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Wireless Network Control System for Electro Stati Precipitator in Cement Plants

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Abstract

Wireless control networks (WCNs), based on distributed control systems of wireless sensor and actuator networks, integrate four technologies: control, computer network and wireless communications. Electrostatic precipitator (ESP) in cement plants reduces the emissions from rotary kiln by 99.8% approximately. It is an important thing to change the existing systems (wireline) to wireless because of dusty and hazardous environments. In this paper, we designed a wireless control system for ESP using Truetime 2 beta 6 simulator, depending on the mathematical model that have been built using identification toolbox of Matlab v7.1.1. We also study the effect ofusing wireless network on performance and stability of the closed loop control system. Simulation results of WCN for ESP show smooth operation with a little bit of perturbation between transient and steady state region.

Keywords: *Distributed Control Systems, IEEE802.15.4 protocol, Wireless Control Networks (WCNs), Wireless Sensor Networks.*

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1. Introduction

Wireless network control systems has very broad application prospects in the military, industry, urban management, environmental monitoring, and many other important areas which have potential practical values.The electrostatic precipitator (ESP) is a filtration device that removes fine particles, such as dust and smoke from the gas stream using the power of the electric charges and electrostatic principles [1].

The cement plants are considered as hazardous places that contain a lot of dangerous materials and emits a huge quantities of air pollutants such as Co$_x$, No$_x$, So$_x$, and dust. These materials cause a lot of diseases and affect the sanitary in general. There are many methods by which they treat these emissions, such as bag falters, wet scrubbers and dust filters (ESPs) as shown in Fig.1. The ESP efficiency is approximately 99.8% which is the best one between other types [2].

The motivation of this paper is to participate the efforts to refurbish the Iraqi cement plants because they have been installed since the eighties of the last century. Also it is required to build a new monitoring pollution system by environmental agencies. The use of the wireless sensor network and WCNs will serve to monitor and control the pollution inside and outside the plant.

The overall system of ESP consists of three main units: power supply, rappers, heaters. The mechanical iron structure is shown in Fig.2. The

ESP uses a technology that depends on a negative high voltage direct current power supply (-HVDCPS). The power supply consists of two main units: transformer-rectifier (TR) set and controller cabinet.

The TR set is used to step up the low voltage to high while the bridge rectifier is used to change the AC voltage to DC with negative polarity. The TR set also sends the current and the voltage values to the controller to make decisions about the control signal triggers which then sent to the actuator (thyristor unit). The control strategy is the well-known PID controller.

The -HVDCPS is used to supply the energy to form the corona which is used to charge the contents of the drain fluid from the smoke chamber of the rotary kiln.

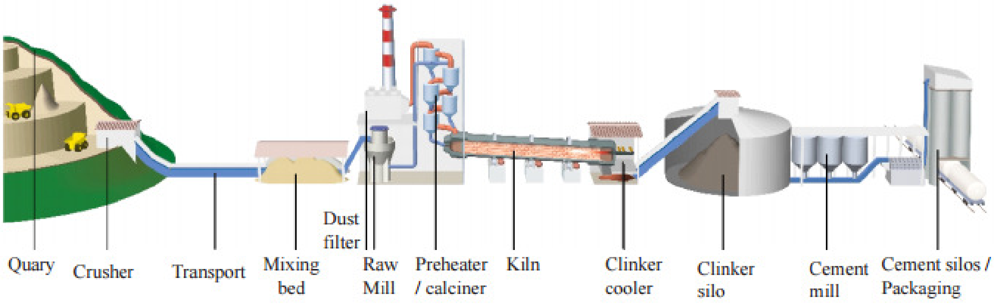

Fig. 1. General layout of the cement plant [1].

According to [3], The best way to understand the principle of operation is through the following activities:

1. Ionization: Charging of particles.
2. Migration: Transporting the charged particles to the collecting surfaces.
3. Collection: Precipitation of the charged particles on to the collecting surfaces.
4. Charge Dissipation: Neutralizing the charged particles on the collecting surfaces.
5. Particle Dislodging: Removing the particles from the collecting surface to the hopper.
6. Particle Removal: Conveying the particles from the hopper to a disposal point.

