi} and u_{di} are calculated as

$$\begin{aligned} u_{qi} &= \hat{R}_i I_{qi} + \hat{L}_{qi}\dot{I}_{qi} + P_i\hat{L}_{di}I_{di}\dot{\theta}_i + \cdots \\ &+ P_i\hat{\lambda}_{afi}\left(\dot{\theta}_{di} + \rho_i\, sat(e_i / \varepsilon)\right) \\ u_{di} &= -P_i\hat{L}_{qi}I_{qi}\dot{\theta}_i \end{aligned} \tag{56}$$

The motor must be sufficiently strong to follow the desired joint under the maximum permitted voltage. Therefore, the following assumption is made.

Assumption 2: The motor is sufficiently strong for tracking the desired trajectory such that:

$$\left|R_i I_{qi} + L_{qi}\dot{I}_{qi} + P_i(L_{di}I_{di} + \lambda_{afi})\dot{\theta}_{di}\right| < v_{mqi} \tag{57}$$

$$\left|R_i I_{di} + L_{di}\dot{I}_{di} - P_i L_{qi}I_{qi}\dot{\theta}_{di}\right| < v_{mdi} \tag{58}$$

The proposed control laws (54)-(55) is based on the electrical equations of PMSM. It is emphasized that the proposed control law is free from robot manipulator dynamic in the form of decentralized structure. This means that each joint is controlled using feedbacks from that joint. According to control law (54)-(55), the control system requires feedbacks of joint position θ_i, velocity $\dot{\theta}_i$, currents I_{qi} and its derivative $\dot{I}_{qi}$, and I_{di}. Where, $\dot{I}_{qi}$ is calculated from measurement of motor's current. It is verified that none of variables from other joints are given in the control law.

3. STABILITY ANALYSIS

Stability analysis of the control system is presented to evaluate the proposed decentralized control. Stability analysis is presented for every individual joint. Then, the stability of the robotic system can be concluded.

Applying control law (54) to the motors expressed by Equations (3) and (4) yields the closed loop system:

$$R_i I_{qi} + L_{qi}\dot{I}_{qi} + P_i(L_{di}I_{di} + \lambda_{afi})\dot{\theta}_i = v_{mqi}\, sat(u_{qi} / v_{mqi}) \tag{59}$$

$$R_i I_{di} + L_{di}\dot{I}_{di} - P_i L_{qi}I_{qi}\dot{\theta}_i = v_{mdi}\, sat(u_{di} / v_{mdi}) \tag{60}$$

To make the dynamics of tracking error well defined such that the robot can track the desired trajectory, we make the following assumption.

Assumption 3: The desired trajectory θ_d must be smooth and its derivatives up to a necessary order exist and are all uniformly bounded.

By multiplying both sides of Equations (3) and (4) by I_{qi} and I_{di}, respectively, one obtains the following equations:

$$I_{qi}v_{qi} = R_i I_{qi}^2 + L_{qi} I_{qi} \dot{I}_{qi} + P_i (L_{di} I_{di} + \lambda_{afi}) I_{qi} \dot{\theta}_i \quad (61)$$

$$I_{di}v_{di} = R_i I_{di}^2 + L_{di} I_{di} \dot{I}_{di} - P_i L_{qi} I_{di} I_{qi} \dot{\theta}_i \quad (62)$$

Motor receives the electrical power [19] expressed by:

$$p_e = 1.5(I_{di}v_{di} + I_{qi}v_{qi}) \quad (63)$$

The electrical power provides the mechanical power expressed as:

$$p_m = 1.5P_i\left(\lambda_{afi} I_{qi} \dot{\theta}_i + (L_{di} - L_{qi}) I_{di} I_{qi} \dot{\theta}_i\right) \quad (64)$$

The power $1.5R_i(I_{qi}^2 + I_{di}^2)$ is the loss in the windings and the power $1.5(L_{qi} I_{qi} \dot{I}_{qi} + L_{di} I_{di} \dot{I}_{di})$ is the time derivative of the magnetic energy. From Equations (61) and (62) for the motors with $L_{di} = L_{qi}$,

$$I_{qi}v_{qi} + I_{di}v_{di} = R_i I_{qi}^2 + R_i I_{di}^2 + L_{qi} I_{qi} \dot{I}_{qi} + \ldots \\ L_{di} I_{di} \dot{I}_{di} + P_i \lambda_{afi} I_{qi} \dot{\theta}_i \quad (65)$$

