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The Internet of Things Infrastructure for Wireless Power Transfer Systems

Md M. Rana[1], Wei Xiang[1], Eric Wang[1] and Bong Jun Choi[2]
[1] College of Science and Engineering, James Cook University, QLD, Cairns, Australia
[2] Dept. of Computer Science, The State University of New York, South Korea and Stony Brook University, USA
Wei Xiang (wei.xiang@jcu.edu.au)

***Abstract*—This paper derives a state-space model of wireless power transfer (WPT) systems to be used for the purpose of state estimation and controller design considering the internet of things (IoT) communication networks. After expressing the WPT systems into a state-space linear equation, the elements of IoT such as sensors are deployed to obtain the state information. Then, an innovative IoT based communication infrastructure is proposed for sensing, actuating and transmitting the information to the control center. In order to know the operating condition of the WPT systems, the Kalman filter based dynamic state estimation algorithm is proposed considering the IoT infrastructure. Afterwards, the optimal controller is designed to regulate the system states. Simulation results indicate that the proposed approaches can accurately estimate and stabilise the WPT states. Therefore, the developed frameworks are valuable in designing the IoT based smart control center for WPT systems.**

***Index Terms*—Control center, dynamic state estimation, internet of things, magnetic coupling, wireless power transfer systems.**

I. INTRODUCTION

Today, the wireless power transfer (WPT) systems gain significant interest due to wider connectivity, higher efficiency, portable, safer and cleaner energy, even when used in hostile environments [1], [2], [3]. For these reasons, the WPT systems are increasingly being used in numerous industrial applications from medical implants to charging of electric vehicles [4]. Basically, the state estimation is the process to know the operating condition of the system [5], [6]. Following that the controller needs to be designed for proper operations and maintaining the stability of the network. For monitoring the WPT system states, the internet of things (IoT) is the potential infrastructure that can provide the wider connectivity, advanced sensing/actuating, information processing and greater flexibility [7], [8], [9]. Therefore, the IoT embedded smart devices can provide two-way communication between the WPT systems and the control center.

There have been several algorithms for the WPT system state estimation and stabilization. To begin with, an extended Kalman filter (EKF) algorithm for a WPT system state estimation is proposed in [10]. In this framework, the WPT system is expressed as a state-space nonlinear equation, where the EKF is used to estimate the system states. For stabilization of the WPT system states, the linear quadratic regulator (LQR) is adopted. The idea is then extended in [11], where the unscented KF (UKF) is used, and it shows that the UKF provides better estimation performance compared with the EKF. Unfortunately, it does not design any communication infrastructure for WPT system state estimations. In reality, the communication infrastructure is the key to transfer information as the WPT systems and monitoring center are generally far away. Interestingly, by using the IoT technology, information of the air quality is transmitted from the IoT sensor nodes to the information processing center through different wireless/wired networks in [12]. On the other hand, there exists several publications on modeling and control of a WPT system, which mainly cover the steady state model [13], [2], [3]. Furthermore, the applications of the IoT infrastructure for the power system is proposed in [14]. Moreover, the potential applications of IoT for sensors networks are described in [15]. Motivated by the aforementioned research gaps in the IoT and WPT communities, this paper proposes a KF based WPT system state estimation and optimal feedback controller. The contributions of this paper are as follows:

- The WPT system incorporating the inductive circuits is represented by a state-space linear equation, where the smart sensors deploy to obtain measurements. This model is useful for estimation of WPT state variables and controller design.
- An innovative IoT based communication infrastructure is proposed, and it provides two-way communication between the WPT systems and the control center. The uniform quantizer and binary phase shift keying techniques are used to design such a communication framework.
- Based on the designed IoT network, the KF based state estimation and an optimal feedback controller is proposed in the context of WPT systems. Simulation results demonstrate that the proposed approaches can properly estimate and stabilise the system states.

Notations: Bold face upper and lower case letters are used to represent matrices and vectors respectively. Superscripts $\mathbf{x}'$ denotes the transpose of $\mathbf{x}$, diag($\mathbf{x}$) denotes the diagonal matrix, and $\mathbf{I}$ denotes the identity matrix. The following notions are used in this study:

i_{pi}	Current through the primary inductor L_{pi}.
i_T	Current through the primary side inductor L_T.
v_{cpi}	Voltage across the primary side capacitor C_{pi}.
i_{so}	Current through the pick-up side inductor L_{so}.
v_{cso}	Voltage across the pick-up output capacitor C_{so}.
i_{si}	Current through the pick-up side inductor L_{si}.

v_{pt}	Voltage across primary side capacitor C_T.
v_{st}	Voltage across the pick-up side capacitor C_s.
R_{pi}	Resistance in the primary side RLC circuit.
L_{pi}	Inductance in the primary side RLC circuit.
C_{pi}	Capacitance in the primary side RLC circuit.
R_{so}	Resistance in the secondary side RLC circuit.
L_{so}	Inductance in the secondary side RLC circuit.
C_{so}	Capacitance in the secondary side RLC circuit.