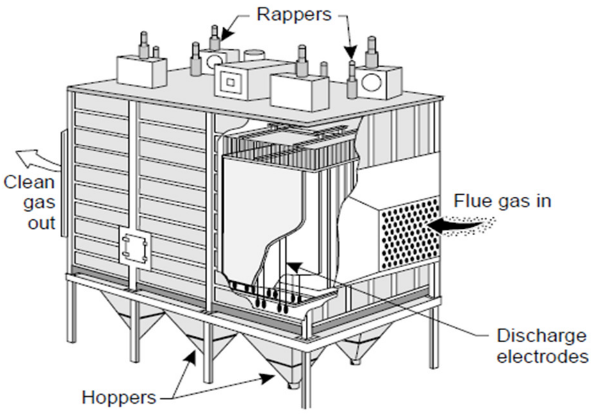

Fig.2. ESP mechanical structure [3].

2. Related Works

The following papers are surveyed to start the work of designing the WCN for ESP in cement plants:

Victor and Anders [4] proposed an expert system based fuzzy logic control system. They implemented an on-line control for ESP used in coal fired boilers.

Kawka et al. [5] analysed a simple communication system and the probability of a two-state Markov network model. The impact on the stability-performance of data loss and the wireless network system.

Sun and El-Farra [6] developed integrated model-based networked control and scheduling for plants with distributed control system having an interconnected unit framework. They used the resource constraints, to exchange the information by wireless sensor network (WSN).

Pajic et al. [7] presented a method of stabilizing the plant resources of a network having limited wireless node. The dedicated controller node, only to face the routing information in traditional networked control system, their approach treats the network itself as the controller.

Design and experimental validation of model predictive control (MPC) of a hybrid dynamical laboratory process with wireless sensors is presented by Bemporad et al. [8]. The laboratory process consists of four infrared lamps, controlled in pairs by two on/off switches, and of a transport belt, where moving parts equipped with wireless sensors.

Kurt huang [9] introduced investigations results and solutions for spark problems in ESPs. A spark control strategy was proposed to overcome this problem in dry process units.

Wei Zeng et al. [10] proposed a measurement architecture using distributed air sniffers, which provides convenient delay measurement, and requires no clock synchronization or instrumentation at the wireless sensor nodes. One challenge in deploying this architecture is how to place the sniffers for efficient network with delays in measurements.

Feng and Wencai [11] addressed time-variant and uncertain network delay in the wireless networked control systems (WNCS), as well as Smith predictor model where real model of the controlled plant might be mismatched.

3. Mathematical Model of ESP

The ESPs are distinguished for two different types of processes according to [12], these are wet and dry. The ESP is a large mechanical structure (as shown previously in Fig. 2) designed and manufactured in a special way. It consists mainly of discharge electrodes (some times called wires) and collecting plates. The plates are fixed in vertical parallel manner to forming gas passages of 30-40cm apart. Discharge electrodes are electrically isolated from plates and suspended in rows between the gas passages as shown in Fig.3. Both are fixed on mechanical frames and housed with an iron container. The hall structured is isolated from environment by glass wool.

A high voltage system provides corona power to discharge electrodes to generate the electrostatic field. The particulate entrained in the gas, is charged while passing through the charged space. The gas stream which contains dust, fumes and different gases receives a negative charge.The dust particles and the gases are then deposited on the plates; which is connected to the ground; forming a dust layer on the collecting plates inside the ESP. Periodic rapping separates the accumulated dust layer from electrodes and plates.

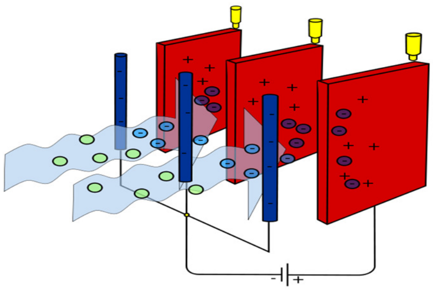

Fig. 3. ESP electrodes and plates structure.

The mathematical model of ESP is built depending on the input and the output data to the system. The input is the triggering gate to the thyristor unit while the output is the value of the DC voltage in Kilo Volt (Kv) from the - HVDCPS. The data is then fed to the identification toolbox of Matlab to find the contineous mathematical model.

