

# Cybersecurity of Electric Vehicles Charging Systems By Using Residual Generation Technique

Mohammad Anvaripour, S.M.Mahdi Alavi\*, Martin J. Hayes, Mehrdad Saif

**Abstract**—With the rapid penetration of electric vehicles (EVs), the security of EV charging systems is becoming an important issue. This paper addresses cyber-physical protection of EV charging systems from the perspective of control theory. By using a residual generation technique, an attack-resilient EV charging system is designed, which detects false data injection under the denial of service (DOS) attack. The effectiveness of the proposed attack-resilient EV charging system is verified experimentally by using a hardware-in-the-loop testbed, developed by the IEEE 802.15.4 wireless sensors.

**Index Terms**—Cybersecurity, Cyber-physical Systems, Electric Vehicles, Charging Systems, Residual Generation.

## I. INTRODUCTION

In the near future, it is expected that a numerous number of electric vehicle (EV) chargers are installed all around the world, [1]. Approximately 80,000 home and public EV chargers were deployed in the United States in 2018 [2]. In China, this number has reached to around 808,000 in January 2019 [3]. Charging points are typically unmanned and partially located in remote areas, where cyber-physical protection is not guaranteed [4]. In order to address this issue, the European network of cyber security (ENCS), and the European distribution system operators' association for smart grids (E.DSO) aimed to standardize cyber-security requirements for EV charging systems [5].

Based on the classification in [5], an EV charging system, as shown in Figure 1, is composed of three main parts: charge points, charge point operators (CPOs), and distribution system operators (DSOs). The charge point is responsible for measurements from EV sensors, control of energy transfer from the charge point to EV, identifying and authorizing EV users via user authentication component, and enabling some remote capabilities such as adjustment of the charge point's maximum energy via the local controller component over a wide area network (WAN). CPO is mainly an interface between the charge point and DSO. Its role is to collect and process the data of charge points. CPO provides charge points with the information about energy limits based on the DSO data. DSO aims to forecast the available capacity of the grid, ensure power supply stability, etc.

EV charging system is susceptible to various cyber-attacks such as denial of service (DOS), and false data injection. In a DOS attack, sending and receiving the data is deteriorated

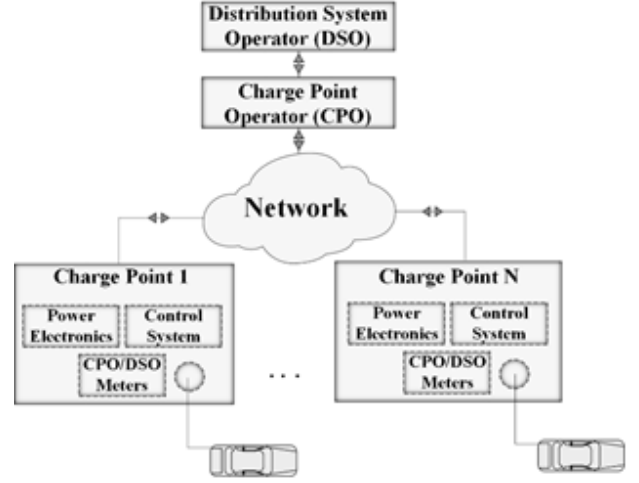


Fig. 1. Schematic of the Electric Vehicle (EV) charging system

by injection a large volume of data, which worsens data transfer time-delay and packet dropout and impairs the system performance [7], [8], [9], [10]. The false data injection aims to change the states', sensors' and actuators' data and deceive the control system and charge algorithms [7], [8], [9], [10], [11]. Design and implementation of attack-resilient cyber-physical systems have been an important research topic of control theory. Modeling of cyber-attacks has been addressed in [7], [8], [9], [10], [11], [12]. Detectability and identifiability of attacks have been discussed in [9]. Several detection and defense mechanisms have been proposed by using physical watermarking [8], observers [12], residual-based detectors [13], detection and identification filters [14].

This paper focuses on the cyber-physical protection of charge points and CPOs in EV charging systems. An attack-resilient EV charging system is designed by using an  $H_\infty$ -based residual generation technique, which detects false data injection under the DOS attack. The effectiveness of the proposed attack-resilient EV charging system is verified experimentally by using the IEEE 802.15.4 wireless sensor technology.

The rest of this paper is organized as follows. In section II, the cyber-physical problem in EV charging systems is stated and formulated. In section III, a method is proposed for the detection of false data injection under DOS. The results are shown and discussed in Section IV.