II. BACKGROUND OF IOT NETWORKS

The IoT is a network of smart objects or so called internet-enabled objects together with web services that interact with these objects [16]. It can allow smart objects to be directly connected to the internet without human intermediation. Sometimes, the internet is also acting as a transmission medium, where the IoT embedded smart devices transmit data to the information processing center for real-time display [17]. It can be applied in different areas such as smart grid, WPT systems, communications, medical and environment monitoring applications. To illustrate, Fig. 1 shows the IoT support in the different fields [18], [19]. With the advent of information and communication technology, the massive amount of data generated by the smart devices can be processed, communicated and stored using the IoT infrastructure. One example of the wireless communication between smart devices is around the human body such as wireless headsets, wearable devices and wireless charging for smart phones [20]. This requires smart software for sensing, collecting and transmitting related data to the control center for monitoring and stabilizing the network. In this regard, the internet and wireless communication technologies can fulfill the demands of customers and utility operators.

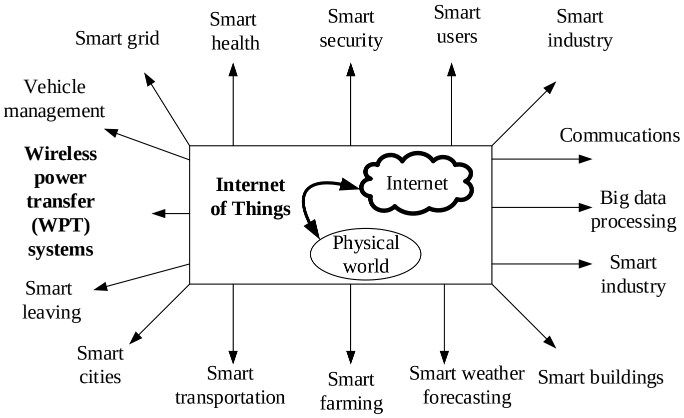

Fig. 1: The IoT application in different areas [18].

From the wireless power transfer perspective, the IoT can provide services for sensing, actuating, data transmission and real-time information processing [21]. Generally, the inductive circuits for wireless power transfer systems are connected to the utility grid as shown in Fig. 2 [22]. Basically, the grid continuously generates the massive amount of data from different places and times. Unfortunately, the power line communication is not able to handle such an enormous amount of information effectively due to low transmission rate and bandwidth constraint. Consequently, the industrial automation system is transformed to the IoT based smart system. In order to monitor the objects, the sensing information is required to be transmitted to the control center over communication networks. This is because the ”things” such as the WPT system and control center are generally far away. For instance, the inductive circuits in a WPT system are in the customer end/highways, while the control centre is geographically far away. Therefore, for the long distance data transmission, the digital communication networks such as cellular, optical fiber and internet may be used [23]. Before designing such an IoT network, the WPT system model is described first.

III. STATE-SPACE REPRESENTATION OF WPT SYSTEMS

The conceptual block diagram of a wireless power transfer system and it equivalent circuit are described in Fig. 3 and Fig. 4, respectively [2], [3]. The primary and secondary sides are separated by an air gap [24]. The energy can be transferred over the gap through inductive coupling between inductor coils. Due to the air gap, the leakage inductance is much larger than the magnetizing inductance [2], [25]. In order to compensate for the leakage inductance, the capacitors are added to both sides of the coils [1], [3]. The full bridge inverter at the primary side is converting the input DC voltage into a square wave, while the rectifying diodes at the secondary side are converting AC voltage into DC voltage [26], [27]. Both the inverter and diodes are separated by the resonant tank circuit. The primary side of the circuit is connected to the grid, which is monitored by the energy management system for proper operation and stability. The secondary side can deliver energy to the appliances such as electric vehicles, cell phones and pacemakers. Overall, the regulated circuits are generally required for the WPT systems [2], [3].

The instantaneous value of the induced voltage $v_{si}(t)$ of the secondary coil is given by [2]:

$$v_{si}(t) = M\frac{di_T(t)}{dt}. \tag{1}$$

Here, M is the mutual inductance between the primary and secondary coils, i_T is the current through the inductor L_T. The instantaneous voltage of the primary coil $v_{ri}(t)$ is given by:

$$v_{ri}(t) = -M\frac{di_{si}(t)}{dt}. \tag{2}$$

Here, i_{si} is the current through the secondary side inductor L_{si}.