From Equation (5) for the motors with $L_{di} = L_{qi}$:

$$\tau_{mi} = 1.5 P_i \lambda_{afi} I_{qi} \quad (66)$$

Thus, τ_{mi} is bounded as:

$$|\tau_{mi}| \le 1.5 P_i \lambda_{afi} |I_{qi}| \quad (67)$$

Since:

$$I_{qi}^2 + I_{di}^2 = I_m^2 \quad (68)$$

where, I_m is the amplitude of the current in abc frame. From Equation (68), I_{qi} is bounded as:

$$|I_{qi}| \le I_m \quad (69)$$

From (66) to reach maximum torque at the upper bound that $|I_{qi}| = I_m$ one can imply from (68) that $I_{di} = 0$. Thus, from Equations (67) and (69), one can imply that:

$$|\tau_{mi}| \le \tau_{\max i} = 1.5 P_i \lambda_{afi} I_{mi} \quad (70)$$

where, $\tau_{\max i} = 1.5 P_i \lambda_{afi} I_{mi}$ occurs under $I_{di} = 0$.

By taking integral from both sides of Equation (65) with $I_{qi}(0) = 0$ and $I_{di}(0) = 0$.

$$\int_0^t (I_{qi}v_{qi} + I_{di}v_{di})dt = R_i I_{qi}^2 t + R_i I_{di}^2 t + \cdots \\ 0.5 L_{qi} I_{qi}^2 + 0.5 L_{di} I_{di}^2 + \int_0^t P_i \lambda_{afi} I_{qi} \dot{\theta}_i dt \quad (71)$$

Since:

$$0 \le R_i I_{qi}^2 t + R_i I_{di}^2 t + 0.5 L_{qi} I_{qi}^2 + 0.5 L_{di} I_{di}^2 \quad (72)$$

Thus:

$$\int_0^t P_i \lambda_{afi} I_{qi} \dot{\theta}_i dt \le \int_0^t (I_{qi}v_{qi} + I_{di}v_{di})dt \quad (73)$$

At the upper bound and under the maximum torque $\tau_{\max i}$ which $I_{di} = 0$, one can write:

$$\int_0^t P_i \lambda_{afi} I_{uqi} \dot{\theta}_{ui} dt = \int_0^t I_{uqi} v_{uqi} dt \quad (74)$$

where, I_{uqi} , $\dot{\theta}_{ui}$ and v_{uqi} are the values of I_{qi} , $\dot{\theta}_i$ and v_{qi} at the upper bound and maximum torque, respectively. By taking time derivative:

$$P_i \lambda_{afi} I_{uqi} \dot{\theta}_{ui} = I_{uqi} v_{uqi} \quad (75)$$

$$\dot{\theta}_{ui} = v_{uqi} / (P_i \lambda_{afi}) \quad (76)$$

From Equations (33) and (53), $\dot{\theta}_i$ is bounded as:

$$|\dot{\theta}_i| \le v_{mqi} / (0.9 P_i \bar{\lambda}_{afi}) \equiv \dot{\theta}_{mi} \quad (77)$$

From Equation (59) under $I_{di} = 0$, one can imply:

$$R_i I_{qi} + L_{qi} \dot{I}_{qi} = w_i \quad (78)$$

$$w_i = v_{mqi} sat(u_{qi} / v_{mqi}) - P_i \lambda_{afi} \dot{\theta}_i \quad (79)$$

Since $|v_{mqi} sat(u_{qi} / v_{mqi})| \le v_{mqi} d$ and $|P_i \lambda_{afi} \dot{\theta}_i| \le 1.1 P_i \bar{\lambda}_{afi} \dot{\theta}_{mi}$, w_i is bounded. The linear Equation (78) is a stable linear system based on the Routh-Hurwitz criterion. Since the input w_i is bounded, the output I_{qi} is bounded.

