Research Article

Maximum Power Control of Hybrid Wind-Diesel-Storage System

Elkhatib Kamal,¹ Magdy Koutb,¹ Abdul Azim Sobaih,¹ and Sahar Kaddah²

¹ Industrial Electronics and Control Department, Faculty of Electronic Engineering, Menoufia University, Menouf 32952, Egypt

² Electrical Engineering Department, Faculty of Engineering, Mansoura University, Mansoura 35516, Egypt

Correspondence should be addressed to Elkhatib Kamal, elkateb.kamal@gmail.com

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Extraction of maximum wind power of variable speed wind turbines in hybrid wind-diesel-storage system (HWDSS) is considered due to economical purposes. The proposed control algorithm utilizes extended fuzzy-linear matrix equalities (FLMEs) systems design of stabilizing fuzzy controllers for nonlinear systems described by Takagi-Sugeno (TS) fuzzy models. The algorithm maximizes the power coefficient for a fixed pitch. Moreover, it reduces the voltage ripple and stabilizes the system over a wide range of wind speed variations. The control scheme is tested for different profiles of wind speed pattern and provides satisfactory results.

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1. INTRODUCTION

Since ancient times, wind turbine technology has been used to improve humankind's quality of life where people have used wind turbines to pump water and mill grain, along with many other uses. Today, wind turbines are used for similar purposes (i.e., water or oil pumping, battery charging, or utility generation) as a cheap, clean source of electricity, and well suited for isolated places with no connections to the electric grid [1].

In remote areas such as small islands, diesel generators are the main power supply. Diesel fuel has several drawbacks: it is quite expensive because transportation to remote areas adds extracost, and it causes pollution via engine exhaust. Providing a feasible, economical, and environmental alternative source to diesel generators is important. A hybrid wind-diesel system with battery storage of wind power can benefit islands and other isolated communities and increase fuel savings. However, control of such system is very important as wind turbine produces excessive fluctuation of power output, which negatively influences the quality of electricity supplied to the load, particularly frequency and voltage [2].

Optimum wind energy extraction is achieved by running the wind turbine generator (WTG) in variable-speed, variable-frequency mode. The rotor speed is allowed to

vary in sympathy with the wind speed, by maintaining the tip speed ratio to a value that maximizes aerodynamic efficiency. In order to achieve this ratio, the permanent magnet synchronous generator load line should be matched very closely to the maximum power line of the wind turbine generator [3].

The problem of wind energy conversion system output power control has been considered extensively [4–7]. Maximization of the wind energy conversion efficiency based on a brushless doubly fed reluctance generator is discussed in [4]. Reference [5] maximizes power based on a standard V/Hz converter and controls the frequency to achieve the desired power at a given turbine speed. Reference [6] maximizes power based on controlling the slip power, which is extracted from the rotor circuits and fed to the grid through a rectifier-inverter branch. The firing angle of the inverter is used to control the slip power. Reference [7] presents a hill-climb searching (HCS) control for the maximum wind turbine power at variable wind speeds.

The main contribution of this research is to maximize the energy from the wind in the presence of a wide range of wind variations using the proposed FLME controller. Also, it provides a robust controller that stabilizes the HWDSS and overcomes the system nonlinearity. In addition, it guarantees good robustness and performance of the controller. Finally,

FIGURE 1: Wind turbine system.

it reduces the voltage ripple on the main bus voltage. The proposed FLME controller is based on the Takagi-Sugeno (TS) fuzzy model and linear matrix inequalities [8–10].

This paper is organized as follows. Section 2 provides system analysis. Section 3 presents the design of the proposed FLME controller. Section 4 shows the stability and robustness conditions for the proposed algorithm. Section 5 presents simulation of the wind turbine. Finally, concluding remarks are made in Section 6 followed by the list of references.

