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# Wireless Event-driven Networked Predictive Control Over Internet

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***Abstract*—In networked control systems, the network uncertainties can degrade the control performance and even result in instability, especially for the Internet-based control system with wireless communication in which the transmission delay could be many times of the sampling period of control systems. NPC (Networked Predictive Control) is an active method to compensate for the effects of network uncertainty. However, control systems need to make long time prediction due to the long transmission distance. Without an accurate mathematical model, the control performance can not be guaranteed. In order to address this problem, a new NPC scheme designed for wireless NPC with long time delay is introduced in this paper. It uses the information of the previous prediction errors to correct the future predictions. A correction algorithm is designed to reduce the predictive errors. To validate the new control schemes, both simulations and experiments have been conducted. The results show that even with "not so" accurate mathematical models, the new schemes can still maintain good control performance in Internet-based NPC with wireless communication.**

## I. INTRODUCTION

In the last decade, network technology has been developed rapidly. More and more network technologies have been applied to control systems [1-8]. With the emergence of high speed network technology, a cluster of devices can be linked together economically to form distributed networks. Due to the use of network, especially Internet, the complexity and costs of distributed control systems are reduced greatly and the maintenance of the systems becomes much easier [9-10]. Control systems with devices from different locations can be integrated together using the existing Internet infrastructure which provides a cheap solution for remote data transmission and data exchanges. Internet based control systems allow remote monitoring and adjustment of plants over the Internet around world.

Recently, wireless networked control systems become a popular research area in control theory and industrial applications. Without requiring network cables, devices can be connected into networks using wireless communication, which is promising for remote industrial controls and factory automations. For example, distributed power generation and microgrids [11-12] play more and more important roles in new energy research area. In these systems, unlike big power stations in conventional grids, small and medium size power generation units are located diversely. Wireless wide area networks (WWAN) such as WiMAX, CDMA, GPRS allow rapid development, flexible installation, fully mobile operation which are ideally suitable for these distributed industrial applications.

The technologies of the Internet of Things are developed rapidly in recent years. The research of NCSs is a key part in Internet of Things. In the future Internet of Things, diversely located objects and devices are connected to Internet using both wired and wireless communication. Information such as control commands and measurement data is transmitted through networks.

In wireless networks, the random time delay and data dropouts induced by the data transmission and traffic congestion are even worse than wired ones. These network uncertainties disturb the control performance and even result in instability. Therefore, a wireless networked predictive control systems are studied in this paper. The networked predictive control consists of the control prediction generator and network delay compensator [13-18]. The control predictive generator provides a sequence of future control predictions and the network delay pick up the appropriate control signal from the sequence to eliminate the effects of network transmission delay. Because of the long time delay in wireless networks, the model based prediction may not be accurate due to the model uncertainties. To tackle this problem, NPC is modified and the prediction errors are corrected using the previous predictive errors in this paper.

## II. DESIGN OF WIRELESS WIDE AREA NPC

### A. Structure of Wireless Wide Area NPC

Fig. 1 is the structure of the proposed Internet-based NPC with wireless communication. It can be separated into two sides: the controller side and the plant side. Both sides are connected to the Internet using wireless connections.

Most of the control calculations are implemented on the controller side. It could be a powerful mainframe computer which has the capability to serve many control loops. The tasks on the plant side are simple. This part can be achieved using a low-cost solution with limited computing capability such as MCU or ARM embedded control board. The diagram of this kind of system is shown in Fig. 2.

