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Architecture of the Internet of Energy Network: An Application to Smart Grid Communications

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ABSTRACT Due to the global warming and energy crisis, the renewable distributed energy resources, such as wind turbines, are integrated into the grid. We model an AC microgrid with energy generating units, local loads, and electronic devices. Then, the set of non-linear differential equations are expressed as a state-space model. As the microgrid is located in the customer premises or remote areas, its condition needs to monitor in real-time. So, the smart sensor requires to deploy around the microgrid, and its sensing information transmits to the energy management system via the Internet as the sensing information is a massive amount of data. Combining the Internet of Things elements, such as sensors (Internet emended), and the Internet as a transmission medium will form the Internet of Energy, which is considered as a sign interest nowadays. Basically, the energy management center estimates the microgrid states to know the operating conditions of these foreseeable intermittent resources. For estimating the microgrid states, the H-infinity-based Mimimax filter is proposed, which will no need to know the exact process and measurement noise statistics. Simulation results show that the proposed approach can well estimate the system states compared with the existing Kalman filter. As a result, this framework will assist to design a suitable microgrid framework and provides effective dynamic state estimations.

INDEX TERMS Dynamic microgrid state estimation, fusion center, Internet of Things, information management system, microgrid.

I. INTRODUCTION

Significant concern arises due to climate change, energy cost and limited resources [1]. The main reason of this concern is to emit the green house gases to generate the electricity from the traditional energy generating units. In order to reduce such emissions, nowadays the renewable distributed energy resources such as solar cell have been widely installed. It not only saves money and losses but also environmentally-friendly. However, it is a changeling task to integrate the renewable microgrids into the main grid as it generation pattern is intermittent in nature [2], [3]. Consequently, it requires to monitor and stabilise the system states in real-time. Interestingly, in order to transmit the sensing massive information, the internet of things (IoT) will be a preferred medium as it can connect anything, anytime. Recently, the vision of smart grid and IoT has combined called the the internet of energy (IoE) [4].

There are many papers available in the literature for power system state estimations. To begin with, a recursive mixed l_1 and l_2 algorithm is used for power system state estimations [5]. The performance bound of this estimation approach is developed. It works well even though there is a bad data in measurements. Unfortunately, the computational complexity of this convex method is very high compared with the traditional estimation techniques such as weighted least squared. Recently, the alternating direction method of multipliers has been explored in [6], and it demonstrates that it provides the better performance compared with the Lagrangian multiplier method. Moreover, the compress sensing based Kalman filter (KF) is proposed in [7]. Here, the system regularization parameter l_1 is replaced by quasi-norm l_p for improving the estimation accuracy. Interestingly, the KF based microgrid state estimation considering the IoT communication network is proposed in [8]. Obviously, it requires to know the exact noise statistics which are generally unavailable. Therefore, the alternative method is required to estimate the system states considering the IoT network as a transmission medium.

This paper proposes the H-infinity based microgrid state estimation algorithm considering the IoT communication network. First of all, the architecture and vision of the IoE network is described. Secondly, the state-space model of an AC microgrid is presented for state estimations. The sensors (an IoT element) deploy to measure the microgrid states, then the massive data is transmitted through the impending

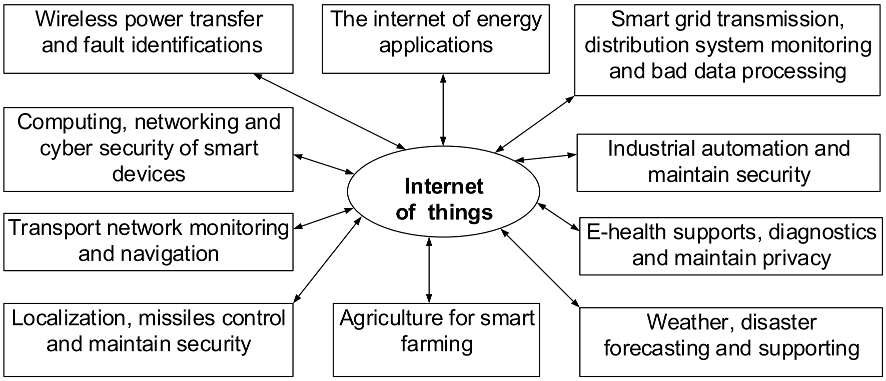

FIGURE 1. The IoT application in different areas [10].