2. SYSTEM ANALYSIS

2.1. Wind turbine modeling

The kinetic energy of the wind due to its speed is captured by the turbine and is converted to mechanical energy. Along with the turbine, there is a generator present at the tower top which is coupled to the wind turbine by a shaft and often with a gear box. The generator converts mechanical energy of turbine to electrical energy and it feeds at demand point. The global scheme of a variable speed is displayed in Figure 1. The expression for aerodynamic power (P_a) captured by the wind turbine is given by the nonlinear expression [11]

$$P_a = 0.5C_p(\lambda)\rho\pi R^2 V^3, \quad (1)$$

where ρ is the air density ($\text{kg}\cdot\text{m}^{-3}$), R is the rotor radius (m), V is the wind speed ($\text{m}\cdot\text{s}^{-1}$), and C_p is the power coefficient defined by the following relation [12]:

$$C_p = (0.44 - 0.0167\beta) \sin \left[\frac{\pi(\lambda - 3)}{15 - 0.3\beta} \right] - 0.00184(\lambda - 3)\beta, \quad (2)$$

where β is the blade pitch angle of the wind turbine, λ is the tip speed ratio (TSR) and is given by [11]

$$\lambda = \frac{\omega_t R}{V}, \quad (3)$$

where ω_t is the rotational speed of the blades.

Referring to (2), optimal TSR λ_{opt} can be obtained as follows:

$$\lambda_{\text{opt}} = \left(\frac{15 - 0.3\beta}{\pi} \right) \cos^{-1} \left[\frac{0.00184\beta(15 - 0.3\beta)}{\pi(0.44 - 0.167\beta)} \right] + 3. \quad (4)$$

Thus, the maximum power captured from the wind is given by

$$P_{a(\text{max})} = 0.5C_{p(\text{max})}(\lambda_{\text{opt}}, \beta)\rho\pi R^2 V^3. \quad (5)$$

A typical $C_p - \lambda$ curve is shown in Figure 2. It can be seen that there is a maximum power coefficient $C_{p(\text{max})}$. Normally,

FIGURE 2: Power coefficient C_p versus TSR λ .

FIGURE 3: Power-wind speed characteristics.

a variable speed wind turbine follows the $C_{p(\text{max})}$ to capture the maximum power up to the rated speed by varying the rotor speed to keep the system at λ_{opt} , then operates at the rated power with power control during the periods of high wind by the active control of the blade pitch angle or the passive regulation based on aerodynamic stall. A typical power-wind speed curve is shown in Figure 3.

2.2. System description

The underlying hybrid wind-diesel-storage system is illustrated in Figure 4. The hybrid generation system is composed of a wind turbine coupled with a synchronous generator, a diesel-induction generator, and an energy storage system. In the given system, the wind turbine drives the synchronous generator that operates in parallel with the storage battery system. When the wind generator alone provides sufficient power for the load, the diesel engine is disconnected from the induction generator. The PEI connecting the load to the main bus is used to fit the frequency of the power supplying the load as well as the voltage.

The dynamics of the system can be characterized by the following equations [2]:

$$\dot{x} = Ax(t) + Bu(t), \quad y = Cx(t), \quad (6)$$

FIGURE 4: Structural diagram of hybrid wind-diesel-storage system.

FIGURE 5: Membership functions of states.

where

$$x(t) = [V_b \ \omega_s]^T, \quad u(t) = [E_{fd} \ I_{ref}]^T, \quad (7)$$

$$A = \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \frac{L_f}{\tau'_{do}\omega_s L_{md}} & \frac{L_f}{\tau'_{do} L_{md}\omega_s} (L_d i_{sd} - (r_{aisq}/\omega_s)) \\ \frac{P_{ind} - P_{ind}}{J_s \omega_s V_b} & -\frac{D_s}{J_s} \end{bmatrix},$$

$$B = \begin{bmatrix} 1 & -\frac{V_c}{J_s \omega_s} \\ 0 & -\frac{V_c}{J_s \omega_s} \end{bmatrix}, \quad C = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix},$$

where V_c is the AC side line-to-line voltage, E_{fd} is the SG field voltage, ω_s is the bus frequency (or angular speed of SG), J_s and D_s are the inertia and frictional damping of SG, i_{sd} and i_{sq} are the direct and quadrature current components of SG, L_d and L_f are the stator d -axis and rotor inductance of SG, L_{md} is the d -axis field mutual inductance, τ'_{do} is the transient open circuit time constant,

FIGURE 6: Wind speed.

FIGURE 7: Rotor speed tracking.

r_a is the rotor resistance of SG, P_{ind} is the power of the induction generator, P_{load} is the power of the load, I_{ref} is the direct current set point, and V_b is the bus voltage. Equation (6) indicates that the model is the linear form for fixed matrices A , B , and C . However, matrices A and B are not fixed, but change as functions of state variables, thus making the model nonlinear. Also, this model is only used as a tool for controller design purposes. The used system parameters are shown in Table 1 [13–15].