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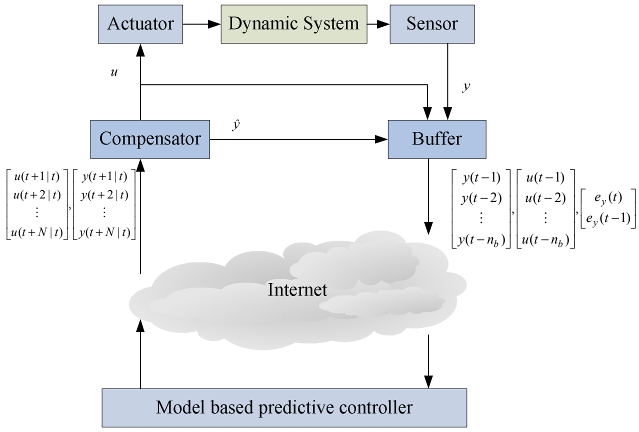

Fig. 1. Structure of Internet-based NPC

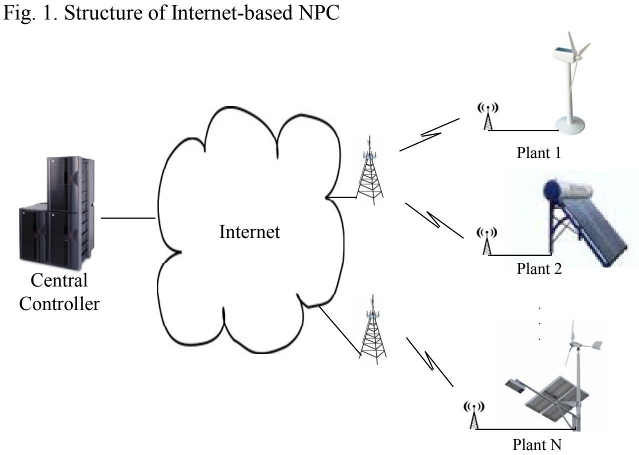

Fig. 2. Diagram of wireless wide area networked control systems

### B. Plant Model and Local Control

It is considered that the dynamic process can be described by the autoregressive moving average model as

$$A(z^{-1})y(t) = B(z^{-1})u(t) \tag{1}$$

where $u(t)$ and $y(t)$ are the open loop input and output of the plant. $A(z^{-1}) \in \Re[z^{-1}, n_a]$ with $a_0 = 1$ and $B(z^{-1}) \in \Re[z^{-1}, n_b]$ with $b_0 = 0$ are the system polynomials.

For the local control without network transmission delay and data dropout, a controller is designed as

$$C(z^{-1})u(t) = D(z^{-1})e(t) \tag{2}$$

where polynomial $C(z^{-1}) \in \Re[z^{-1}, n_c]$ and $c_0 = 0$ and $D(z^{-1}) \in \Re[z^{-1}, n_d]$ and

$$e(t) = r(t) - y(t) \tag{3}$$

where $r(t)$ is the reference input and $y(t)$ is the system output.

### C. Start of a Control Cycle

In this method, a control cycle is initiated by the plant side rather than controller side, which is similar to the method in [14-15]. At each sampling period, the previous plant output sequence $y(t)$, previous control sequence $u(t)$, previous prediction error sequence $e_y(t)$ and a timestamp $t$ which indicates the current plant side time are packed together and sent out in a single packet to the controller side, which initiates a control cycle. The three sequences in the packet are

$$\begin{bmatrix} y(t-1) \\ y(t-2) \\ \vdots \\ y(t-n_l) \end{bmatrix}, \begin{bmatrix} u(t-1) \\ u(t-2) \\ \vdots \\ u(t-n_l) \end{bmatrix}, \begin{bmatrix} e_y(t) \\ e_y(t-1) \end{bmatrix} \tag{4}$$

where $n_l$=max($n_a$, $n_b$, $n_c$, $n_d$).

### D. Design of Controller

The controller is event driven rather than time driven. It is only when the plant side receives the data from the feedback channel does the controller generates control predictions. Without receiving new data from the plant side, it is in an "idle state."