After applying KVL and KCL, the differential equations of the WPT are given by [2], [3]:

$$\dot{i}_{pi} = -\frac{R_{pi}}{L_{pi}}i_{pi} - \frac{1}{L_{pi}}v_{cpi} - \frac{1}{L_{pi}}v_{pt} + \frac{1}{L_{pi}}v_{pi}. \tag{3}$$

$$\dot{v}_{cpi} = \frac{i_{pi}}{C_{pi}}. \tag{4}$$

$$\dot{v}_{pt} = \frac{i_{pi}}{C_T} - \frac{i_T}{C_T}. \tag{5}$$

$$\dot{i}_T = \gamma[\frac{v_{pt}}{L_T} - \frac{R_T}{L_T}i_T - \beta v_{st} - \beta R_{si}i_{si}]. \tag{6}$$

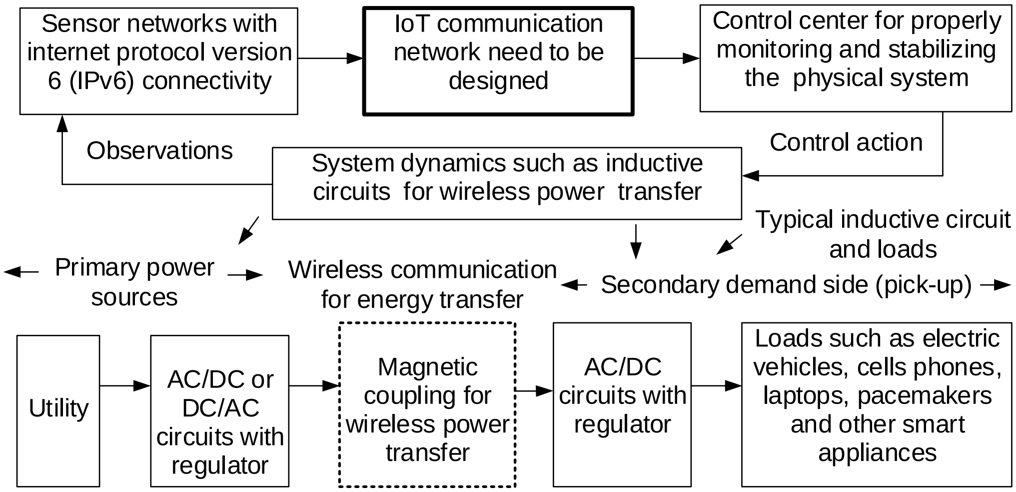

Fig. 2: Wireless power transfer systems and IoT infrastructure [22].

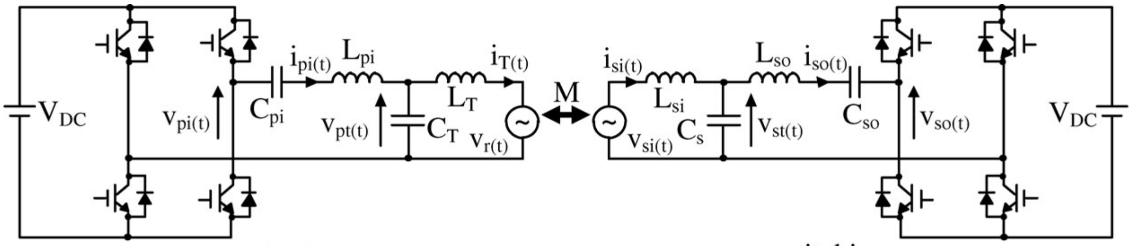

Fig. 3: Conceptual block diagram of a typical wireless power transfer system [2], [3].

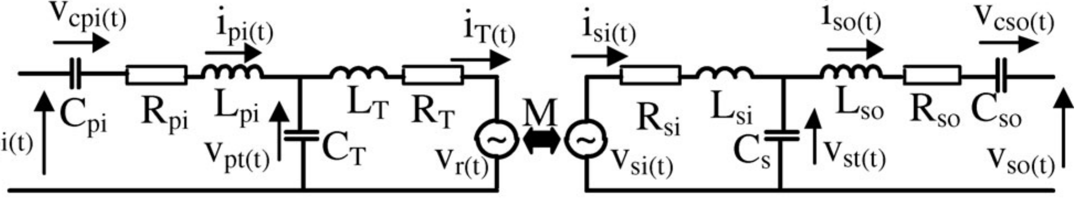

Fig. 4: Equivalent circuit representation of IPT system [2], [3].

$$\dot{i}_{so} = -\frac{R_{so}}{L_{so}} i_{so} - \frac{v_{cso}}{L_{so}} + \frac{v_{st}}{L_{so}} - \frac{v_{so}}{L_{so}}. \tag{7}$$

$$\dot{v}_{cso} = \frac{i_{so}}{C_{so}}. \tag{8}$$

$$\dot{v}_{st} = -\frac{i_{so}}{C_s} + \frac{i_{si}}{C_s}. \tag{9}$$

$$\dot{i}_{si} = \gamma[\beta v_{pt} - \beta R_T i_T - \frac{v_{st}}{L_{si}} - \frac{R_{si} i_{si}}{L_{si}}]. \tag{10}$$

Here, $\beta = \frac{M}{L_{si} L_T}$ and $\gamma = \frac{1}{1 - M\beta}$.