3. THE PROPOSED FLME CONTROLLER

3.1. Takagi-sugeno's fuzzy plant model

The Takagi-Sugeno fuzzy model represents a nonlinear system by partitioning the system into subsystems and then combining them with linguistic rules. In this paper, three linear subsystems are considered for the nonlinear state-space models (6). The continuous fuzzy dynamic model, proposed by Takagi-Sugeno, is described by fuzzy IF-THEN rules, which represent local linear input-output relations of

FIGURE 8: Per unit wind turbine produced power.

FIGURE 10: Wind speed.

FIGURE 9: Bus voltage.

FIGURE 11: Rotor speed tracking.

nonlinear systems [16]. The i th rule of this fuzzy model is given by *Plant Rule*

$$\text{IF } q_1(x(t)) \text{ is } N_1^i \text{ AND } \dots \text{ AND } q_\psi(x(t)) \text{ is } N_\psi^i. \quad (8)$$

$$\text{Then } \dot{x}(t) = A_i x(t) + B_i u(t), \quad y = C_i x(t),$$

where N_Ω^i is a fuzzy set, $\Omega = 1, 2, \dots, \psi$, $i = 1, 2, \dots, p$, $x(t) \in R^{n \times 1}$ is the state vector, $u(t) \in R^{n \times 1}$ is the input vector, $A_i \in R^{n \times n}$ and $B_i \in R^{n \times m}$ are system matrices of appropriate dimensions, p is the number of IF-THEN rules ($p = 3$). $q_1(x(t)), \dots, q_\psi(x(t))$ are the premise variables. The plant dynamics are then described by

$$\dot{x}(t) = \sum_{i=1}^p h_i(x(t)) [A_i x(t) + B_i u(t)], \quad (9)$$

where

$$h_i(x(t)) = \frac{\Gamma_i(x(t))}{\sum_{i=1}^p \Gamma_i(x(t))}, \quad (10)$$

$$\Gamma_i(x(t)) = \prod_{\Omega=1}^{\psi} N_\Omega^i(x(t)), \quad h_i > 0, \quad \sum_{i=1}^p h_i(x(t)) = 1.$$

3.2. Fuzzy controller

Three controllers are designed for the three linear subsystems, and then the total control output is obtained by

defuzzification. A state feedback by linear matrix equalities (LMEs) is used to design a controller for each subsystem. The control is performed so that the power coefficient is maximized, thus the maximum power captured from the wind is obtained.

The j th rule of fuzzy controller is given by *Plant Rule*

$$\text{IF } f_1(x(t)) \text{ is } M_1^j \text{ AND } \dots \text{ AND } f_\psi(x(t)) \text{ is } M_\psi^j. \quad (11)$$

$$\text{Then } u(t) = G_j x(t) + r,$$

where M_ϕ^j is a fuzzy set $\phi = 1, 2, \dots, \psi$, $j = 1, 2, \dots, c$, r is the reference input, $f_1(x(t)), \dots, f_\psi(x(t))$ are the premise variables, c is the number of IF-THEN rules ($c = 3$), and G_j are local feedback gains. The inferred output of the fuzzy controller is given by

$$u(t) = \sum_{j=1}^c m_j(x(t)) [G_j x(t) + r], \quad (12)$$

FIGURE 12: Per-unit wind turbine produced power.

where

$$m_j(x(t)) = \frac{\omega_j(x(t))}{\sum_{j=1}^c \omega_j(x(t))}, \quad (13)$$

$$\omega_j(x(t)) = \prod_{\phi} M_{\phi}^j, \quad m_j > 0, \quad \sum_{j=1}^c m_j = 1.$$

3.3. Parallel design approach (PDA)

It allows the stability criterion to be satisfied more easily. It is used when the membership functions are known and the same rule antecedents of the TS fuzzy plant model are used in the fuzzy controller. Referring to (9) and (12), the fuzzy control system is given by

$$\dot{X}(t) = \sum_{i=1}^p \sum_{j=1}^p h_i(x(t)) h_j(x(t)) [H_{ij}X(t) + B_i r], \quad (14)$$

where $H_{ii} = A_i + BG_i$.

For each subspace, different model ($i = j = 1, 2, 3$), ($p = c = 1, 2, 3$) is applied. The degree of membership function for states $V_b \psi$ and ω_s is depicted in Figure 5. Each membership function also represents model uncertainty for each subsystem.