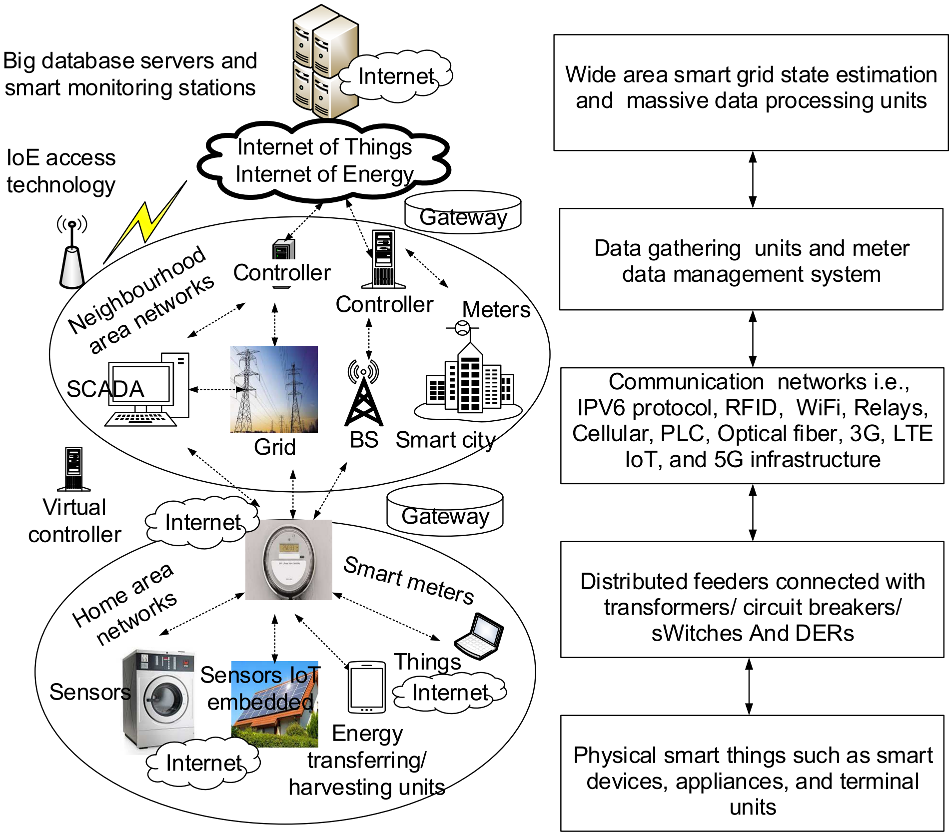

FIGURE 2. The potential architecture of the IoE communication network.

IoT network. The H-infinity based dynamic state estimation is explored, which will no need know the exact noise statistics. Numerical results illustrate that the proposed approach improves the estimation accuracy compared with the existing KF method. Consequently, this framework will assist to design the IoE based energy management system.

The rest of the article is organised as follows. The architecture and vision of the IoE communication is described in Section II. In Section III presents the state-space microgrid model, and its estimation algorithm is in Section IV. The simulation results and conclusion are in Section V and VI, respectively.

Notation: Bold face lower and upper case letters are used to represent vectors and matrices, respectively; superscripts $\mathbf{x}'$ denotes the transpose of $\mathbf{x}$ and $\mathbf{I}$ is the identity matrix.

II. THE IoE COMMUNICATION ARCHITECTURE

The IoT is gaining significant interest in the smart grid and communication communities. Basically, the IoT vision is to connect anything, anywhere and anytime into the global information network [9]. For this reason, the IoT infrastructure is widely used in the smart grid monitoring, telemetric services, military communication, big data processing and weather forecasting. To illustrate, Fig. 1 shows the application of the IoT in different areas. It can be seen that the IoT will support the massive data transmission and reception efficiently using the advance communication technologies. The sensing information from the physical layer is transmitted to the control centre through the access technology, which can be powered by the fifth generation (5G) communication standards for an example. The IoE elements such as smart sensors, and actuators can sense and control the physical objects such as microgrids [11], [12]. The internet protocol version six in wireless sensor networks (WSN) will assist such kind of connectivity at anytime, anyplace and anywhere. Therefore, the sensor can send their information to the fusion centre through the internet as a transmission medium. Generally speaking, the image/energy information is a missive amount of data, so it is very difficult to transmit as it needs more communication resources and bandwidth [13].