Now (3)-(10) can be expressed as a state-space equation as follows [2], [3]:

$$\dot{\mathbf{q}} = \mathbf{F}\mathbf{q} + \mathbf{G}\mathbf{u} + \mathbf{n}. \tag{11}$$

The system state matrix $\mathbf{F}$ is given at the top of the next page, $\mathbf{q} = [i_{pi} \; v_{cpi} \; v_{pt} \; i_T \; i_{so} \; v_{cso} \; v_{st} \; i_{si}]'$ is the system state, the nonzero elements of input matrix $\mathbf{G}$ are: $G_{1,1} = 1/L_{pi}$, $G_{5,1} = -1/L_{so}$, $\mathbf{u} = [v_{pi} \; v_{so}]'$ is the system input, and $\mathbf{n}$ is the process noise whose covariance matrix is $\mathbf{Q}$

Now, the above system is expressed as a discrete-time state-space linear framework as follows:

$$\mathbf{q}(k+1) = \mathbf{F}_d \mathbf{q}(k) + \mathbf{G}_d \mathbf{u}(k) + \mathbf{n}(k), \tag{13}$$

where $\mathbf{F}_d = \mathbf{I} + \mathbf{F}\Delta t$, $\mathbf{I}$ is the identity matrix, Δt is the sampling period, and $\mathbf{G}_d = \mathbf{G}\Delta t$.

Generally speaking, the IoT based smart devices such as sensors and actuators are available for sensing and monitoring the WPT systems [19]. In order to sense and monitor the physical system, the system operators deploy a set of sensors whose measurements are described by:

$$\mathbf{y}(k) = \mathbf{C}\mathbf{q}(k) + \mathbf{v}(k), \tag{14}$$

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$$\mathbf{F}=\begin{bmatrix}-\frac{R_{pi}}{L_{pi}} & -\frac{1}{L_{pi}} & -\frac{1}{L_{pi}} & 0 & 0 & 0 & 0 & 0\\ \frac{1}{C_{pi}} & 0 & 0 & 0 & 0 & 0 & 0 & 0\\ \frac{1}{C_T} & 0 & 0 & -\frac{1}{C_T} & 0 & 0 & 0 & 0\\ 0 & 0 & \frac{\gamma}{L_T} & -R_T\frac{\gamma}{L_T} & 0 & 0 & -\gamma\beta & -\gamma\beta R_{si}\\ 0 & 0 & 0 & 0 & -\frac{R_{so}}{L_{so}} & -\frac{1}{L_{so}} & \frac{1}{L_{so}} & 0\\ 0 & 0 & 0 & 0 & \frac{1}{C_{so}} & 0 & 0 & 0\\ 0 & 0 & 0 & 0 & -\frac{1}{C_s} & 0 & 0 & 1/C_s\\ 0 & 0 & \gamma\beta & -\gamma\beta R_T & 0 & 0 & -\frac{\gamma}{L_{si}} & -\frac{\gamma R_{si}}{L_{si}}\end{bmatrix}. \tag{12}$$

where **y** is the observation information, **C** is the sensing matrix and **v** is the measurement noise (Gaussian distribution) with zero mean and covariance matrix **R**.

Usually, the sensors have limited communication capabilities; therefore, they are not able to send the sensing information to the long distance transmission. For instance, the energy management system is geographically far away from the WPT systems. Consequently, it will need a suitable communication infrastructure which provides two-way communication between them. Inspired by the smart grid papers in [5], [28], this paper proposes an IoT based innovative communication infrastructure for WPT system as shown in Fig. 5. To facilitate this infrastructure, the sensing information is quantized to obtain the bit information. This is due to the fact that the digital modulation scheme is used for long distance signal transmission. So, the bit information is modulated using the binary phase shift keying (BPSK) to obtain $\mathbf{m}(k)$ signal [5], [28]. The modulated signal is then transmitted through the channel, which causes the signal distortions. Combining the sensing information with the BPSK is referred to as the IoT network. Sometimes the internet is used as a transmission channel due to the fact that it can support the big data transmission and greater connectivity. The received signal at the control center is written as follows.

$$\mathbf{r}(k)=\mathbf{m}(k)+\mathbf{d}(k), \tag{15}$$

where $\mathbf{d}(k)$ is the channel noise, which is considered the Gaussian distribution. The received signal then follows the demodulation and dequantization processes; finally, it is used for the state estimation purpose.

IV. PROPOSED FRAMEWORK

In order to estimate the WPT system states, this study proposes a mean squared based KF recursive algorithm. Based on the communication network, the followings are the modified steps for the KF algorithm [5], [29], [30]:

$$\hat{\mathbf{q}}^{-}(k)=\mathbf{F}_d\hat{\mathbf{q}}(k-1)+\mathbf{G}_d\mathbf{u}(k-1), \tag{16}$$

where $\hat{\mathbf{q}}(k-1)$ is the initial estimated states and its error covariance is:

$$\mathbf{P}^{-}(k)=\mathbf{F}_d\mathbf{P}(k-1)\mathbf{F}'_d+\mathbf{Q}, \tag{17}$$

where $\mathbf{P}(k-1)$ is the initial estimated covariance matrix. The optimal Kalman gain is computed as follows:

$$\mathbf{K}(k)=\mathbf{P}^{-}(k)\mathbf{C}'[\mathbf{C}\mathbf{P}^{-}(k)\mathbf{C}'+\mathbf{R}]^{-1}. \tag{18}$$

The desired state estimation and it error covariance are obtained as follows:

$$\hat{\mathbf{q}}(k)=\hat{\mathbf{q}}^{-}(k)+\mathbf{K}(k)[\mathbf{y}_d(k)-\mathbf{C}\hat{\mathbf{q}}^{-}(k)]. \tag{19}$$

$$\mathbf{P}^{+}(k)=\mathbf{P}^{-}(k)-\mathbf{K}(k)\mathbf{C}\mathbf{P}^{-}(k). \tag{20}$$

Here, $\mathbf{y}_d(k)$ is the dequantized version of the received signal as shown in Fig. 5.