4. STABILITY AND ROBUSTNESS FOR THE PROPOSED ALGORITHM

A proof of the stability and robustness conditions for the plant dynamics described by (9) is shown in the appendix. The main result is summarized in Lemma 1.

Lemma 1. Under PDA, the fuzzy control system as given by (14) is stable if

$$\mu[TH_{ii}T^{-1}] \leq -\zeta, \quad (15)$$

where ζ is nonzero positive constant and T is a transformation matrix. The analysis given in the appendix indicates that $\|x(t)\|$ will go to its steady state faster if we use larger values of ζ . Calculation of G_j of the fuzzy controller that satisfies the

TABLE 1: System parameters.

Rated power	1 [MW]
Blade radius	37.38 [m]
Air density	0.55 [kg/m ³]
Rated wind speed	12.35 [m/s]
Cut-in speed	4 [m/s]
Cut-out speed	25 [m/s]
Blade pitch angle	0°
Rated line ac voltage	230 [V]
AC rated current	138 [A]
DC rated current	239 [A]
Rated load power	40 [kW]
The inertia of SG	1.11 [kg m ²]
Rated power of IG	55 [kW]
The inertia of the IG	1.40 [kg m ²]
Torsional damping	0.557 [Nm/rad]
Rotor resistance of SG	0.96 [Ω]
Stator d -axis inductance of SG	2.03 [mH]
Rotor inductance of SG	2.07 [mH]
d -axis field mutual inductance	1.704 [mH]
The transient open circuit time constant	2.16 [ms]

FIGURE 13: Bus voltage.

stability and robustness conditions is formulated as an LME problem.

$$\text{If } T^T = T, P = TT,$$

$$G_j = -RB_j^T P, \quad \forall j, \quad (16)$$

$P > 0$, $R \in \kappa^{m \times m}$ are symmetric positive definite matrices. The transformation matrix (T) should be found in such a way that the uncertainty free system is stable [17]. Using (14),

$$PH_{ii} + H_{ii}^T P < 0, \quad (17)$$

$$PA_i + A_i^T P - 2xPBRB^T P = -\sigma I \quad P > 0, \quad \forall i,$$

where σ is robustness index.

FIGURE 14: Wind speed.

FIGURE 16: Per-unit wind turbine produced power.

FIGURE 15: Rotor speed tracking.

FIGURE 17: Bus voltage.

5. SIMULATION RESULTS

The proposed controller for the HWDSS is tested for many cases of wind speed variations. Four wind speed signals are tested in this section to prove the effectiveness of the proposed algorithm.

5.1. Random variation of wind speed signal

In this case, the wind speed signal is considered as a random wave as shown in Figure 6. The rotor speed to capture the maximum power from the wind turbine is shown in Figure 7 (solid line). It is clear that the dotted curve in Figure 7 which represents the actual rotor speed coincides with the solid curve. As the wind speed ranges between the cut-in and rated speed of the wind turbine, the produced power curve takes almost the wind speed curve as shown in Figure 8. The power generated at wind speed of 12 m/s is 0.75 Mw. Comparing this value with that obtained using PI controller [14] which is 0.4 Mw, it is clear that a 45% increase is obtained in the maximum value. Figure 9 shows that the voltage profile is nearly constant and that the voltage ripple is reduced to 90% compared with the adaptive fuzzy logic control [15].

5.2. Sinusoidal variation of wind speed signal

In this case, the wind speed signal is considered as a sine wave as shown in Figure 10. The rotor speed to capture the maximum power from the wind turbine is shown in Figure 11 (solid line). It is clear that the dotted curve in Figure 11 which represents the actual rotor speed coincides with the solid curve. As the wind speed ranges between the cut-in and rated speed of the wind turbine, the produced power curve takes almost the wind speed curve as shown in Figure 12. Figure 13 shows that the voltage profile is nearly constant and the voltage ripple is reduced to 90% compared with [15].

5.3. Step change of wind speed

In this case, a big step change of wind speed is tested as shown in Figure 14. Figure 15 shows the rotor speed while the dotted line in this figure represents the actual rotor speed that the controller is able to capture. It is clear from this figure that the controller effectively tracks the rotor speeds. Figure 16 indicates the output power of the wind turbine as a per-unit value, it is clear that when the wind speed is below the cut-in speed or over cut-off speed, the power reaches zero. Figure 17 indicates that the bus voltage is nearly constant.