From Equation (78), we have:

$$L_{qi} \dot{I}_{qi} = w_i - R_i I_{qi} \quad (80)$$

Since w_i and I_{qi} are bounded, $\dot{I}_{qi}$ is bounded.

4. A COMPARATIVE STUDY

Torque control is a common strategy to control robot manipulators. The position control of robot manipulator is implemented using a torque control law. In this strategy, the dynamics of motors are excluded from the control problem. Then, the commonly used strategies such as the DTC or FOC may be used to drive the PMSM of direct-drive robot manipulators. There would be some shortcomings with the torque control strategy.

First, the control law becomes complex due to complexity of manipulator dynamics. In addition, modeling of a direct-drive robot manipulator faces uncertainties including parametric uncertainty, un-modeled dynamics. Then, the control law becomes much complicated to guarantee stability and provide a satisfactory performance. On the other hand, the dynamical terms such as coriolis and centrifugal torques are highly dominant in the dynamics of a direct-drive robot. Therefore, using robots in high-accuracy and high-speed applications is a challenging problem.

A torque control law can be suggested using the model of robot manipulator in Equation (1) as:

$$\mathbf{T}^* = \mathbf{D}(\boldsymbol{\theta})\left(\ddot{\boldsymbol{\theta}}_\mathbf{d} + \mathbf{k}_2(\dot{\boldsymbol{\theta}}_\mathbf{d} - \dot{\boldsymbol{\theta}}) + \mathbf{k}_1(\boldsymbol{\theta}_\mathbf{d} - \boldsymbol{\theta})\right) + \mathbf{C}(\boldsymbol{\theta},\dot{\boldsymbol{\theta}})\dot{\boldsymbol{\theta}} + \mathbf{g}(\boldsymbol{\theta}) \tag{81}$$

where, the control design parameters are given by gain diagonal matrices $\mathbf{k_p}$ and $\mathbf{k_d}$. As a result of applying Equation (81) to robot manipulator in Equation (1), we have:

$$\ddot{\boldsymbol{\theta}}_\mathbf{d} - \ddot{\boldsymbol{\theta}} + \mathbf{k}_2(\dot{\boldsymbol{\theta}}_\mathbf{d} - \dot{\boldsymbol{\theta}}) + \mathbf{k}_1(\boldsymbol{\theta}_\mathbf{d} - \boldsymbol{\theta}) = \mathbf{0} \tag{82}$$

Using $\mathbf{k}_1 > 0$ and $\mathbf{k}_2 > 0$, then $\mathbf{x} \to \mathbf{x_d}$ as $t \to \infty$ where $\mathbf{x}$ stands for the system states expressed as $\mathbf{x} = \begin{bmatrix} \boldsymbol{\theta} & \dot{\boldsymbol{\theta}} \end{bmatrix}$ and $\mathbf{x_d} = \begin{bmatrix} \boldsymbol{\theta}_\mathbf{d} & \dot{\boldsymbol{\theta}}_\mathbf{d} \end{bmatrix}$. Applying control law (81) requires the model of robot in (1) that is very large, highly nonlinear, heavily coupled and computationally extensive. In addition, the control law (81) requires feedbacks of $\boldsymbol{\theta}$ and $\dot{\boldsymbol{\theta}}$. Then, the actuators of robot are driven so that the proposed torque control is implemented.

On the other hand, The FOC is a commonly strategy used to drive the PMSM [20]. The FOC is formed by two inner current control loops and one outer speed control loop. The outer loop provides the reference current in q axis corresponding to the reference torque for one of the inner loops while the other one is a zero reference current in d-axis to achieve the maximum torque. FOC achieves a fast response with smooth starting and acceleration. However, accurate information requires the motor parameters and load conditions to guarantee good drive performance in terms of precision, bandwidth and disturbance rejection [21].