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## II. MODELING AND PROBLEM STATEMENT OF CYBER-PHYSICAL EV CHARGING SYSTEM

The operation of the cyber-physical EV charging system is as follows. Charge points collect and send the information of EV batteries to CPO through a WAN, in real-time. It is assumed that attackers inject a large volume of data, which causes random packet dropout and DOS. Simultaneously, a bias is occurred on the battery sensor, which could be due to either a cyber-attack or hardware/software malfunctions. CPO aims to detect and inform the charge point of the sensor fault in the present of packet dropout.

### A. Mathematical Modeling

In this work, state-of-charge (SOC) of the battery is used as the metric for the determination of the battery state. 0% SOC means battery is discharged, and 100% SOC means battery is fully charged. The first-order discrete-time Randles equivalent circuit model [15], [16] of the EV battery is used for the computation of its SOC as follows [17].

$$x_{(k+1)T_s} = Ax_{kT_s} + Mh_{kT_s} + B_1u_{kT_s} + B_2f_{kT_s} \quad (1)$$

$$y_{kT_s} = Cx_{kT_s} \quad (2)$$

with

$$A = \begin{bmatrix} 1 & 0 \\ 0 & 1 - \frac{T_s}{R_1C_1} \end{bmatrix}, \quad B_1 = \begin{bmatrix} T_s \\ T_s \end{bmatrix}, \\ B_2 = \begin{bmatrix} T_s/Q \\ T_s \end{bmatrix}, \quad C = \begin{bmatrix} 1 & 0 \end{bmatrix}.$$

In these equations,  $x = [SOC \ q]^T$  is the state vector given in terms of battery's SOC and the amount of charge  $q$ . The superscript T denotes the transpose operator.  $u$  is the battery current,  $y$  is the output of the system,  $Q$  denotes the charge capacity, and  $R_1$  and  $C_1$  are the Randles circuits parameters, representing electrochemical reactions inside the batteries. The values of these parameters are chosen within the typical range of batteries as follows:  $Q = 3921C$ ,  $R_1 = 0.01\Omega$ , and  $C_1 = 100F$ .  $A$ ,  $B_1$ ,  $B_2$ , and  $C$  are system matrices. The variable  $h$  accounts for the tolerance of measurements, which can be weighted by the gain of  $M$ . In this paper, 1% tolerance is considered on the SOC and  $q$  measurements, which is equivalent to  $M = 10^{-2}[1 \ 1]^T$ , and a zero-mean random function  $h$  is used with the variance of 0.01. The variable  $f$  represents the fault due to false data injection or hardware/software malfunctions.  $T_s$  is the sampling time, chosen 0.5s. For simplicity,  $T_s$  is omitted from the subscripts hereafter, i.e.,  $x(kT_s)$  is written as  $x_k$ .

The battery's SOC,  $y$ , is digitized and transmitted through WAN to CPO. CPO might not receive the data due to the DOS cyber-attack. The received data at CPO is then formulated as follows:

$$z_k = \alpha_k \text{round}(Cx_k) + D_1w_k \quad (3)$$

where  $\alpha_k$  is a random variable. It is 1 when  $y_k$  is successfully received to CPO, otherwise it is 0. It is assumed that the random variable  $\alpha_k$  is a Bernoulli distributed sequence with

$$\text{Prob}\{\alpha_k = 1\} = \mathbb{E}\{\alpha_k\} = \alpha \quad (4)$$

where  $\alpha$  is a positive real number within the interval  $(0, 1]$ , and  $\mathbb{E}\{\alpha_k\}$  stands for the expectation of the random variable  $\alpha_k$ . The packets are then dropped with an expectation of

$$\alpha' = 1 - \alpha. \quad (5)$$

This model of packet drop has widely been used in the networked control and fault diagnosis systems, see [18] and references therein. Due to the existence of the random variable  $\alpha$ , the cyber-physical EV charging system (1)-(4) is stochastic. The signal  $w_k$  represents the computational errors due to the rounding function. It is assumed that  $w_k$  is white Gaussian number sequence with zero mean and bounded standard deviation.

### B. Problem Statement

The problem is then stated as follows: *By using the received data  $z_k$ , CPO aims to detect  $f_k$  under random packet drop with the probability  $\alpha$ .*

### C. Assumptions

In this work, It is assumed that  $h_k$  is bounded with respect to  $x_k$ , i.e., there is a matrix  $H$  which yields

$$\|Mh_k\| \leq \|Hx_k\|. \quad (6)$$

It is also assumed that the battery model (1)-(2) is asymptotically mean-square stable.