The aim of the controller is to stabilise the system states. After estimating the system states and according to the separation principle [31, p. 427], let's define the following feedback control law to stabilize the system states:

$$\mathbf{u}(k)=-\mathbf{D}\mathbf{q}(k). \tag{21}$$

Here, **D** is the feedback gain matrix to be designed.

The feedback gain is obtained by minimizing the following performance index:

$$J=\sum_{i=1}^{L}[\mathbf{q}'(k)\mathbf{Q}_w\mathbf{q}(k)+\mathbf{u}'(k)\mathbf{R}_w\mathbf{u}(k)], \tag{22}$$

where $\mathbf{Q}_w$ and $\mathbf{R}_w$ are the weight matrices. Considering the above performance criteria, the linear quadratic regulator (LQR) gain is given by:

$$\mathbf{D}=(\mathbf{G}_d\mathbf{P}\mathbf{G}'_d+\mathbf{R}_w)^{-1}\mathbf{G}'_d\mathbf{P}\mathbf{F}_d. \tag{23}$$

The solution of **P** is obtained after solving the following Riccati equation [28], [32]:

$$\mathbf{P}=\mathbf{F}'_d\mathbf{P}\mathbf{F}_d+\mathbf{F}'_d\mathbf{P}\mathbf{G}_d(\mathbf{G}_d\mathbf{P}\mathbf{G}'_d+\mathbf{R}_w)^{-1}\mathbf{G}'_d\mathbf{P}\mathbf{F}_d+\mathbf{Q}_w. \tag{24}$$

The LQR controller can be modified considering the linear matrix inequality approach [33], [32], which is our future work. The performance of the proposed approach is verified the following section.

V. SIMULATION RESULTS AND DISCUSSIONS

The aim of this paper is to develop a state-space model of the WPT system to be used for the purpose of state estimation and controller design. After expressing the WPT system into the state-space equation, the IoT embedded smart sensors are deployed to obtain measurements. Then, an innovation IoT communication infrastructure is proposed for WPT system sensing, actuating and monitoring applications. Based on the infrastructure, the KF based state estimation and optimal feedback controller are designed. Overall, a block diagram of the simulation setup is presented in Fig. 5. It can be seen that

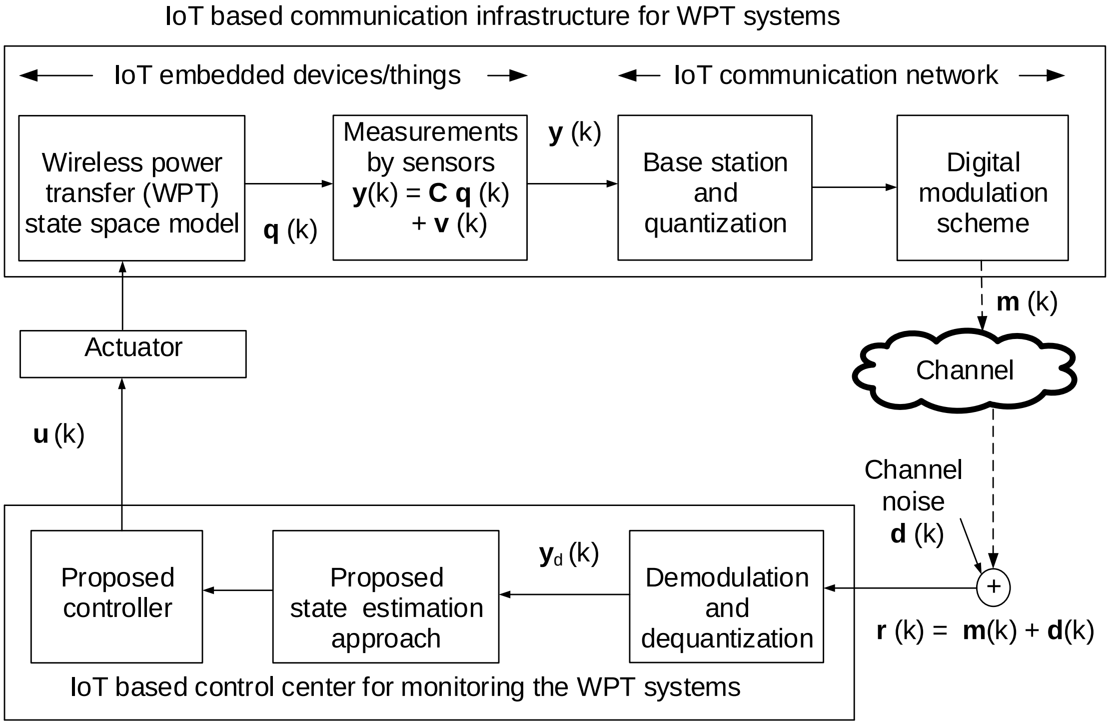

Fig. 5: Proposed IoT based communication for WPT systems inspired by [5], [28].

the proposed infrastructure provides two-way communication between WPT systems and the control center. The simulation parameters are summarised in Table I [2], [3].