It is assumed that at a time instance, the controller receives a packet from the plant side. Inside the packet, the sequence of plant outputs $y$ (including $y(t), y(t-1), \cdots, y(t-n_a)$ ), previous control sequence $u$ (including $u(t), u(t-1), \cdots, u(t-n_a)$ ) and a time stamp which indicates the time at which the packet is packed and sent out. Because the controller is event-driven and the time delay compensation is based on the round trip time delay measurement, it is noted that variable $t$ indicates the plant side time instance at which the packet is packed and sent out. It has nothing to do with the time instance at which the controller receives the packet. Using the round trip delay prediction, the future control sequence can be generated using the algorithm described below without knowing any information about the controller time at all.

For the sake of simplicity of analysis, it is assumed that the maximum time delay is bounded within $N$ steps. The following defines the operation on the predictions:

$$x(t+i \mid t) = q^{-1}x(t+i+1 \mid t) \quad \text{for } i = 0,1,\cdots \tag{5}$$

$$x(t-1) = q^{-1}x(t \mid t) \tag{6}$$

$$x(t-i-1) = q^{-1}x(t-i) \quad \text{for } i = 1,2,\cdots \tag{7}$$

where represents $x(.)$, $y(.)$ or $u(.)$, and $x(t+i|t)$ denotes the $i$-th step-ahead prediction of $x(t)$ based on the previous data up to time $t$.

Based on the data up to plant side time $t$, and the mathematical model of the plant, the one-step plant output prediction with model uncertainty correction can be calculated as

$$y(t+1 \mid t) = (1 - A(q^{-1}))y(t+1 \mid t) + B(q^{-1})u(t+1) + c_m \tag{8}$$

where $c_m$ is the correction factor, and $m$ is a counter on the controller side. $c_m$ is calculated using the information of previous prediction errors. The initial value of $m$ is 1 and each time the controller process a packet from the plant side, $m$ is increased by 1. The details of the calculation of $c_m$ are introduced in Section *2.E*.

The corresponding one-step prediction for control signal is

$$\begin{aligned} u(t+1\mid t) &= (1-C(q^{-1}))u(t+1\mid t) \\ &\quad + D(q^{-1})(r(t+1)-y(t+1\mid t)) \end{aligned} \tag{9}$$

Using the same method recursively, the future plant output predictions can be obtained based on the data calculated at the previous step.

$$y(t+k\mid t) = (1-A(q^{-1}))y(t+k\mid t) + B(q^{-1})u(t+k) + c_m \tag{10}$$

where $k$=1,2,…,$N$. The future control predictions are

$$\begin{aligned} u(t+k\mid t) &= (1-C(q^{-1}))u(t+k\mid t) \\ &\quad + D(q^{-1})(r(t+k)-y(t+k\mid t)) \end{aligned} \tag{11}$$

where $k$=1,2,…,$N$.

After $N$-step calculations, the future control sequence $U(t|t)$ and future plant output $Y(t|t)$ are obtained, where

$$U(t\mid t) = [u(t+1\mid t), u(t+2\mid t), \cdots, u(t+N\mid t)]^T \tag{12}$$

$$Y(t\mid t) = [y(t+1\mid t), y(t+2\mid t), \cdots, y(t+N\mid t)]^T \tag{13}$$

They are packed together with the timestamp $t$ and sent back to the plant side.

### *E. Calculation of Model Uncertainty Correction Factor*

In conventional NPC, if the mathematical model of the plant is not accurate enough, the control performance would be degraded greatly. It normally results in big static errors in some practical applications. Because the prediction is not accurate due to the model uncertainty, the controller "thought" the plant "had" reached the target position, so it stops the adjustment of the control signals. However, the plant doesn't follow the controller's prediction. Therefore, the static errors can not be corrected.