FIGURE 18: Wind speed.

FIGURE 20: Per-unit wind turbine produced power.

FIGURE 19: Rotor speed tracking.

FIGURE 21: Bus voltage.

5.4. Sinusoidal variation of wind speed signal

This case is another sinusoidal wind speed signal but its minimum values is 8 m/s and its maximum value is 26 m/s which is bigger than the cut-off speed of the turbine as shown in Figure 18. Figure 19 indicates the effectiveness of the algorithm which tracks the rotor speed for different wind speed, while Figure 20 shows the output power from the wind turbine, which indicates that when the speed become over the cut-off speed, the power equals zero. Figure 21 indicates that the bus voltage is nearly constant and voltage ripple reduced to 90% compared with [15], since the ripple voltage reduced to 0.045 V with the proposed algorithm, but in [15] the ripple voltage is 0.4 V.

Comparing the results of the proposed algorithm with that given in [14, 15], it could be seen that the proposed controller has the following advantages.

- (i) It can control the plant well over a wide range of wind speeds.
- (ii) The generated power is increased up to 45% compared with [14].

(iii) The algorithm is more robust in the presence of high nonlinearity.

(iv) Bus voltage is nearly constant and voltage ripple is reduced to 90% compared with [15].

6. CONCLUSION

This paper presents a hybrid power system consisted of a wind turbine, a diesel generation unit, and energy storage devices. Both the wind power generator and the SG operate at variable speeds so as to maximize the wind energy capture as a force source and minimize the diesel fuel consumption for economic purpose. Both types of generation units are connected to the ac load system through PEI to stabilize the system frequency. The control is performed so that the power coefficient is maximized. The operating principles have been discussed and the simulation model of the systems has been developed. The proposed algorithm utilizing FLME is simple and leads to robust control performance. Simulation results have confirmed that maximum power conversion efficiency obtained increases to the order of 45% compared with previous methods and voltage ripple reduced to 90%. Maximum power control of hybrid wind power generation with storage battery is achieved.

APPENDIX

Proof of the stability and robustness conditions

Consider the Taylor series [17]

$$x(t + \Delta t) = x(t) + \dot{x}(t)\Delta t + \Phi(\Delta t), \quad (\text{A.1})$$

where $\Phi(\Delta t) = x(t + \Delta t) - x(t) - \dot{x}(t)\Delta t$ is the error term and $\Delta t > 0$ is

$$\lim_{\Delta t \rightarrow 0^+} \frac{\Phi(\Delta t)}{\Delta t} = 0. \quad (\text{A.2})$$

From (14) and (A.1) and multiplying a transformation matrix $T \in R^{n \times n}$ of rank n to both sides and taking norm on both sides of the above equation, we have

$$\begin{aligned} & \|T(x(t + \Delta t))\| \\ & \leq \left\| \sum_{i=1}^p \sum_{j=1}^c h_i(x(t)) m_j(x(t)) (I + TH_{ij} T^{-1} \Delta t) \right\| \|Tx(t)\| \\ & \quad + \left\| \sum_{i=1}^p \sum_{j=1}^c h_i(x(t)) m_j(x(t)) [TBr] \Delta t \right\| + \|T\Phi(\Delta t)\|, \end{aligned} \quad (\text{A.3})$$

where $\|\cdot\|$ denotes the L_2 norm for vectors and L_2 induced norm for matrices, from (A.3),

$$\begin{aligned} & \lim_{\Delta t \rightarrow 0^+} \frac{\|T(x(t + \Delta t))\| - \|Tx(t)\|}{\Delta t} \\ & \leq \lim_{\Delta t \rightarrow 0^+} \frac{\{\mathcal{A}(\|I + TH_{ij} T^{-1} \Delta t\| - 1) \|Tx(t)\|\}}{\Delta t} \\ & \quad + \lim_{\Delta t \rightarrow 0^+} \frac{\{\|\mathcal{A}[TBr] \Delta t\| + \|T\Phi(\Delta t)\|\}}{\Delta t}, \end{aligned} \quad (\text{A.4})$$

where $\mathcal{A}$ denotes $\sum_{i=1}^p \sum_{j=1}^c h_i(x(t)) m_j(x(t))$. From (A.2) and (A.4),