TABLE I: WPT system parameters for simulation [2], [3].

Symbols	Values	Symbols	Values
R_{pi}	0.0152Ω	R_T	0.0158Ω
R_{si}	0.0179Ω	R_{so}	$0.0122\ \Omega$
C_{so}	2.5329×10^{-3}F	C_s	2.47×10^{-3}F
C_{pi}	2.5307×10^{-3}F	L_{so}	46.28×10^{-3}H
L_{si}	23.48×10^{-3}H	L_T	22.84×10^{-3}H
L_{pi}	46.51×10^{-3}H	C_T	2.49×10^{-3}F
M	8×10^{-3}H	$\mathbf{Q}$	$0.0005*\mathbf{I}$
$\mathbf{R}$	$0.05*\mathbf{I}$	Δt	0.0001

The dynamic responses of the WPT system are shown in Figs. 6-13. It can be seen that the estimated WPT state responses converge to the actual state values as time proceeds. It is also observed that the proposed algorithm outperforms the existing least mean square fourth approach in [34], [35]. For example, Fig. 9 shows the current i_T across the inductor L_T and its estimation result. Clearly, it can be seen that the proposed scheme requires 40 time steps, while the existing approach needs 300 time steps. This is due to the fact that the designed optimal gain can effectively reduce the estimation errors while the existing least mean square fourth approach is difficult to find the optimal gain due to suboptimal nature of the gain expression. Similar high estimation accuracy is obtained of all WPT system states.

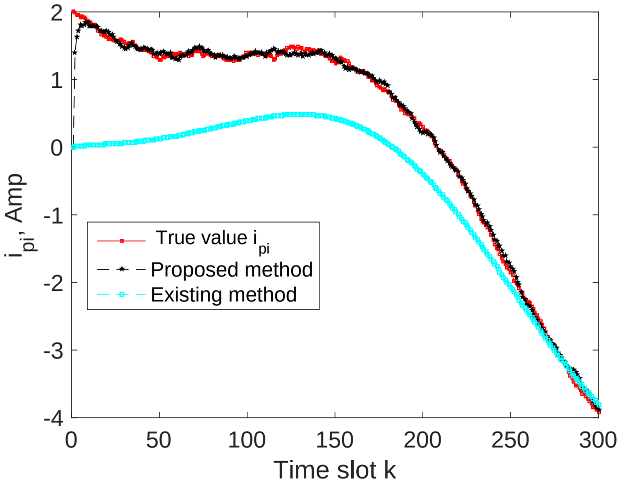

Fig. 6: Current i_{pi} through inductor L_{pi} and its estimation.

After applying the proposed controller, it can be seen from Fig. 14 that the proposed approach can stabilise the system states within a few time steps. In other words, the proposed method requires the time step k=1300 for state stabilization.

VI. CONCLUSION AND FUTURE RESEARCH

After providing an overview of the IoT network, the wireless power transfer system is presented. It can be expressed as a state-space model where sensors deploy to get state information. Then, an innovative IoT communication infrastructure is proposed for monitoring and controlling the WPT system. Based on the communication network, the Kalman filter based state estimation and optimal feedback controller are developed. Simulation results show that the proposed approach outperform the existing method. This paper can serve as a step

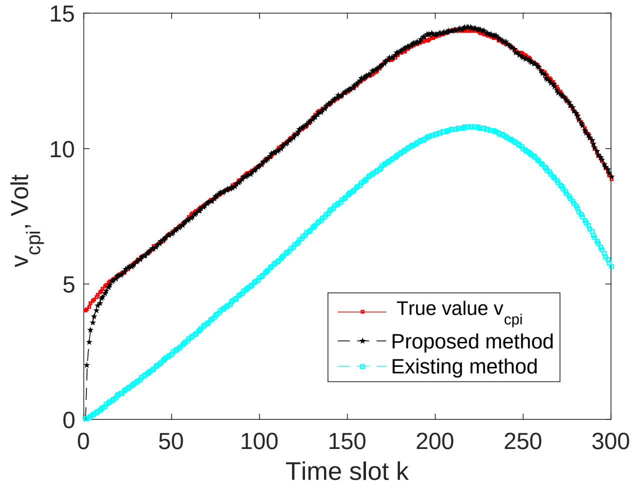

Fig. 7: Voltage v_{cpi} across C_{pi} and its estimation.