*Definition 1:* (Definition 1 in [18]) The stochastic system (1)-(4) is said to be asymptotically mean-square stable if there exist real scalars  $0 < \phi \leq 1$ ,  $\mu_1 \geq 0$  and  $\mu_2 > 0$ , such that:

$$\mathbb{E}\{\|x_k\|^2\} \leq \mu_1 + \mu_2(1 - \phi)^k, \text{ for } k \in \mathbb{I}_0^+. \quad (7)$$

where,  $\mathbb{I}_0^+$  is the set of positive integers including zero, i.e.,  $\mathbb{I}_0^+ = \{0, 1, 2, 3, \dots\}$ . The notation  $\|x_k\|$  refers to the Euclidean vector norm of  $x_k$  which is  $\|x_k\| = (x_k^T x_k)^{1/2}$ .  $\square$

In fact, the embedded controller within the charge point is designed to make (1)-(4) asymptotically mean-square stable.

## III. DETECTION METHOD USING RESIDUAL GENERATION

In the proposed method, a residual filter is designed, which aims to track  $f_k$ . The residual filter takes feedback from  $z_k$  and generates a residual signal  $r_k$  as follows:

$$\hat{x}_{k+1} = A_f \hat{x}_k + B_f z_k \quad (8)$$

$$r_k = C_f \hat{x}_k \quad (9)$$

where,  $\hat{x}_k$  is the state vector of the residual filter. Let us assume that both  $x_k$  and  $\hat{x}_k$  belong to the same space  $\mathbb{R}^2$ .  $A_f$ ,  $B_f$ , and  $C_f$  are matrices of the residual filter. This paper presents a method for the design of these parameters.

In practice, it is sometimes desired to weight the variable  $f$  as follows [19]:

$$\bar{x}_{k+1} = A_t \bar{x}_k + B_t f_k \quad (10)$$

$$\bar{f}_k = C_t \bar{x}_k + D_t f_k \quad (11)$$

where  $\bar{x}_k$  is the state vector of the weighting function.  $A_t$ ,  $B_t$ ,  $C_t$ , and  $D_t$  are matrices of the weighting function, which

are determined prior to the design, based on the nature of the system and design requirements. It is simple to show that the combination of (1)-(11) results in the following compact state-space equations [18]:

$$\eta_{k+1} = \hat{A}\eta_k + (\alpha_k - \alpha)\tilde{A}\eta_k + \hat{M}\hat{h}_k + \hat{B}d_k + (\alpha_k - \alpha)\tilde{B}d_k \quad (12)$$

$$e_k = \hat{C}\eta_k + \hat{D}d_k \quad (13)$$

where,

$$e_k = r_k - \bar{f}_k, \quad (14)$$

and,

$$\eta_k = \begin{bmatrix} x_k \\ \hat{x}_k \\ \bar{x}_k \end{bmatrix}, \quad \hat{h}_k = \begin{bmatrix} h_k \\ 0 \\ 0 \end{bmatrix}, \quad d_k = \begin{bmatrix} w_k \\ v_k \\ f_k \end{bmatrix}, \quad (15)$$

$$\text{round}(Cx_k) - Cx_k = v_k, \quad \hat{A} = \begin{bmatrix} A & 0 & 0 \\ \alpha B_f C & A_f & 0 \\ 0 & 0 & A_t \end{bmatrix},$$

$$\tilde{A} = \begin{bmatrix} 0 & 0 & 0 \\ B_f C & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad \hat{M} = \begin{bmatrix} M \\ 0 \\ 0 \end{bmatrix},$$

$$\hat{B} = \begin{bmatrix} B_1 & 0 & B_2 \\ B_f D_1 & \alpha B_f & 0 \\ 0 & 0 & B_t \end{bmatrix}, \quad \tilde{B} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & B_f & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$\hat{C} = [0 \quad C_f \quad -C_t], \quad \hat{D} = [0 \quad 0 \quad -D_t].$$

By using the system dynamics (12)-(15), the cyber-security problem of the EV charging system is formulated as an  $H_\infty$  problem as follows:

*Problem Formulation in  $H_\infty$  framework:* Consider the cyber-physical EV charging system (12)-(15). Given a positive constant  $\gamma$ , find the parameters  $A_f$ ,  $B_f$ , and  $C_f$  such that the overall system is asymptotically mean-square stable for  $d_k = 0$ , and the residual filter satisfies

$$\mathbb{E}\{e_k^T e_k\} - \gamma^2 \mathbb{E}\{d_k^T d_k\} < 0 \quad (16)$$

for all admissible  $w_k$ ,  $v_k$  and  $f_k$ .