In order to cope with this problem, a model uncertainty correction algorithm is introduced in this paper. Based on the history prediction error sequence obtained from the plant side, the controller estimates the correction values for the future prediction. The estimation method is similar to the idea of PI control. Different from the PI control algorithm, the target of the method is to minimize the prediction errors rather than the control residuals. Therefore, the input is the prediction error rather than residual. The transfer function between prediction error $e_y(t)$ and the correction factor $c(t)$ is

$$c(t) = (k_p + k_i \frac{Tz^{-1}}{1-z^{-1}})e(t) = \frac{k_p - (k_p - k_i T)z^{-1}}{1-z^{-1}} e_y(t) \tag{14}$$

where the proportional gain $k_p$ and integral gain $k_i$ are the two parameters of the algorithm. Written in the incremental form, (14) is described as

$$\Delta c(t) = (1-z^{-1})c(t) = (k_p - (k_p - k_i T)z^{-1})e_y(t) \tag{15}$$

where $\Delta c(t)$ is the increase of $c(t)$.

With $\Delta c(t)$ calculated by using (15), the correction factor can be obtained,

$$c(t) = c(t-1) + \Delta c(t) \tag{16}$$

However, due to the stochastic nature of the Internet, the time delay is random. Therefore, the previous correction value $c(t\text{-}1)$ may not be available on the controller side. In order to simplify the analysis, the correction factor on the controller side $c_m$ is used to replace $c(t)$. Equation (16) can be rewritten as

$$c_m = c_{m-1} + \Delta c(t) \tag{17}$$

Combine with (16), the model uncertainty correction factor is obtained as

$$c_m = c_{m-1} + k_p e_y(t) - (k_p - k_i T)e_y(t-1) \tag{18}$$

With the previous correction factor $c_{m\text{-}1}$ and previous prediction errors $e_y(t)$ and $e_y(t\text{-}1)$ available, it is straightforward to calculate the current correction factor $c_m$.

If the transmission delay between the plant side and the controller is constant and there is no data dropout, $c_m$ is equal to the corresponding $c(t)$. However, in real network environment, the packet with plant side timestamp $t$ may arrive earlier than the packet with timestamp $t$-1. In that case, $c_m$ is not $c(t)$ but it is close to $c(t)$.

### *F. Design of Plant Side*

The plant side receives the packet from the controller, in which the timestamp $t$ the control sequence $U(t|t)$ and plant output sequence $Y(t|t)$ are packed. To calculate the RTT delay, the timestamp $t$ is picked up and compared with the current plant side time $t_c$

$$t_d = t_c - t \tag{19}$$

where $t_d$ is the RTT delay.

According to the time delay measurement $t_d$, the $t_d$-th value in the sequence $U(t|t)$ is picked up and applied to the plant actuator.

$$u(t+t_d) = u(t+t_d\mid t) \tag{20}$$

Similarly, the $t_d$-th value in sequence $Y(t|t)$ is also picked up as the predicted plant output.

$$\hat{y}(t+t_d) = y(t+t_d\mid t) \tag{21}$$

The predicted plant output $\hat{y}(t+t_d)$ is then compared the real plant output $y(t+t_d)$. The prediction error $e_y(t+t_d)$ is obtained as

$$e_y(t+t_d) = y(t+t_d) - \hat{y}(t+t_d) \tag{22}$$

The history data of the plant output $y$, control signal $u$ and prediction error $e_y$ are buffered as below

$$\begin{bmatrix} y(t_c-1) \\ y(t_c-2) \\ \vdots \\ y(t_c-n_b) \end{bmatrix}, \begin{bmatrix} u(t_c-1) \\ u(t_c-2) \\ \vdots \\ u(t_c-n_b) \end{bmatrix}, \begin{bmatrix} e_y(t_c) \\ e_y(t_c-1) \end{bmatrix} \tag{23}$$

These data are packed with the current time stamp $t_c$ and sent out the controller side, which initiates another control cycle.

## III. SIMULATION RESULTS

In order to validate the proposed method, a speed control system for a cooling fan is considered. The control system is designed to drive a fan to the target speed. The mathematical model is identified as

$$G(z^{-1}) = \frac{B(z^{-1})}{A(z^{-1})} = \frac{0.4662z^{-1} - 0.2843z^{-2}}{1 - 1.396z^{-1} + 0.4681z^{-2}} \tag{24}$$

where the input is the PWM duty cycle (ranged from 0 to 1) applied to the fan motor and the output is the voltage reading from the speed sensor (ranged is from 0v to 3v). The power supply voltage is 12v and the sampling time is 0.1s.