On the other hard, the smart grid goal is to monitor and control the energy generating units by providing two-way communication at anytime and anyplace between the grid and energy management system. Obviously, the electricity generating units and monitoring centres are located far away. To fulfill the vision of smart grids, the IoT will be the potential infrastructure to support the two-way communication [13]. This is due to the fact that the microgrid is located in the remote areas where the wired communications such as optimal fiber is very expensive to install. Therefore, the wireless communication based IoT infrastructure will be potential network as it is easy to install and offers efficient two-way connectivity. Interestingly, the vision of IoT and smart grid is combined called the internet of energy (IoE) [4]. To demonstrate, Fig. 2 shows the communication architecture to support the IoE visions. From the diagram, it can be seen that the control centre can obtain the measurement information from the various points and transmit therm through the IoT networks. The connectivity of these smart devises are also supported by this network. Therefore, the IoE communication infrastructure will support the big data transmission, processing and taking by providing two-way communication between them. In other words, the designing such a communication networks is the key to sense, monitor and control the physical objects at anytime of course anyplace [13], [14].

III. MODELLING THE IoT BASED PHYSICAL OBJECT: MICROGRID

One of the most important features of smart grid technology is to integrate the renewable distributed microgrids into the electricity network. The microgrid incorporating distributed energy resources (DERs) such as solar panels and wind turbines are connected to the grid. Generally speaking, the microgrid provides clean energy to the consumers, and it operates both in islanded as well as grid connected modes. To demonstrate, the schematic diagram of an isolated microgrid is illustrated in Fig. 3 [15]–[17]. From the diagram, it can be seen that the microgrid is connected with the grid/another microgrid through the point common coupling point (PCC). Basically, the energy generating unit of a microgrid entails of AC/DC voltage sources, DC/AC converter and series RLC filter. The load is connected to the PCC, and the local loads are equivalent to resistive, capacitive and constant power load (CPL). After applying the KVL and KCL, the dynamic of a microgrid in the dq-frame is expressed as follows [15]–[17]:

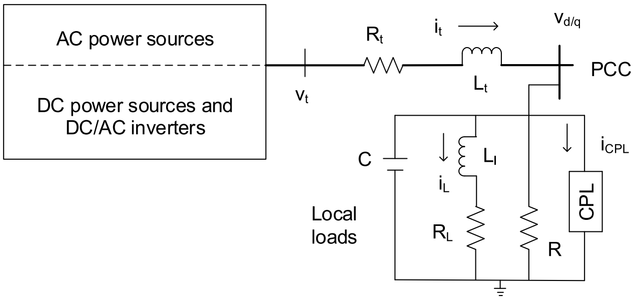

FIGURE 3. The structure of an AC microgrid [15], [16].

$$\dot{i}_{td} = (-R_t i_{td} + \omega L_t i_{tq} - v_d + v_{td})/L_t. \quad (1)$$

$$\dot{i}_{tq} = (-R_t i_{tq} - \omega L_t i_{td} - v_q + v_{tq})/L_t. \quad (2)$$

$$\dot{i}_{Ld} = (-R_L i_{Ld} + \omega L_l i_{Lq} + v_d)/L_l. \quad (3)$$

$$\dot{i}_{Lq} = (-R_L i_{Lq} - \omega L_l i_{Ld} + v_q)/L_l. \quad (4)$$

$$\dot{v}_d = (i_{td} - i_{Ld} - v_d/R + \omega C v_q - i_{CPLd})/C. \quad (5)$$

$$\dot{v}_q = (i_{tq} - i_{Lq} - v_q/R + \omega C v_d - i_{CPLq})/C. \quad (6)$$

Here, i, R, L, C, ω, v_d, and v_t are the current, resistor, inductor, capacitor, frequency, PCC voltage and line voltage, respectively. For instance, i_{td} and i_{tq} represent the line current in the d-q frame.