According to [13], the electrical operating points of ESP are voltage (Kv) and current (mA). The value of corona depends on these electrical operating points. Therefore, the whole process of an ESP is mainly depends on the applied voltage and current. The relation to corona discharge is [2]

$$I = A*(V - Vc) \qquad \ldots (1)$$

Where A is a constant, V_C is the corona starting voltage, I is the electric current and V is the applied voltage. At an electrode separation ($d > 5$ cm), the starting voltage of negative corona is ($15*d$ Kv) where d is the separation between the electrodes in cm.

As demonstrated in [14], this corona production field is determined experimentally, then the relationship between electric field and corona effect is represented by

$$E_c = 3.126\times10^6 d_r [1+0.0301(\frac{d_r}{r_w})^{0.5}] \qquad \ldots(2)$$

Where E_c, d_r, r_w is the corona onset field at the wire surface (V/m), the relative gas density and the radius of the wire (m) respectively. Under the wire and direct plate, the maximum current density is given by

$$J = \mu\varepsilon_o (\frac{V^2}{l^3}) \qquad \ldots(3)$$

Where J, μ, V, l is maximum current density (A/m^2), the ion mobility (m^2 /Vs), applied voltage and the shortest distance from the wire to collecting plate respectively.

The value of the field when sparking is going to start is given by this relation

$$E_s = 6.3\times 10^5 \left(\frac{273}{T} P\right)^{1.65} \quad \ldots(4)$$

Where E_s, T, P is sparking field strength (V/m), absolute temperature (K), the gas pressure (atm) respectively and aESP collection efficiency (η) is

$$\eta = 1 - \exp(-\omega_e f) \quad \ldots(5)$$

And hence,

$$\eta = 1 - \exp(-\omega_e A/Q) \quad \ldots(6)$$

Where ω_e, f, A, Q is the migration velocity (m/s), the specific collection area, the area of the collecting electrode" (m^2), the gas flow rate (m^3/s) respectively.The following relationship with voltage and current effects on the collection efficiency can be formulated as

$$\eta = V^n I \quad \ldots(7)$$

This relation is useful for industrial applications of ESPs where n value is 2. Working at maximum available voltage and improve collection performance of ESP. The electric field due to positive line charge (E_1) and negative line charge (E_2) can make the total potential due to both values of the electric fields is [15]-[16]

$$E = (E_1 - E_2) \quad \ldots(8)$$

The electric field can be also given by

$$E = \frac{\rho * l}{2\pi\varepsilon_o} \ln\left(\frac{\sqrt{r_1^2 + b^2}}{\sqrt{r_1^2 + a^2}}\right) \quad \ldots(9)$$

Where ρ, ε_o, r_1, b and a are space permeability,permittivity, distance from point P depending on the geometrical plane shown in Fig. 4. The mirror image of both wire and infinite plane of coolecting electrode are used to analyse the electric field inside the ESP.

The four general steps in ESP process which depends on electric field charge are as follows [3]:

1. Locate the charge to collect particles.
2. Collector into a particle.
3. Collectors will neutralize the charge.
4. Remove the collected particle.

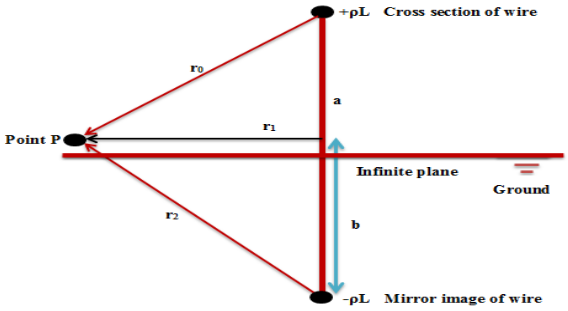

Fig. 4. Mirror image of a wire and infinite plane.

The transfer function of the ESP can be obtained as follows : to model the dynamics between input and those of the final output, an industrial experiment has been carried out. During stable operation of the plant, the inlet flow was reduced to 1% for one hour. The flow was then increased to 8%, and simultaneously, high frequency sampling started in the final product stream. Sampling lasted one hour. Thus, the step response of the system had been determined.