The following Proportional-integral Controller is designed when the network transmission delay and data dropout is not considered.

$$G_c(z^{-1}) = \frac{D(z^{-1})}{C(z^{-1})} = \frac{0.33 - 0.23z^{-1}}{1 - z^{-1}} \tag{25}$$

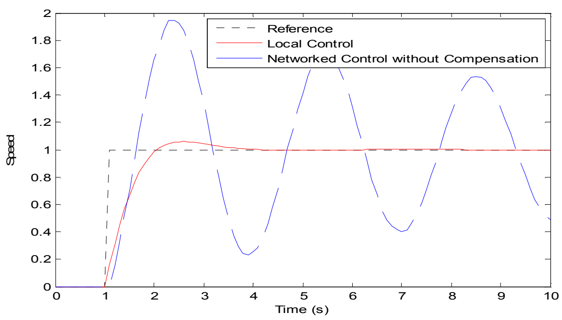


Fig. 3. Simulation of networked control without compensation

The unit step response of local control without communication delay and the networked control without any network uncertainty compensation are shown in Fig. 3. It indicates that the performance of local control is quite good. However, in the networked environment, the round trip time delay varies from 4 to 6 steps (0.4s to 0.6s), the control performance degrades greatly with huge overshoot and very long settling time, which is unacceptable in practical applications.

In order to compensate for the effects of the network uncertainty, the NPC methods proposed in this paper has been adopted. Fig. 4. shows the simulation results. For comparison, two simulations have been conducted. One is the conventional NPC, the other is the NPC with model uncertainty correction designed for NCS on WWANs. Because the mathematical model in simulation is perfectly accurate, the NPC methods can fully compensate for the effects of the network uncertainty. Therefore, there is no model prediction error at all. The results of local control and NPC with and without model uncertainty are exactly the same.

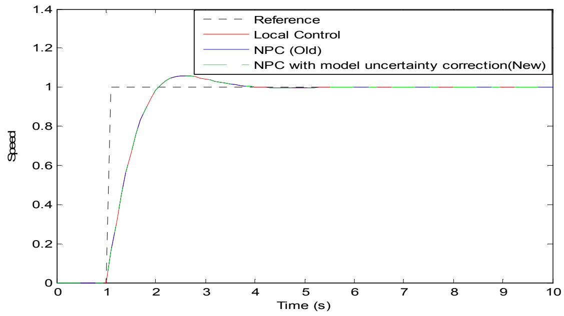


Fig. 4. Simulation of long –distance WNPC without model uncertainties

The mathematical model can not always reflect the dynamical behaviors of the real plant in practical applications. If the power supply voltage of the cooling fan changes from 12v to 10v, correspondingly, the mathematical model (24) will be change to

$$G(z^{-1}) = \frac{B(z^{-1})}{A(z^{-1})} = \frac{0.3885z^{-1} - 0.2369z^{-2}}{1 - 1.396z^{-1} + 0.4681z^{-2}} \tag{26}$$

If the NPC algorithm still uses the old mathematical model to calculate the predictive control sequence, the prediction errors will be inevitable, which results in big static error shown in Fig. 5. The target output should be 1 for the unit step response, but the real output finally settles down at 0.84. The control performance has been degraded greatly. It shows the prediction errors can result in big static error if the model is not accurate.