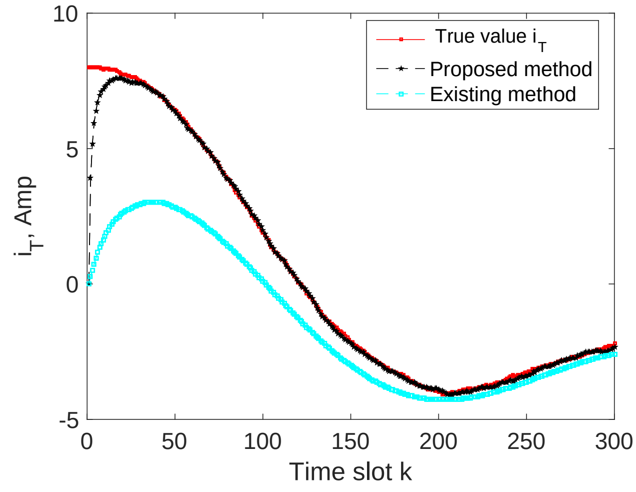

Fig. 9: Current i_T across L_T and its estimation.

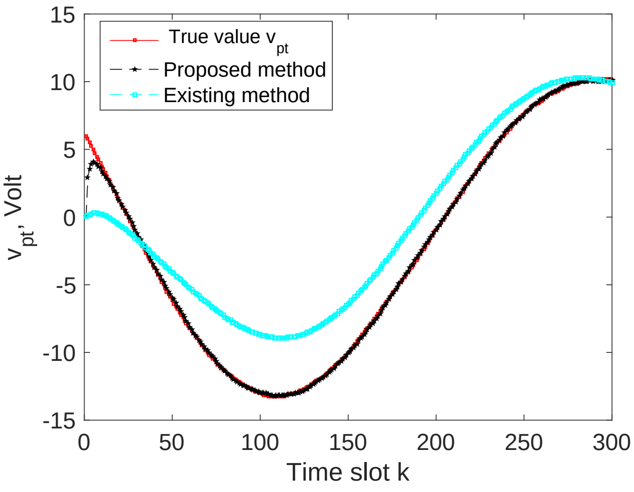

Fig. 8: Voltage v_{pt} across C_T and its estimation.

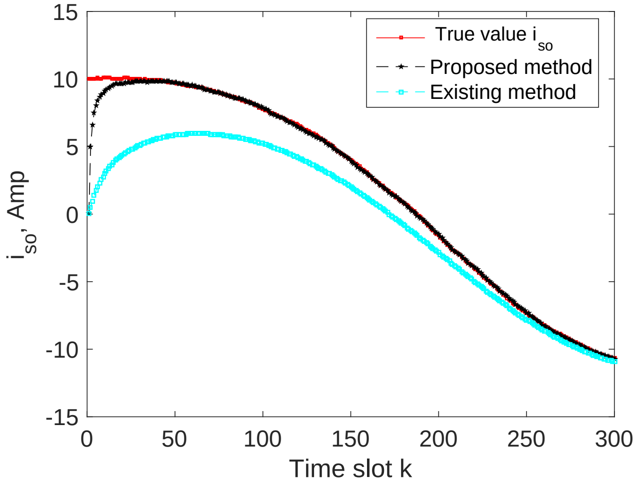

Fig. 10: Current i_{so} through inductor L_{so} and its estimation.

for future research on the IoT communication networking as well as wireless information and power transfer communities. Although our proposed system model and algorithm are useful for WPT applications, the work presented here has some limitations. Therefore, further investigations will include the following aspects:

- Considering the networked induced time-varying delay is one of our future work [36].
- In order to obtain better performance, an adaptive control algorithm with delay should be consider in future research [37] [38].

VII. ACKNOWLEDGEMENT

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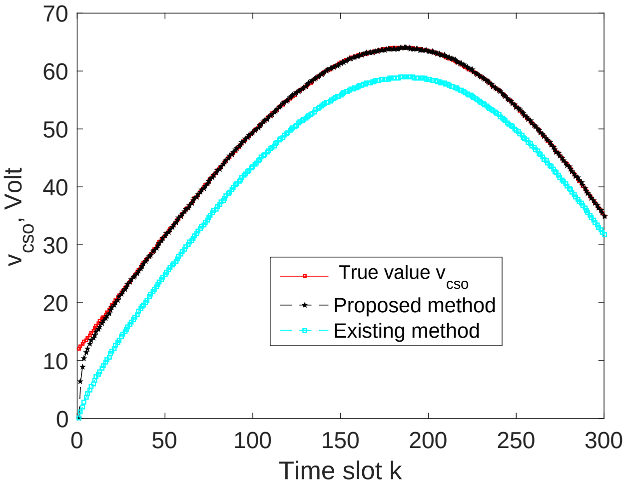

Fig. 11: Voltage v_{cso} across C_{cso} and its estimation.