A first order dynamics with time delay is described by (10), the steady state minimum and maximum values of operation operating points, L and τ, the delay time and first order time constant, respectively. The unknown parameters had been identified using *Newton-Raphson* non-linear regression. The operating point was represented by Minimum and Maximum values as MinOP and MaxOP. Their values are the following: MinOP = 1 %, MaxOP = 4.5 %, L = 0.9 min, τ = 11.8 sec. The transfer function of the ESP can be obtained from the step response of the operation principle of the given system under two cases:

1. Normal operation as shown in Fig.5, where operation means the output voltage of the system.
2. System with decreased rise time as in Fig.6.

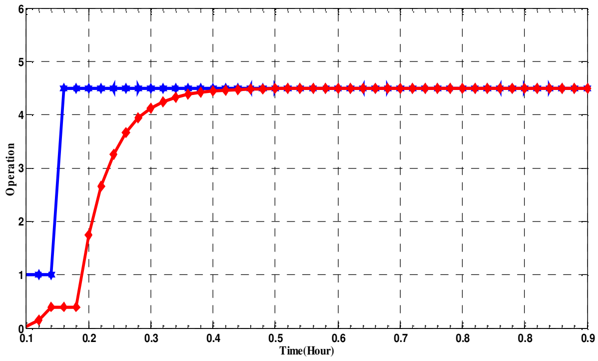

Fig. 5. The normal operation of the ESP cement plant.

Increasing the speed of operation will lead to increase the overshoot by approximately 5% which should be reduced during the controller design as shown in in Fig.6.

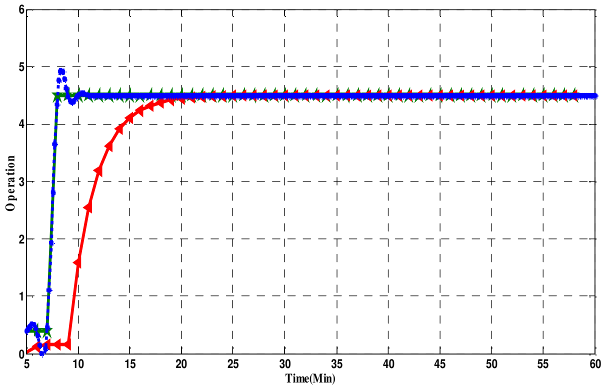

Fig. 6. Increasing the speed of response for operation.

The parameters of the process model (first-order plus dead-time) assumes [17], that is

$$G(s)=\frac{k}{\tau s+1}e^{-Ls} \quad \ldots(10)$$

$$G(s)=\frac{4.5}{11.8s+1}e^{-0.9s} \quad \ldots(11)$$

Where *k* is the process gain. The output equation for step input of the excitation amplitude approximation is given by

$$C(t)=kA\left\{1-\exp\left[-\frac{t-L}{\tau}\right]\right\}(t-L) \quad \ldots(12)$$

Rise in the index of the steady state level of the *KA*, which at the start with the slope of the initial rise of tangent 1:00 constant τ after the steady state level is reached to *C(t)* in eq.(12). Further, increase time constant of the exponential is one after reaching 63% of the final value. Therefore, parameter estimation based on step response of a process using a tangent line approximation.

Adjusting rules used to determine the value of PID controller parameters. The most popular tuning rules due to the *Ziegler-Nichols* first method. The PID controller design parameter for this operation k_p=3.147, T_i= 18, T_D= 4.5, hence the best parameters of PID controller transfer function needed for best operation is [17]

$$C_{PID}(s)=K_p(1+\frac{1}{T_i s}+T_D s) \quad \ldots(13)$$

$$C_{PID}(s)=3.147(1+\frac{1}{18s}+4.5s) \quad \ldots(14)$$

$$C_{PID}(s)=3.147\frac{81s^2+18s+1}{18s} \quad \ldots(15)$$

The closed-loop transfer function of over all system can be formulated as

$$T(s)=\frac{1147s^2+254.9s+14.16}{212.4s^2+18s}e^{-0.9s} \quad \ldots(16)$$

The Bode plot of the designed and simulated system is shown in Fig.7. As illustrated in this figure, the closed loop system is stable and the performance is acceptable.