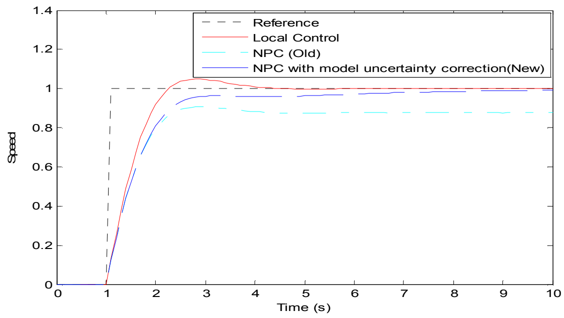


Fig. 5. Simulation of long-distance WNPC with model uncertainties

To cope with this problem, the model uncertainty compensation method proposed in this paper is applied. The previous prediction errors are used to correct the future predictions, and the "PI" correction algorithm tries decreasing the prediction errors as the control process going on. In this case, the both parameters $k_p$ and $k_i$ are 0.1. With the prediction becoming more accuracy, the plant output is quickly approaching the target, as shown in Fig. 5. The control performance has been improved significantly comparing with the conventional NPC.

## IV. Experimental Results

### A. Test Rig

A networked cooling fan speed control test rig has been setup to validate the effectiveness of the proposed control algorithm. The whole system consists of three parts: a PC based remote controller on the controller side and a networked module made by Chinese Academy of Sciences (CAS) and a cooling fan on the plant side. The PC and the networked module are connected via Internet and long-distance wireless network. The picture of the test rig is shown in Fig. 6. It can be seen that the cooling fan is placed on the left hand side and the networked module is on the right hand side.

The PC controller with the IP address 202.114.106.29 is located in the campus of Wuhan University. The networked module is connected to the GPRS wireless network provided by China Mobile. The PC controller works as the server side and the networked module works as the client side, so the communication channel between them can be established. The communication protocol adopted in the experiments is UDP. The diagram of the whole wireless networked control system is shown in Fig. 7.

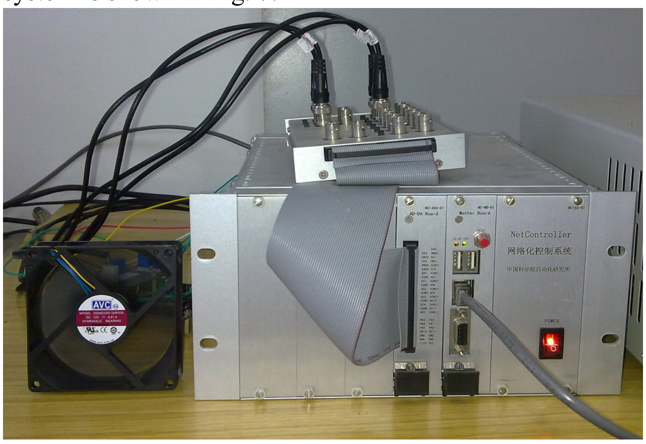


Fig. 6. Cooling fan control test rig

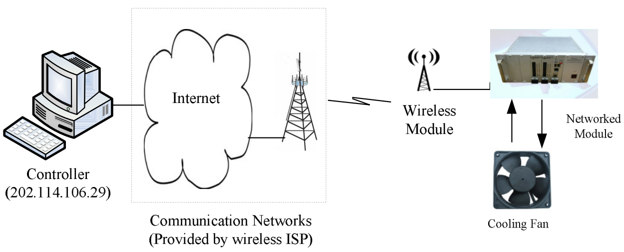


Fig. 7. Experimental diagram

### B. Experimental Results

The round trip time delays are measured during the experiments, which are shown in Fig. 8. It can be seen the round trip time delay varies from 4 to 7 steps (0.4 to 0.7s).

Fig 9. shows the experimental results of local control without network and networked control without time delay compensation. The target speed jumps from 1000RPM to 2200 RPM at 1s. It can be seen that in local control, the control performance is good, but network uncertainty degrades the control performance greatly.