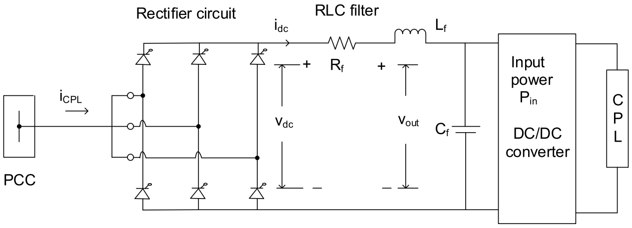

FIGURE 4. 3-phase diode rectifier and RLC filter in an AC microgrid [15], [16].

Usually, the CPL is connected to the AC bus via the rectifier circuit, RLC filter and converter. To clarify, Fig. 4 shows the schematic diagram of a CPL in the considered microgrid. The dynamic equation of RLC dc-link filter is expressed as follows:

$$\dot{i}_{dc} = (v_{dc} - R_f i_{dc} - v_{out})/L_f. \quad (7)$$

$$\dot{v}_{out} = (i_{dc} - \frac{P_{in}}{v_{out}})/C_f. \quad (8)$$

Here, i, P_{in}, v, L, and C represent the maximum current, converter/inverter input power, peak voltage, inductor and capacitor, respectively. For example, i_{dc} and v_{out} are the RLC filter current and output voltage, respectively. With appropriate firing angle and switching function in the rectifier circuit, the CPL line current i_{CPLd} for Eq. (5) is given by [18]:

$$i_{CPLd} = S_w i_{dc} = \sqrt{\frac{3}{2}}\frac{2\sqrt{3}}{\pi} i_{dc}. \tag{9}$$

$$i_{CPLq} = 0. \tag{10}$$

$$v_{dc} = S_w v_d = \sqrt{\frac{3}{2}}\frac{2\sqrt{3}}{\pi} v_d. \tag{11}$$

Here, the maximum magnitude of the stitching function S_w is equal to $\sqrt{\frac{3}{2}}\frac{2\sqrt{3}}{\pi}$ [16].

Now the above nonlinear set of system equations is linearised around the operating point $x^\star$ i.e., $x_i - x_i^\star$ where $x_i^\star$ is the operating point [15], [16]. After simple algebraic manipulations, the continuous-time state-space model of a microgrid is expressed as follows:

$$\dot{\mathbf{x}} = \mathbf{A}_c\mathbf{x} + \mathbf{B}_c u + \mathbf{n}, \tag{12}$$

where $\mathbf{x} = [\Delta i_{td}\ \Delta i_{tq}\ \Delta i_{Ld}\ \Delta i_{Lq}\ \Delta v_d\ \Delta v_q\ \Delta i_{dc}\ \Delta v_{out}]$,

$$\mathbf{A}_c = \begin{bmatrix} \frac{-R_t}{L_t} & \omega & 0 & 0 & \frac{-1}{L_{lt}} & 0 & 0 & 0 \\ -\omega & \frac{-R_t}{L_t} & 0 & 0 & 0 & \frac{-1}{L_t} & 0 & 0 \\ 0 & 0 & \frac{-R_L}{L_l} & \omega & \frac{1}{L_l} & 0 & 0 & 0 \\ 0 & 0 & -\omega & \frac{-R_L}{L_l} & 0 & \frac{1}{L_l} & 0 & 0 \\ \frac{1}{C} & 0 & \frac{-1}{C} & 0 & \frac{-1}{RC} & \omega & -\frac{S_w}{C} & 0 \\ 0 & \frac{1}{C} & 0 & -\frac{1}{C} & -\omega & \frac{-1}{RC} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{S_w}{L_f} & 0 & -\frac{R_f}{L_f} & \frac{-1}{L_f} \\ 0 & 0 & 0 & 0 & 0 & 0 & \frac{1}{C_f} & \frac{P_{in}}{C_f v_{out}^{2\star}} \end{bmatrix},$$