The parameters of the residual filter (8)-(9) are designed by using the following lemma.

*Lemma 1:* (Theorem 2 in [18]) By defining  $\alpha_1 = \mathbb{E}\{(\alpha_k - \alpha)^2\} = \alpha(1 - \alpha)$ , the cyber-physical EV charging system (12)-(15) is asymptotically mean-square stable for  $d_k = 0$ , and the residual filter satisfies (16) for a given  $\gamma > 0$ , if there exist  $X = X^T \succ 0$ ,  $Y = Y^T \succ 0$ ,  $P_t = P_t^T \succ 0$ ,  $\tau > 0$ ,  $\tilde{A}_f$ ,  $\tilde{B}_f$  and,  $\tilde{C}_f$  such that the following LMI holds:

$$\Lambda = \begin{bmatrix} \Lambda_{11} & \Lambda_{12} \\ \Lambda_{12}^T & \Lambda_{22} \end{bmatrix} \prec 0 \quad (17)$$

with  $\Lambda_{11}$ ,  $\Lambda_{12}$ , and  $\Lambda_{22}$  given in the box below.

$$\Lambda_{11} = \begin{bmatrix} -I & 0 & 0 & 0 & \begin{bmatrix} 0 & \tilde{C}_f \end{bmatrix} \\ * & -\begin{bmatrix} Y & X \\ X & X \end{bmatrix} & 0 & 0 & \begin{bmatrix} \alpha_1 \tilde{B}_f C & \alpha_1 \tilde{B}_f C \\ 0 & 0 \end{bmatrix} \\ * & * & -\begin{bmatrix} Y & X \\ X & X \end{bmatrix} & 0 & \begin{bmatrix} YA + \alpha \tilde{B}_f C & YA + \alpha \tilde{B}_f C + \tilde{A}_f \\ XA & XA \end{bmatrix} \\ * & * & * & -P_t & 0 \\ * & * & * & * & -\begin{bmatrix} Y - \tau H^T H & X - \tau H^T H \\ X - \tau H^T H & X - \tau H^T H \end{bmatrix} \end{bmatrix}$$

$$\Lambda_{12} = \begin{bmatrix} -C_t & 0 & \begin{bmatrix} 0 & 0 & -D_t \end{bmatrix} \\ 0 & 0 & \begin{bmatrix} 0 & \alpha_1 \tilde{B}_f & 0 \\ 0 & 0 & 0 \end{bmatrix} \\ 0 & \begin{bmatrix} YM \\ XM \end{bmatrix} & \begin{bmatrix} YB_1 + \tilde{B}_f D_1 & \alpha \tilde{B}_f & YB_2 \\ XB_1 & 0 & XB_2 \end{bmatrix} \\ P_t A_t & 0 & \begin{bmatrix} 0 & 0 & P_t B_t \end{bmatrix} \\ 0 & 0 & 0 \end{bmatrix}$$

$$\Lambda_{22} = \begin{bmatrix} -P_t & 0 & 0 \\ * & -\tau I & 0 \\ * & * & -\gamma^2 I \end{bmatrix}$$

Under a feasible solution for (17), the FDF parameters (8)-(9) are obtained as follows:

$$A_f = (X - Y)^{-1} \tilde{A}_f, \quad B_f = (X - Y)^{-1} \tilde{B}_f, \quad C_f = \tilde{C}_f \quad (18)$$

*Proof:* See [18].