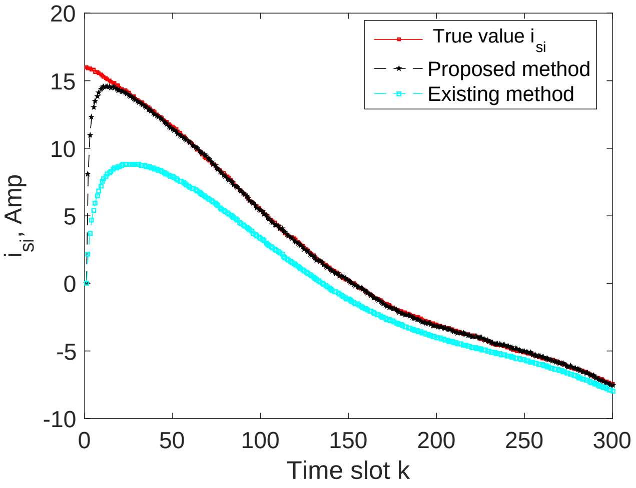

Fig. 13: Current i_{si} through inductor L_{si} and its estimation.

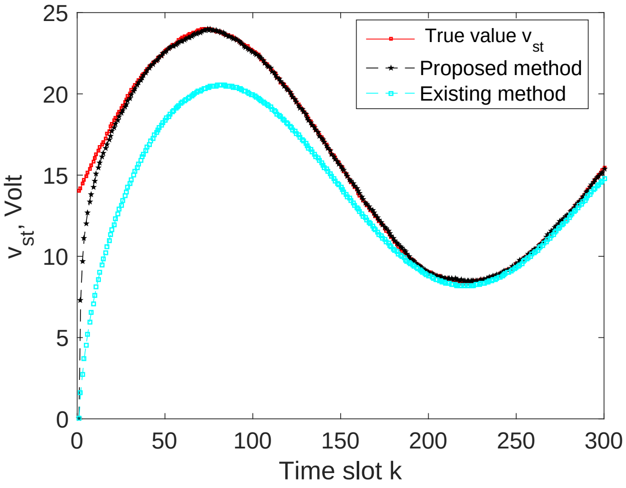

Fig. 12: Voltage v_{st} across C_S and its estimation.

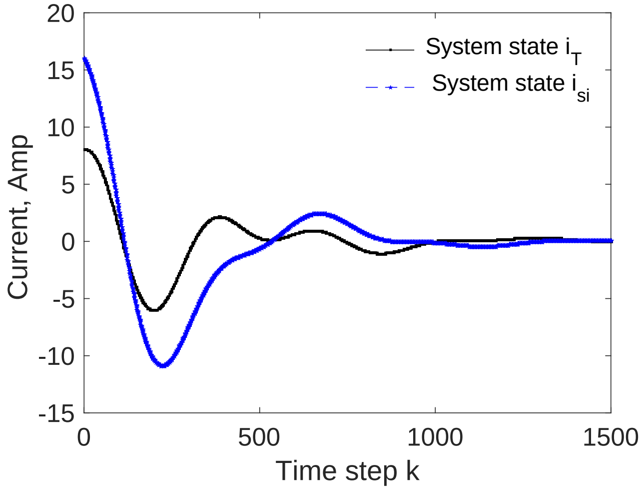

Fig. 14: Controlling the state currents i_T and i_{si}.

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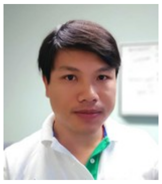
Wei Xiang received his B.Eng. and M.Eng. degrees, both in electronic engineering, from the University of Electronic Science and Technology of China, Chengdu, in 1997 and 2000, respectively, and his Ph.D. degree in telecommunications engineering from the University of South Australia, Adelaide, in 2004. He is currently Foundation Professor and Program Director of Electronic Systems and IoT Engineering at James Cook University, Cairns, Australia.



Eric (Gengkun) Wang received his B.Eng. degree in mechanical engineering and his M.Eng. degree in mechatronic engineering from the University of Science and Technology, Beijing, China, in 2006 and 2009, respectively. He completed his PhD in telecommunications engineering from the University of South Queensland, Australia. He has been working as a Post-Doctoral Research Fellow with the School of Electrical and Mechanical, USQ for two and a half years. He has authored more than 20 high quality papers, and participated in many national and international research projects. He was the runner-up in The Asia-Pacific Robot Contest (ABU Robocon) 2006, and received the best paper award from the IEEE Wireless Communications and Networking Conference, Cancun, Mexico, in 2011.

Bong Jun Choi received the B.Sc. and M.Sc. degrees from Yonsei University, Seoul, South Korea, both in electrical and electronics engineering, and the Ph.D. degree from the University of Waterloo, Waterloo, ON, Canada, in electrical and computer engineering. He is currently an Assistant Professor at the Department of Computer Science, State University of New York Korea, Incheon, South Korea, and jointly a Research Assistant Professor at the Department of Computer Science, Stony Brook University, New York, NY, USA. His current research interests include energy efficient networks, distributed mobile wireless networks, smart grid communications, and network security.