$S_w = \sqrt{\frac{3}{2}}\frac{2\sqrt{3}}{\pi}$, $\mathbf{B}_c = [0\ 0\ 0\ 0\ 0\ 0\ 0 - 1/(v_{out}^\star C_f)]'$ and $u = \delta P_{in}$. The symbol $\mathbf{n}$ is the process uncertainties due to linearization and variations in microgrid parameters by the surrounding ambient conditions. The process noise $\mathbf{n}$ is the zero mean Gaussian distribution [19]–[21] whose covariance matrix is $\mathbf{Q}(k)$. In order to apply the discrete-time estimation algorithm, the system is expressed as a disrate-time state-space model as follows:

$$\mathbf{x}(k+1) = \mathbf{A}\mathbf{x}(k) + \mathbf{B}u(k) + \mathbf{n}(k), \tag{13}$$

where $\mathbf{A} = \mathbf{I} + \Delta_t\mathbf{A}_c$, $\mathbf{B} = \Delta_t\mathbf{B}_c$, and Δ_t is step size parameter.

In order to monitor the microgrid farm, the service provider deploys the IoT elements such as sensors around the microgrids. The IoE infrastructure for sensing and estimating the system state is illustrated in Fig. 5. Basically, the voltage and current sensors are deployed to measure the microgrid states. Then it transmits to the energy management system through the internet which adds noise. The received signal at the energy management system is given by:

$$\mathbf{y}(k) = \mathbf{C}\mathbf{x}(k) + \mathbf{w}(k), \tag{14}$$

where $\mathbf{C}$ is the observation matrix and $\mathbf{w}(k)$ is the noise which considers zero mean Gaussian distribution with $\mathbf{R}(k)$ covariance matrix. In order to estimate the system states, the H-infinity based dynamic state estimation algorithm is proposed.

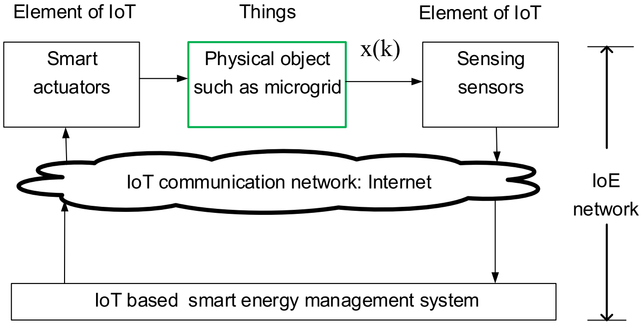

FIGURE 5. The IoE structure in the context of smart grid state estimation.

TABLE 1. System parameters using Matlab.

Parameters	Values	Parameters	Values
R_t	1.5×10^{-3} Ohm	R_L	5 Ohm
R_l	76 Ohm	R_f	$50 \times 10^{-3} Ohm$
L_l	$111.9 \times 10^{-3} H$	L_t	$70 \times 10^{-6} H$
C_f	$1 \times 10^{-3} H$	C	$62.855 \times 10^{-6} F$
P_{in}	0.7 pu W	Δ_t	0.000001
$\mathbf{Q}$	$0.00001\mathbf{I}$	$\mathbf{R}$	$0.0012\mathbf{I}$

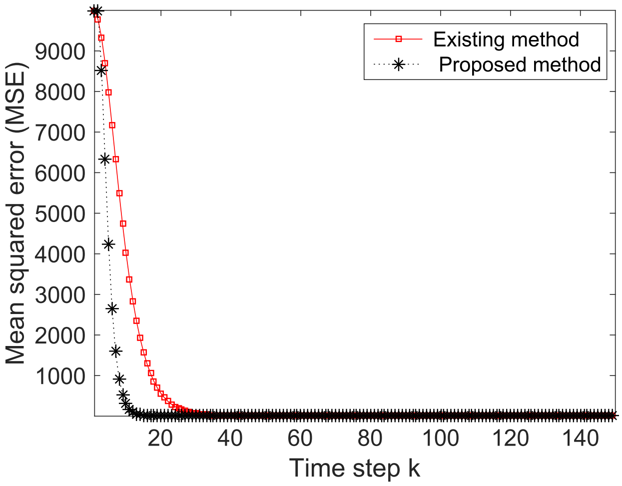

FIGURE 6. Estimation performance comparison.