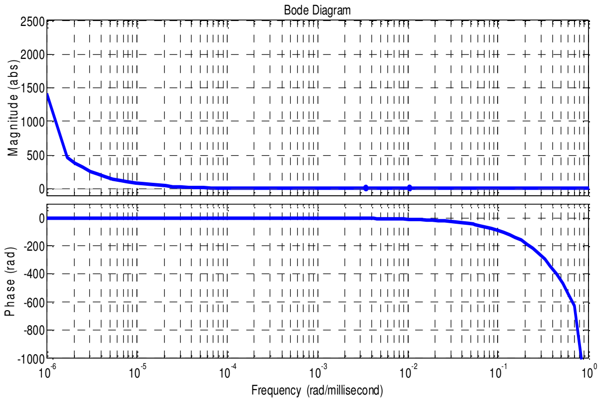

Fig. 7. Bode plot of the designed system.

4. Simulation Results of WCN

The IEEE 802.15 standard protocol scheme is to support the short distances. It offers two versions, high rate wireless personal area network WPAN (802.15.3) supports high data rate and quality-of-service (QoS) constraints for multimedia applications and suitable for ad-hoc mode . Low-cost, low power low rate WPAN (802.15.4) data transfer rate and a relaxed performance requirements are available in ad-hoc mode, supported data speed is 250, 40, and 20 Kbps [18].The schematic representation of the wireless closed-loop control system is shown in Fig. 8. The wireless network uses either Zigbee or Wi-Fi protocols in the simulation.

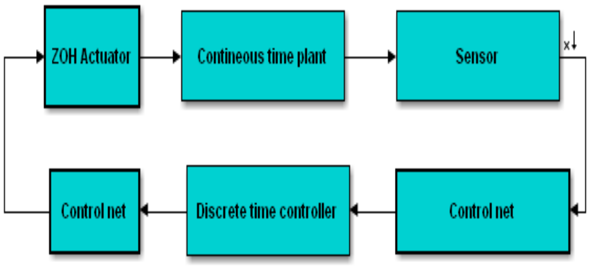

Fig. 8. Block diagram of WCN.

A wireless technology used for control systems often provides a range of meters to few kilometres. Automation of these applications depends on requirements of range, for example, plant compared with relatively low process automation requirements of wireless coverage [19].

Simulation results have been done using TrueTime 2 beta 6 simulator [20], [21] with the proposed block diagram as shown in Fig.9.

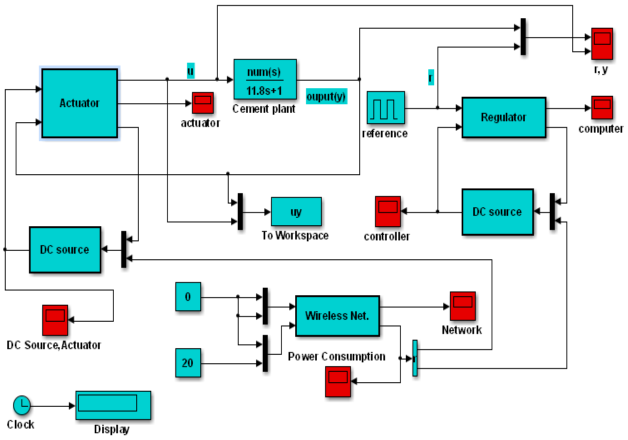

Fig. 9. The WCN scheme for ESP using Truetime.

The stability of the operation ensures the effectiveness of designing the controller as illustrated in Fig. 10.

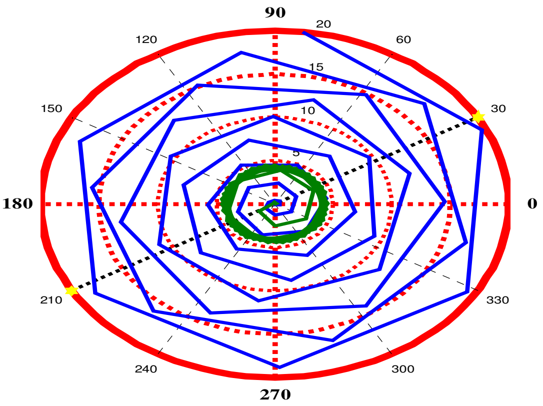

Fig.10. Stability analysis of the WCN system.