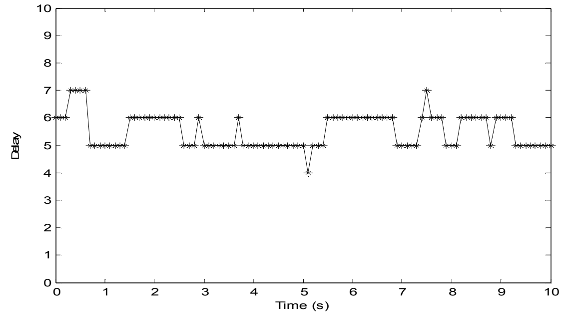


Fig. 8. Round trip time delay measurement

In order to compensate for the network uncertainty, NPC algorithm is adopted. The experiments of both the conventional NPC and NPC with model uncertainty correction proposed in this paper have been conducted. Because the mathematical model identified is quite accurate, both the old and new methods are able to maintain good control performance in the networked environment, which is shown in Fig. 10.

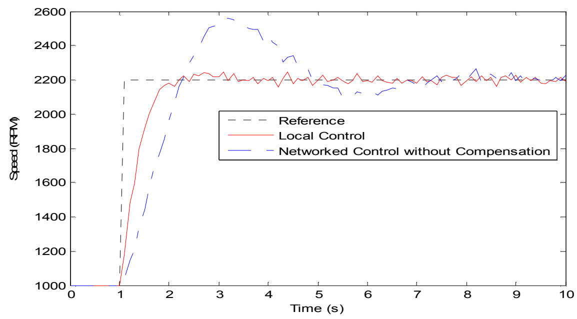


Fig. 9. Results of local control and networked control without delay compensation

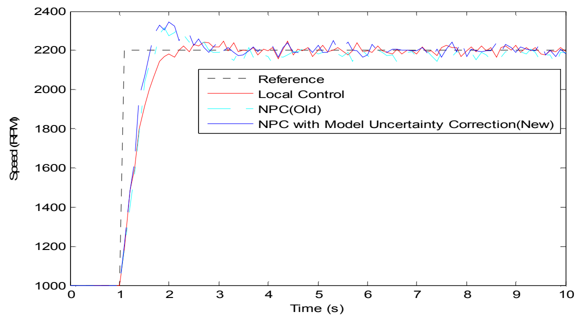


Fig. 10. Results of networked predictive control

When the working condition of the cooling fan is changed, the old method no longer works properly. For example, if the power supply voltage decreases from 12V to 10V, the old method results in a big static error, which is similar to the simulation results. As shown in Fig. 11, the static error is around 200RPM which is not acceptable in practical applications. However, if the new method proposed in this paper has been adopted, the result is very close to the local control even with a not so accurate mathematical model. Same with the simulations, both parameters $k_p$ and $k_i$ for the model correction algorithm are 0.1. The results prove that the proposed methods can compensate for the effects of both network uncertainties and model uncertainties in the NPC system effectively.

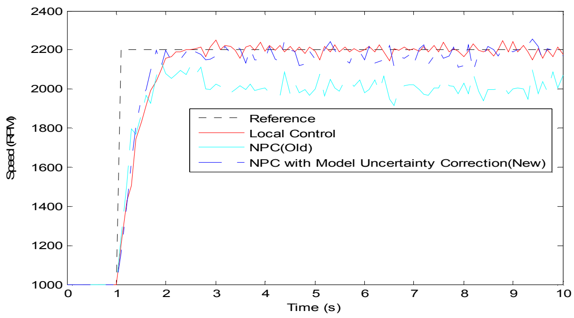


Fig. 11. Results of networked predictive control with 10v power supply

## V. Conclusions

In this paper, a new wireless Internet-based NPC with model uncertainty compensation has been introduced. It is designed for the networked control systems on with wireless communication. In these systems, because of the long transmission delay, the control systems have to cope with the cases that the time delay is many times of the sampling period. The NPC method is able to cope with that situation very well, but it requires very accurate mathematical models. With imperfect models, the control performances would be affected. In this paper, based on the NPC, a model uncertainty correction algorithm is designed to tackle this problem. In order to validate the proposed method, both simulations and experiments have been conducts. The results show that even not so accurate models, the new NPC scheme can still maintain good control performance in WWAN based networked control systems.

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