IV. H-INFINITY BASED STATE ESTIMATION ALGORITHM

The H-infinity is a recursive algorithm which computes the system state, gain and covariance matrix based on the worst case noise values. In contrast to the traditional KF method, the H-infinity will no need to know the exact noise statistics. Instead, it uses the worst case noise statistics which minimize the cost function and provides an accurate estimation. In short, the smart energy management system implements the following H-infinity steps as follows [22], [23]:

$$\hat{\mathbf{x}}(k+1) = \mathbf{A}\hat{\mathbf{x}}(k) + \mathbf{B}u(k) + \mathbf{K}(k)[\mathbf{y}(k) - \mathbf{C}\hat{\mathbf{x}}(k)]. \tag{15}$$

Here, $\hat{\mathbf{x}}(k)$ is the initial estimation result, and the gain $\mathbf{K}(k)$ is computed as follows:

$$\mathbf{K}(k) = \mathbf{P}(k)[\mathbf{I} - \theta\bar{\mathbf{H}}(k)\mathbf{P}(k) + \mathbf{C}'\mathbf{R}^{-1}(k)\mathbf{C}\mathbf{P}(k)]^{-1}\mathbf{C}'\mathbf{R}^{-1}(k). \tag{16}$$

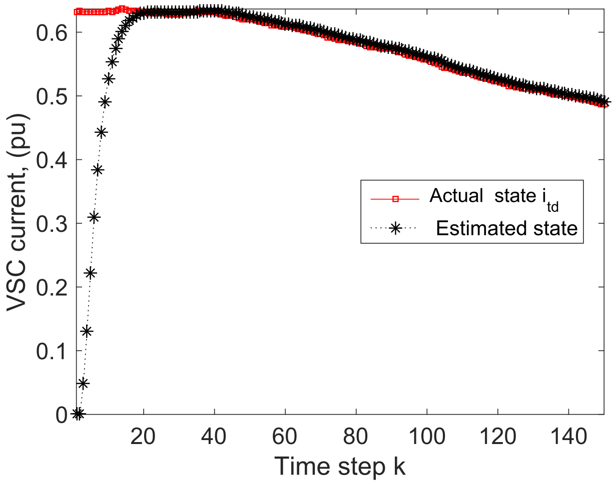

FIGURE 7. VSC current in d-frame i_{td} and its estimation.

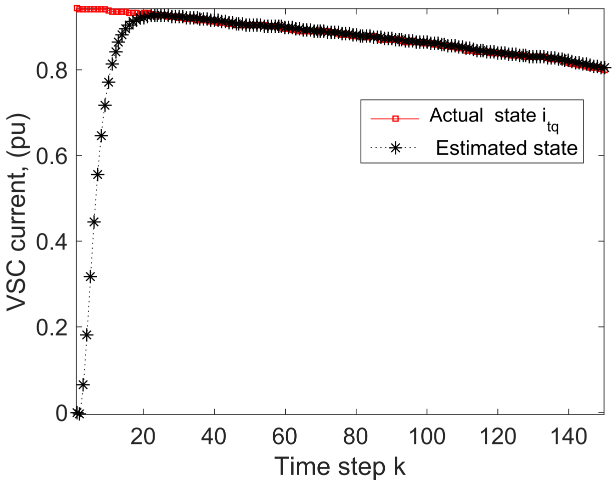

FIGURE 8. VSC current in q-frame i_{tq} and its estimation.

Here, $\mathbf{P}(k)$ is the initial error covariance, θ is the user specified bound and $\bar{\mathbf{H}}(k) = \mathbf{L}(k)\mathbf{H}(k)\mathbf{L}'(k)$, where $\mathbf{L}(k)$ as well as $\mathbf{H}(k)$ are the performance variables chosen by the engineer based on the specific problem. The estimated covariance matrix $\mathbf{P}(k+1)$ is given by:

$$\mathbf{P}(k+1) = \mathbf{A}\mathbf{P}(k)[\mathbf{I} - \theta\bar{\mathbf{H}}(k)\mathbf{P}(k) + \mathbf{C}'\mathbf{R}^{-1}(k)\mathbf{C}\mathbf{P}(k)]^{-1}\mathbf{A}' + \mathbf{Q}(k). \tag{17}$$

In each iteration, the following condition must hold:

$$\mathbf{P}^{-1}(k) - \theta\bar{\mathbf{H}}(k) + \mathbf{C}'\mathbf{R}^{-1}(k)\mathbf{C} > \mathbf{0}. \tag{18}$$

In the next section, the performance of the proposed algorithm is verified through the numerical simulations.