Utilization of the FOC base on TCS for position control of robot driven by PMSM is a case that will be compared with the proposed strategy. The FOC is performed using the PI controllers as follows:

$$v_{qi} = k_{Pqi}\left(I_{qi}^* - I_{qi}\right) + k_{Iqi}\int_0^t \left(I_{qi}^* - I_{qi}\right)dt \tag{83}$$

where, k_{Pqi} and k_{Iqi} are the controller gains and I_{qi}^* is the desired current in q-axis calculated from Equation (5) in non-salient rotor for $L_{di} = L_{qi}$ given by:

$$I_{qi}^* = 2\tau_{mi}^* / (3P_i\lambda_{afi}) \tag{84}$$

where, τ_{mi}^* is given by Equation (81). A zero reference current in d-axis $I_{di}^* = 0$ is provided using a PI controller as:

$$v_{di} = -k_{Pdi}I_{di} - k_{Idi}\int_0^t I_{di}dt \tag{85}$$

where, k_{Pdi} and k_{Idi} are the controller gains.

5. SIMULATON RESULTS

A comparison on the control performances between adaptive VCS and FOC is presented through simulations. All control approaches are applied on a direct-drive three-link articulated robot manipulator driven by PMSM. The robot is a rigid articulated robot manipulator with the details given by reference [9]. The parameters of motors are given in Table 1.

The controllers are selected with the same structure for three joints but their gains might be different. The desired trajectories for $i = 1,2,3$ are given the same in the form of:

$$\theta_{di} = 3t^2 - 2t^3 \tag{86}$$

where the operating time is given $1\sec$. The desired trajectory starts from zero and after $1\sec$ reaches $1\,rad$. The goal of control system is to track the desired trajectory expressed by Equation (86) from the initial configuration of the robot.

Simulation 1: We apply the VCS on the control system using control law (54) and (55). The performance of adaptive control is shown in Figure 1 where the maximum tracking error for joint 2 is about $1.57\times10^{-4}\,rad$. The tracking error is really ignorable while the robot starts under a high load. It is worthy to note that the joint 2 has the most load torque. The control efforts behave smoothly as shown for the controller 2 in Figure 2.

Simulation 2: We apply the FOC on the control system using control laws (83)-(85). The performance of FOC is shown in Figure 3 where the maximum tracking error for joint 2 is $0.0284\,rad$.

TABLE 1. The specifications of the PMSM

L_d	L_q	λ_{af}	R	J	B	P
0.001	0.001	1	1	0.008	0.001147	4

The tracking error is not as small as the one for the VCS. The maximum tracking error for joint 2 is 180 times larger than VCS. The control efforts rapidly increase to a high value but reduce with oscillations as shown for the controller 2 in Figure 4.