This figure can cope with the step response of the plant after 25 Min delay in the operation shown in Fig.11.

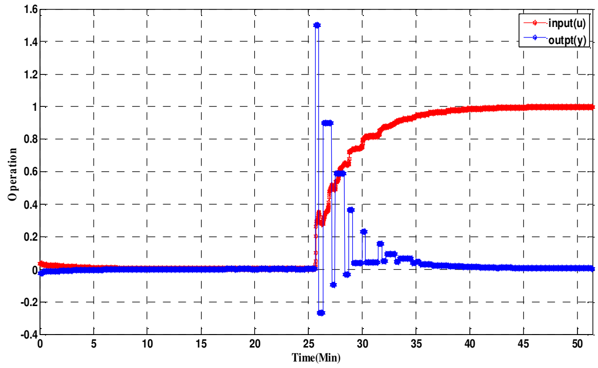

Fig. 11. Step response of the designed system.

The 85% duty cycle control is obtained with the operation of the system during the transient region (0-10) min as shown in Fig.12.

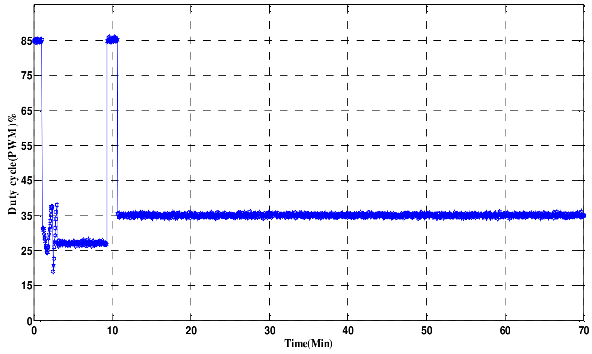

Fig. 12. Duty cycle control of ESP power supply.

During this period of operation the electrostatic voltage is increased from (0-24) Kv in the first 4 min and increased to the nominal 60 Kv after 10 min as shown in Fig.13. Both Fig.12. and Fig.13 shows smooth operation with a little bit of perturbation between transient and steady state region.

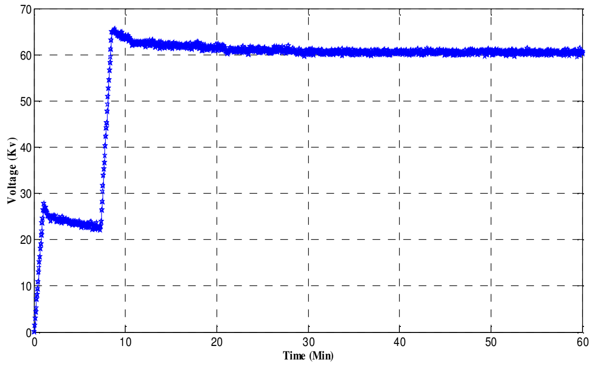

Fig. 13. Output data from the designed system.

5. Conclusions

This paper proposed a WCN for EPS in cement plants based on a robust wireless network. During the simulation with Truetime software, one can monitor and control the ESP activities wirelessly. Wireless closed-loop control systems are suited to the environment of our dusty weather which is always have a lot of pollutants, so maintenance is very difficult, wireless network is becoming a strong competition against the wire network. Wi-Fi and Zigbee protocols are good choice for short distances, low-rate and real-time control system, with its low-power, low-cost and low latency. The simulation shows that both of them can be used to form wireless network measurement and control system.

6. References

[1] Neundorfer company, “Electrostatic precipitatorknowledgebase lessons”, Retrieved October,2010. http://www.neundorfer.com/knowledge_base

[2] James H. Turner, Gray P. Grenier, William M. Vatuvak “Electrostatic precipitator” Chapter 6, December 1995.

[3] Parker K. “ Electrical operation of electrostatic precipitator” 2nd edition, 2007.

[4] Victor R. and anders ” On-line precipitator control with an expert system” in proceedings of ICESP, Korea, Sept., 1998.