V. SIMULATION RESULTS AND DISCUSSION

The simulation parameters are illustrated in Table 1. The considered parameters are based on the balanced load conditions. Moreover, the noise statistics are independent Gaussian distribution. The discritization step size parameter is 0.000001.

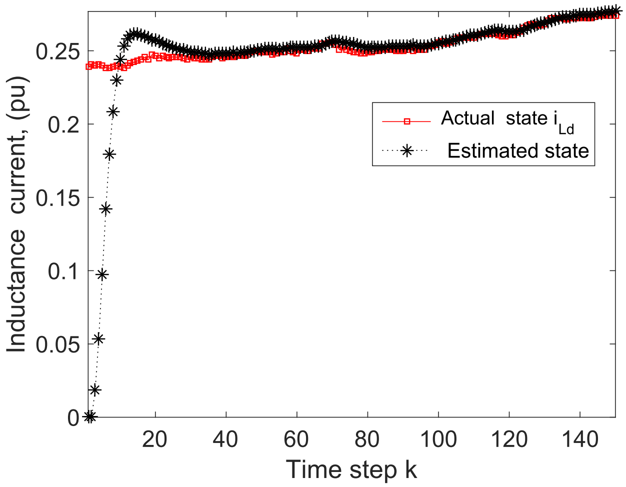

FIGURE 9. Inductance current in d-frame i_{Ld} and its estimation.

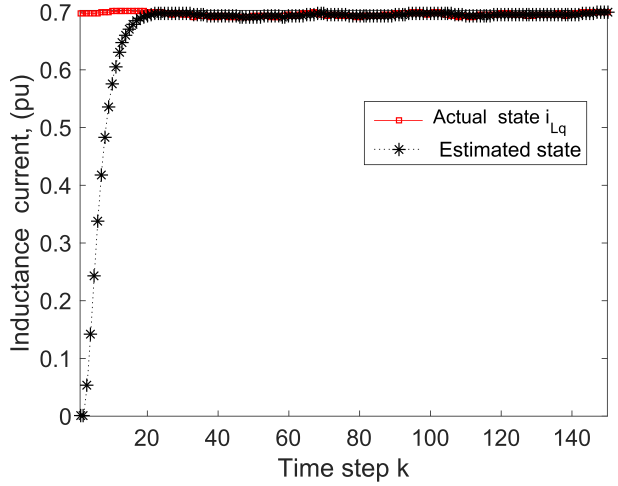

FIGURE 10. Inductance current in q-frame i_{Lq} and its estimation.

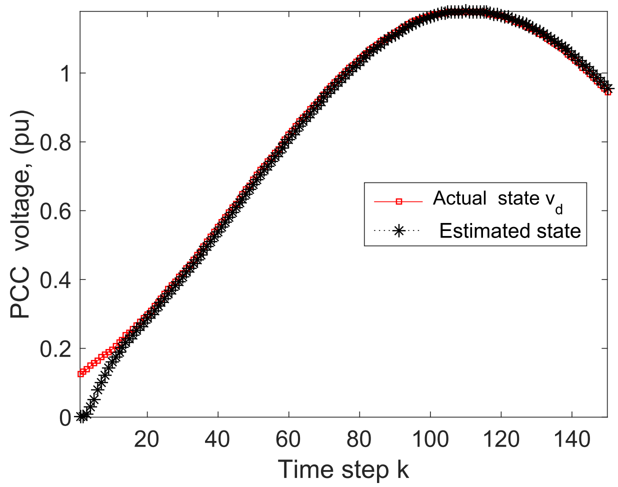

FIGURE 11. PCC voltage in d-frame v_d and its estimation.