#### IV. RESULTS

In this section the effectiveness of the proposed residual based attack-resilient EV system is evaluated by using a hardware-in-the-loop experimental setup. A general picture of the hardware-in-the-loop testbed is shown in Figure 2, developed by using the IEEE 802.15.4 TelosB wireless sensors technology [20]. The first-order discrete-time Randles equiv-

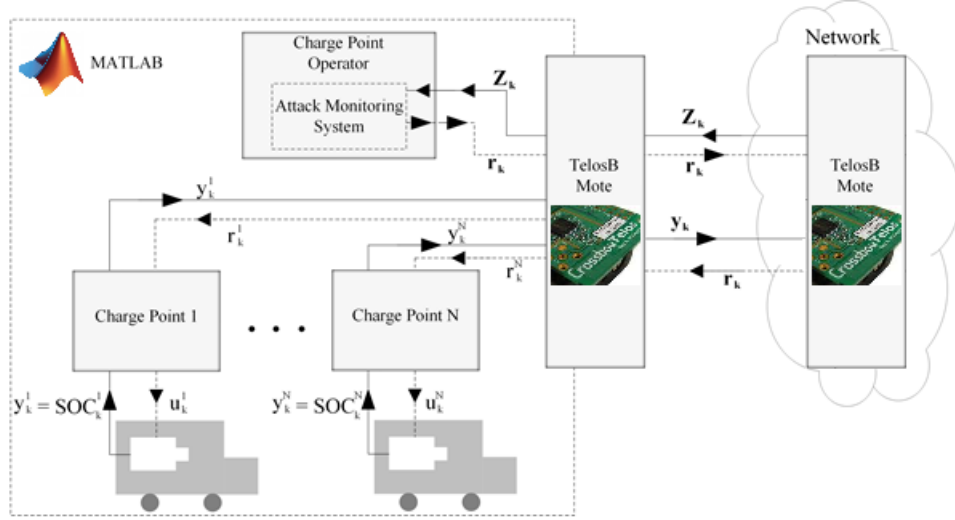


Fig. 2. Cybersecurity of EV charging systems using the residual generation.

alent circuit models of the EV batteries are implemented in MATLAB. At every time step, batteries' SOC's are measured by the charge points' meters, and transmitted to CPO through a wireless link. By using the received signals  $z_k$ , the residual filters, implemented in CPO, aim to detect the bias of SOC measurement under the DOS attack, which caused random packet dropouts. CPO then sends back the information of biases to charge points, to appropriately adjust the charging currents. In the proposed methodology, one residual filter per charge point is designed in a decentralized fashion. Without loss of generality, the results of the system with one charge point are given and discussed in the following.

In this testbed, the packet drop occurs if the strength of the received signal is low. The strength of the received signal is quantified by a received signal strength indicator (RSSI) in the IEEE 802.15.4 WSN standard [21], [22]. Power outage, shadowing and fading effects, and channel congestion cause low RSSI values. To generate packet dropouts, the AA battery of the TelosB is unplugged manually from the sensor node in this experiment. The actual injected bias is fed back to the residual filter, with no weighting function, i.e.,

$$A_t = 0, B_t = 0, C_t = 0, D_t = 1$$

Let assume the packet drop's expectation value is  $\alpha = 0.5$ . By solving (17), the parameters of the residual filter are obtained as follows:

$$A_f = \begin{bmatrix} 0.5221 & -0.058 \times 10^{-3} \\ -2038.3 & 0.3434 \end{bmatrix},$$

$$B_f = \begin{bmatrix} 0.121 \times 10^{-3} \\ 0.4938 \end{bmatrix},$$

$$C_f = \begin{bmatrix} -3.9814 & 0.8895 \times 10^{-3} \end{bmatrix}.$$

Figure 3 shows the system performance under no packet drop for 25%, 50%, and 75% false-injection biases which occur at  $t = 25s$ . Figure 3(a) shows a representative snapshot of  $y_k$ , and  $z_k$  signals under no packet drop, when a 25% bias,  $f_k = 0.25$ , is injected at  $t = 25s$ . Figure 3(b) shows the performance of the proposed false-injection detection filter