[5] Kawka P. and Alleyne A. “Stability and feedback control of wireless networked systems ” American Control Conference, 2005.

[6] Sun Y. and El-Farra N. ”Resource aware quasi-decentralized control of networked process systems over wireless sensor networks” Chemical Engineering Science Vol. 69, Iss. , 2012.

[7] Pajic M., Sundaram S., Pappas G. and Mangharam R.” The wireless control network: A new approach for control over networks” IEEE Transactions on Automatic Control, Vol. 56, Iss. 10, 2011.

[8] Bemporad, Alberto Di Cairano, Stefano Henriksson, Erik Johansson, Karl Henrik ”Hybrid model predictive control based on wireless sensor feedback: An experimental study” International Journal of Robust and Nonlinear Control, Vol. 20, Iss. 2, 2010.

[9] Kurt Huang ” Spark and its effects on ESP ” In ICESPX, Australia, 2006.

[10] Wei Zeng, Xian Chen, Yoo-ah Kim and Zhengming Bu “Delay monitoring for wireless sensor networks: an architecture using air sniffers ” 2010.

[11] Feng Du and Wencai Du ” Fuzzy immune control and new Smith predictor for wireless networked control systems” Chinese Control and Decision Conference, 2009.

[12] Muhammad Ahmad and Jhanzeb. “Modeling and simulation of an electrostatic precipitator” Master thesis in Electrical Engineering, Linnaeus University School of Computer Science ,Physics and Mathematics, Sweden, 2011.

[13] Mizuno A. “Electrostatic precipitation” IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 7, No. 5, October, 2000.

[14] Sabah O. Hamad "Removal of cement dust from air by electrostatic precipitator", M. Sc. Thesis, university of Baghdad, Feb., 2005.

[15] David K. Cheng “Field and wave electromagnetics”, 2nd Edition, 1998.

[16] Astrom K. and Hagglund T. “Advanced PID controllers”, ISA Press, Research Triangle Park, 2006.

[17] Nastasi C., Pagano P., Marinoni M. and Lipari G. ” Model based real-time networked applications for wireless sensor networks” IEEE International Conference on Pervasive Computing and Communications, 2009.

[18] Pellegrini F., Miorandi D., Vitturi S., and Zanella A. "On the use of wireless networks at low level of factory automation systems" IEEE Transactions on Industrial Informatics, Vol.2, No.2, 2006.

[19] Henriksson D., Cervin A., Ohlin M. and Karl-Erik Årzén “TrueTime: real-time control system simulation with MATLAB/Simulink,” Department of automatic control, Lund University, 2006.

[20] Khalaf S. Gaied, Ziad H. Salih, Mehdi J. Marie, Dr.Ahmed R. Ajel,” Nonlinear Compensation Empyoing Matrix Converter with DTC Controller “ International Journal of Innovative Technology and Exploring Engineering (IJITEE) ISSN: 2278-3075, Volume-6 Issue-4, September 2016

منظومة شبكة السيطرة اللاسلكية للمرسبة الكهروستاتيكية المستخدمة في معامل السمنت

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الخلاصة

يعمل المرسب الكهروستايتيكي في مصانع السمنت على تقليل الانبعاثات من الفرن الدوار بنسبة ٩٩,٨ % تقريبا ومن المهم تغير انظمة السيطرة من الانظمة الحالية (السلكية) الى الشبكات اللاسلكية بسبب البيئة المتربة والخطرة.
في هذا البحث استخدمنا شبكات التحكم اللاسلكي والتي تسيطر على انظمة التحكم من خلال اجهزة الاستشعار اللاسلكية وشبكات المحركات عن طريق دمج عدة طرق تكنولوجية مثل السيطرة عن بعد واستخدام شبكة الكومبيوتر والاتصالات اللاسلكية, كما قمنا بتصميم النموذج الرياضي الخاص بهكذا عملية باستخدام البرنامج ماتلاب ...كما درسنا تاثير استخدام الشبكة اللاسلكية على اداء واستقرار نظام التحكم في الحلقة المغلقة. واظهرت النتائج من قبل المحاكاة سلاسة الاداء مع قليل من الاضطراب بين منطقة عابرة ومنطقة ثابتة.