$$\begin{aligned} \frac{d\|Tx(t)\|}{dt} & \leq \sum_{i=1}^p \sum_{j=1}^c h_i(x(t)) m_j(x(t)) \mu[TH_{ij} T^{-1}] \|Tx(t)\| \\ & \quad + \left\| \sum_{i=1}^p \sum_{j=1}^c h_i(x(t)) m_j(x(t)) [TBr] \right\|, \end{aligned} \quad (\text{A.5})$$

where

$$\begin{aligned} \mu[TH_{ij} T^{-1}] & = \lim_{\Delta t \rightarrow 0^+} \frac{\|I + TH_{ij} T^{-1} \Delta t\| - 1}{\Delta t} \\ & = \eta_{\max} \left(\frac{TH_{ij} T^{-1} + (TH_{ij} T^{-1})^*}{2} \right), \end{aligned} \quad (\text{A.6})$$

where $\eta_{\max}(\cdot)$ is the largest eigenvalue, $*$ is the conjugate transpose, from (A.5),

$$\begin{aligned} \frac{d\|Tx(t)\|}{dt} & \leq \sum_{i=1}^p \sum_{j=1}^c h_i(x(t)) m_j(x(t)) (\mu[TH_{ij} T^{-1}]) \|Tx(t)\| \\ & \quad + \left\| \sum_{i=1}^p \sum_{j=1}^c h_i(x(t)) m_j(x(t)) [TBr] \right\|. \end{aligned} \quad (\text{A.7})$$

Let

$$\mu[TH_{ii} T^{-1}] \leq -\zeta, \quad \forall i, \quad (\text{A.8})$$

from (A.7) and (A.8),

$$\frac{d}{dt} (\|Tx(t)\| e^{\zeta(t-t_0)}) \leq \sum_{i=1}^p \sum_{j=1}^c h_i(x(t)) m_j(x(t)) \| [TBr] \| e^{\zeta(t-t_0)}, \quad (\text{A.9})$$

where $t_0 < t$ is an arbitrary initial time, based on (A.9) there are two cases to investigate the system behavior.

$$(1) \quad r = 0, \quad (2) \quad r \neq 0. \quad (\text{A.10})$$

If condition (A.8) is satisfied, the closed loop system (14) is stable, and $\|x(t)\| \rightarrow 0$, as $t \rightarrow \infty$.

Proof (1) ($r = 0$)

$$\begin{aligned} \frac{d}{dt} (\|Tx(t)\| e^{\xi(t-t_0)}) & \leq 0 \\ \|Tx(t)\| & \leq \|Tx(t_0)\| e^{-\xi(t-t_0)}. \end{aligned} \quad (\text{A.11})$$

Since ξ is a positive value, $\|x(t)\| \rightarrow 0$ as $t \rightarrow \infty$

Proof (2) ($r \neq 0$)

From (A.9),

$$(\|Tx(t)\| e^{\xi(t-t_0)}) \leq \|Tx(t_0)\| + \|T \overset{\Delta}{B} r\| \int_{t_0}^t e^{\xi(\tau-t_0)} d\tau, \quad (\text{A.12})$$

where

$$\|T \overset{\Delta}{B} r\| \leq \max_i \|TBr\|_{\max} \leq \|TBr\|, \quad (\text{A.13})$$

then

$$\|Tx(t)\| \leq \|Tx(t_0)\| e^{-\xi(t-t_0)} + \frac{\|T \overset{\Delta}{B} r\|}{\xi} (1 - e^{-\xi(t-t_0)}). \quad (\text{A.14})$$

Since the right-hand side of (A.14) is finite if r is bounded, the system states (14) are also bounded.

The above analysis gives an upper bound of $\|Tx(t)\|$ under the two different considered cases. The result is given

by (A.11) and (A.14). Similarly, a lower bound of $\|x(t)\|$ can be obtained by following the same analysis procedure with

$$x(t - \Delta t) = x(t) - \dot{x}(t)\Delta t + \phi(\Delta t), \quad (\text{A.15})$$

where $\phi(\Delta t) = x(t - \Delta t) - x(t) + \dot{x}(t)\Delta t$ is the error term and $\Delta t > 0$ and ϑ is governed by the following

Let

$$\mu[-TH_{ii}T^{-1}] \leq \vartheta, \quad \forall i, \quad (\text{A.16})$$

since ϑ is a positive value.

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