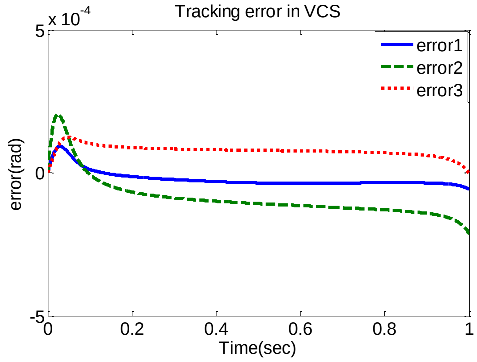

Figure 1. Tracking performance of the VCS

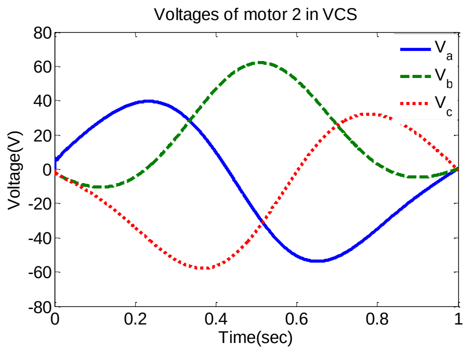

Figure 2. The phase voltages of motor 2 in VCS

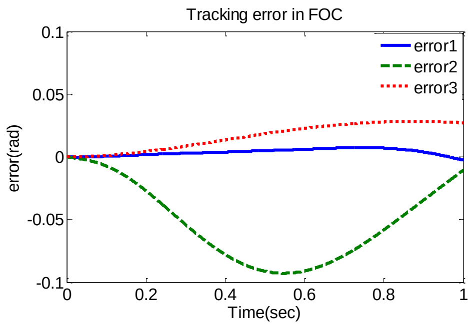

Figure 3. Tracking performance of the FOC

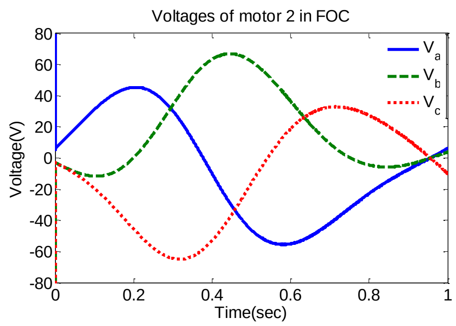

Figure 4. The phase voltages of motor 2 in FOC

After a while the motor voltages behave similar to the ones in the VCS. They rapidly increase to compensate the load torque then behave smoothly.

6. CONCLUSION

A state space model of the robotic system including a robot manipulator and the permanent magnet motors has been derived. This model which is in non-companion form shows that the robotic system is of order 4 with heavy coupling and high nonlinearity. Then, a novel adaptive control of direct-drive robots driven by permanent magnet synchronous motors has been developed. It has an advantage to the previous adaptive control approaches so far. It is free from manipulator model. As a result, it can efficiently overcome the challenging problems such as nonlinearity, uncertainty and largeness of the robot dynamics. The dynamical problems associated with direct-drive robots in performing high speed tasks have been suitably replied. These capabilities are due to using the VCS instead of the TCS. The proposed adaptive has formed based on the motor dynamics which is much simpler than the robot dynamics. The control method has obtained a good tracking performance with guaranteed stability and robustness against all uncertainties of robot manipulator and parametric uncertainty of motors. The control method has rigorously verified by stability analysis and evaluated by simulation results. We suggest to researchers in order to develop VCS base on PMSM, we suggest consider uncertainties in the control system.

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Adaptive Voltage-based Control of Direct-drive Robots Driven by Permanent Magnet Synchronous Motors

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چکیده

کنترل ردگیری ربات‌های رانده شده بدون چرخ دنده در سرعت‌های بالا، چالش برانگیز است. در کنترل حرکتِ سرعت بالا، گشتاورهای پیچشی و گریز از مرکز غالب است. دینامیک سیستم رباتیک شامل بازوی ماهر ربات و عملگرها غیرخطی، دارای تزویج متقابل و عدم قطعیت با محاسبات بسیار سنگین، به فرم غیر کانونیکال است. این مقاله کنترل تطبیقی جدید ربات‌های رانده شده توسط موتورهای سنکرون مغناطیس دائم بدون چرخ‌دنده را جهت غلبه بر این پیچیدگی‌ها، در کاربرد ردگیری ارائه نموده است. نوآوری مقاله، در پیشنهاد قانون کنترل مستقل از مدل ربات توسط استراتژی کنترل ولتاژ به منظور کنترل ردگیری ربات‌های رانده شده توسط محرکه الکتریکی است. علاوه بر این، مدل فضای حالت کل سیستم رباتیک شامل بازوی ربات و موتورهای سنکرون مغناطیس دائم بدون چرخ‌دنده ارائه شده است. استراتژی کنترل ولتاژ متفاوت از استراتژی مرسوم کنترل گشتاور بازوهای رباتیک است. کنترل موقعیت موتورهای سنکرون مغناطیس دائم به طور موثر و کارا در کنترل بازوی ربات به کار گرفته شده است. این ایده، پیچیدگی‌های کنترل بازوی ماهر ربات را به شکل بسیار ساده و موثری به موتور الکتریکی منتقل می‌کند. روش کنترلی پیشنهاد داده شده در عین سادگی پیاده‌سازی، عملکرد بهتری را در مقایسه با کنترل گشتاور نتیجه می‌دهد. پایداری روش کنترلی پیشنهادی با تحلیل پایداری اثبات شده است. نتایج شبیه‌سازی نشان از برتری روش کنترلی پیشنهاد داده شده را در مقایسه با کنترل گشتاور دارد. کنترل گشتاور مبتنی بر کنترل برداری میدان، به روی مدل بازوی رباتیک رانده شده توسط موتورهای سنکرون مغناطیس دائم، شبیه‌سازی شده است.

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