After modelling the microgrid the proposed algorithm is applied for system state estimations. From the simulation result in Fig. 6, it shows that the proposed method achieves

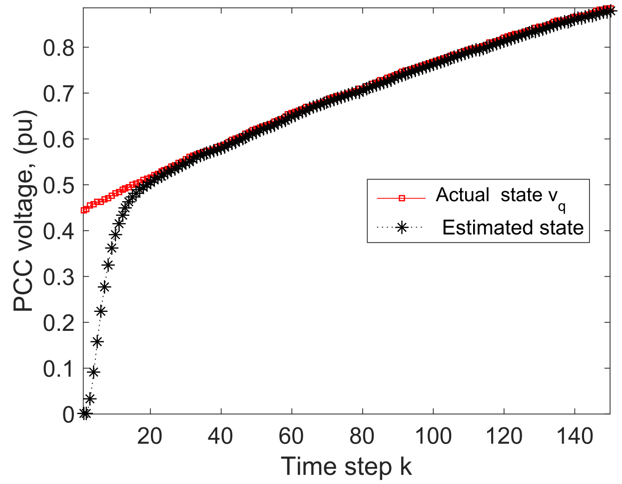

FIGURE 12. **PCC voltage in q-frame v_q and its estimation.**

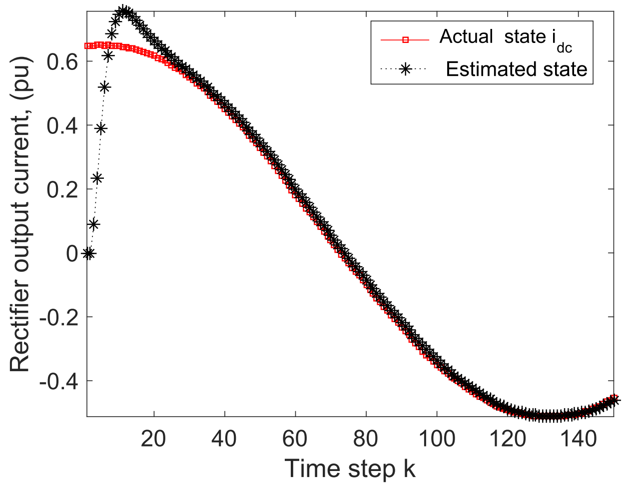

FIGURE 13. **Rectifier output current i_{dc} and its estimation.**

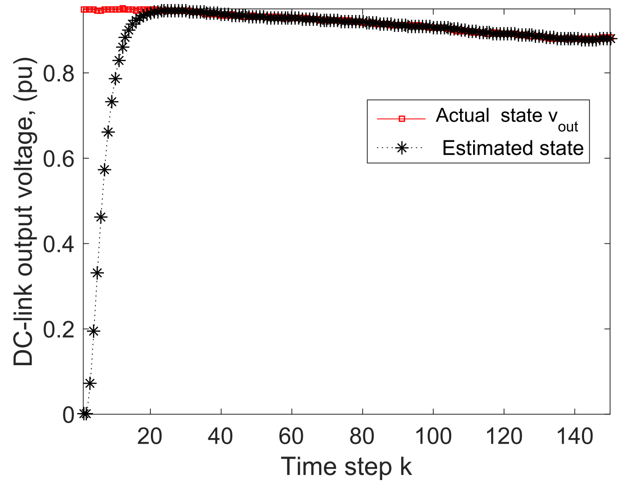

FIGURE 14. **DC output voltage v_{out} and its estimation.**

better mean squared error performance compared with the existing method [8]. Moreover, the state variation vs time step is illustrated in Figs. 7-14. For instance, Fig. 7 shows the VSC current variation, and it can be seen that the proposed approach can estimate the system state writhing few time steps. The similar kind of estimation performance is obtained. Note that the system is open loop, so the generated states are vary randomly with time, which totally depends on the state transition matrix **A**. In the future, we will apply a suitable control algorithm to stabilise the system states.

VI. CONCLUSION AND FUTURE WORK

This paper proposes the H-infinity based centralised microgrid state estimation. The microgrid is expressed as a state-space model, then we applied the H-infinity based state estimation algorithm. It shows that the proposed algorithm achieves better performance than the existing approach. So, this framework will assist the vision of IoT network in the context of smart grid communication systems. The future work will include the packet loss parameter in the estimation process.

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MD MASUD RANA research interests are in the theoretical and algorithmic studies in signal processing and optimizations, statistical learning and inferences for high dimensional data, distributed optimizations and adaptive algorithms, and their applications in communications, networked systems, and smart grid.

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