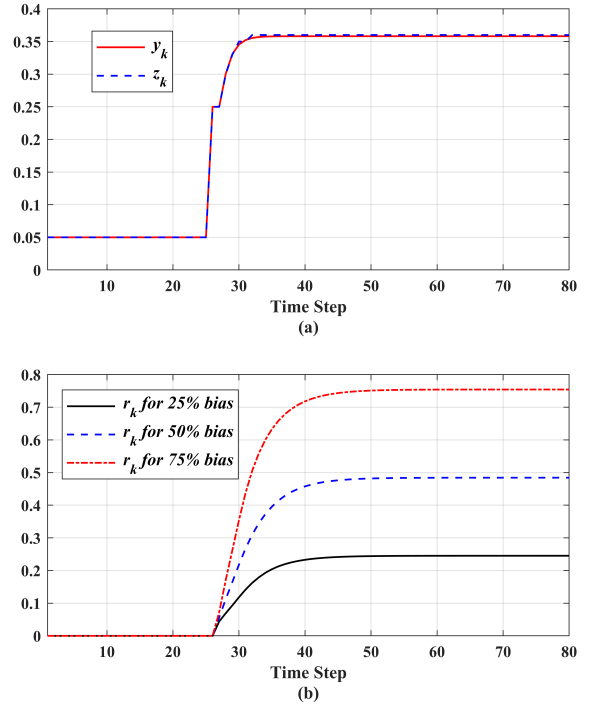


Fig. 3. A representative figure of  $y_k$ , and  $z_k$  signals under no packet drop, when a 25% bias,  $f_k = 0.25$  is injected at  $t = 25s$ . (b) The performance of the proposed false-injection detection filter for 25%, 50% and 75% biases which occur at  $t = 25s$  under no packet drop. This figure shows the generated residual signals  $r_k$ , which satisfactorily track  $f_k = 0.25, 0.5, \text{ and } 0.75$ .

for 25%, 50%, and 75% biases which occur at  $t = 25s$  under no packet drop. This figure shows that the generated residual signals  $r_k$ 's satisfactorily track  $f_k = 0.25, 0.5, \text{ and } 0.75$ .

Figure 4 shows the system performance under the DOS attack with 50% packet drop for 25%, 50%, and 75% false-injection biases which occur at  $t = 25s$ . Figure 4(a) shows a representative snapshot of  $y_k$ , and  $z_k$  signals under 50% packet

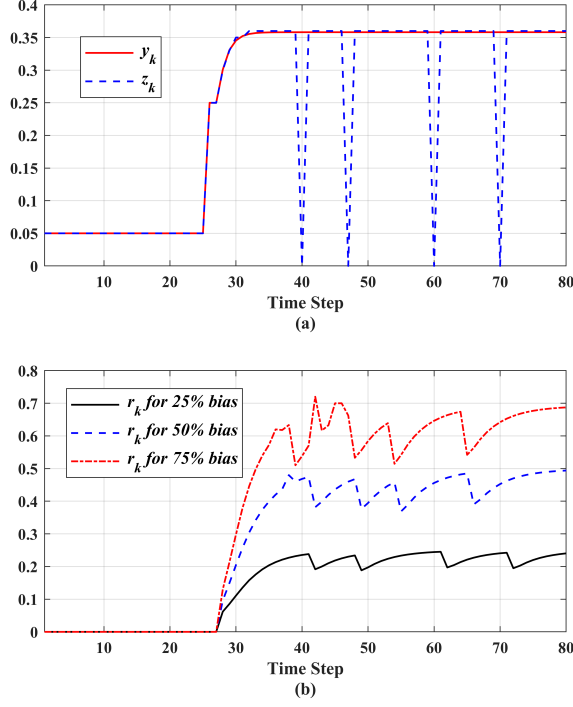


Fig. 4. A representative figure of  $y_k$ , and  $z_k$  signals under 50% packet drop, when a 25% bias,  $f_k = 0.25$  is injected at  $t = 25s$ . (b) The performance of the proposed false-injection detection filter for 25%, 50% and 75% biases which occur at  $t = 25s$  under 50% packet drop. This figure shows the generated residual signals  $r_k$ , which satisfactorily track  $f_k = 0.25, 0.5, 0.75$ .

drop, when a 25% bias,  $f_k = 0.25$ , is injected at  $t = 25s$ . Figure 4(b) shows the performance of the proposed false-injection detection filter for 25%, 50%, and 75% biases which occur at  $t = 25s$ . This figure also shows the generated residual signals  $r_k$ 's, which satisfactorily track  $f_k = 0.25, 0.5, \text{ and } 0.75$ .

Both experiments demonstrate the detection of false-injection biases with and without DOS cyber attacks.

## V. CONCLUSIONS AND FUTURE WORKS

In this paper, the cyber-physical protection of EV charging system has been addressed. A residual generation technique has been presented to provide an attack-resilient EV charging system which detects false data injection under the DOS cyber attack. The effectiveness of the proposed method was practically evaluated on a hardware-in-the-loop testbed developed by using the IEEE 802.15.4 wireless sensors technology. The results illustrate a satisfactory level of bias estimation under the DOS attack. As the future work, the charge control algorithm at the charge point is modified to compensate possible false data, based on the information received from CPO.

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