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Kalman-Filter-Based State Estimation for System Information Exchange in a Multi-bus Islanded Microgrid

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Keywords: state estimation, information exchange, islanded microgrid, droop control.

Abstract

State monitoring and analysis of distribution systems has become an urgent issue, and state estimation serves as an important tool to deal with it. In this paper, a Kalman-Filter-based state estimation method for a multi-bus islanded microgrid is presented. First, an overall small signal model with consideration of voltage performance and load characteristic is developed. Then, a Kalman-Filter-Based state estimation method is proposed to estimate system information instead of using communication facilities, where the estimator of each DG unit can dynamically obtain information of all the DG units as well as network voltages just by local voltage and current itself. The proposed estimation method is able to provide accurate states information to support system operation without any communication facilities. Simulation and experimental results are given for validating the proposed small signal model and state estimation method.

1 Introduction

Distributed power systems, combing distributed generator (DG) units, local loads and energy storing devices, received an increasing attention in recent years. Microgrid[1], for instance, is presented as a small scale distributed power system to provide power to local loads. In general, a microgrid is allowed to operate either in a grid-connected mode or an islanded mode [2].

For islanded microgrids, distribution management system (DMS) performing monitoring, analysis and control has become an urgent issue[3].The complexity and dynamic nature of islanded microgrids makes it difficult to monitor and manage the whole system. Generally, communication facilities are employed to support monitoring and management in islanded microgrids. For instance, it is used for state monitoring [4], power quality control [5] and optimal management [6], etc. However, communication facilities tend to bring side effects due to the data drop-out and latency [7], which thus makes islanded operation less reliable and ineffective. Besides, distribution management system (EMS) requiring communication links are relatively expensive.

To lessen the communication system burden, state estimation methods [3-4] are presented to obtain system information. It would be dramatically beneficial to support monitoring and control of islanded microgrids towards a more reliable and flexible operation. However, communication links are still required to support state estimation process (even if low bandwidth communication) in these conventional state estimation methods [3-4].

In addition, system dynamic model is particularly essential for state estimation implementation. Small signal model of islanded microgrids is available to represent system dynamic responses under load disturbances [8]. Previous small signal model of a stand-alone microgrid have been established in [9]. The small signal dynamic model considering active and reactive power management strategies is presented in [6], which is developed to examine system sensitivity to parameters variation. A systematic small signal model of islanded microgrids, including DG units, power controllers, network dynamic as well as load performances, has been proposed in [8]. However, the virtual resistors, which are assumed between each node and ground for defining network voltages, may lead to an inaccurate small signal network model and thus voltage responses may not be considered accurately. Besides, it has a negative influence on dynamic stability of the system.

To estimate system information accurately, a small signal model of islanded microgrid with a consideration of network voltage dynamic and load characteristic is first proposed. Then, a Kalman-Filter-Based state estimation method without communication facilities is developed to obtain system information according to the proposed small signal model. The proposed estimator of each DG unit can obtain dynamic responses of all the DG units as well as network voltages just through local voltage and current itself without any communication facilities.

2 State estimation in microgrid

State estimation methods have received plenty of attentions in distribution systems [10]. Fig.1 illustrates state estimation scheme with communication infrastructure in distribution management system [3-4] (DMS). In detail, an autonomous state estimation method [3] is presented to implement monitoring and analysis of distribution systems. A multi-microgrid state estimator based on conventional weight least square algorithm is proposed in [11]. A Belief Propagation-Based state estimator of distribution system is adopted to lessen communication system burden in [12]. However, communication facilities are required to support state estimation process. In particular, when various DG units and loads are located far away from each other, the fixed communication infrastructures make islanded microgrids less flexible and reliable. In [13], an independent local Kalman state estimation approach is presented, which is based on local models of power network associated with a virtual disturbance model without communication facilities. But it is difficult to estimate network voltages and states of all the DG units. To deal with the issue, this paper proposes a communication-less state estimation method for islanded microgrids.

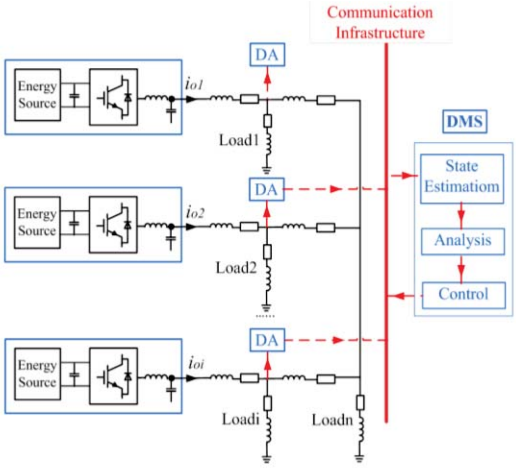


Fig.1. Conventional state estimation scheme with communication infrastructure in DMS.

3 The proposed state estimation method

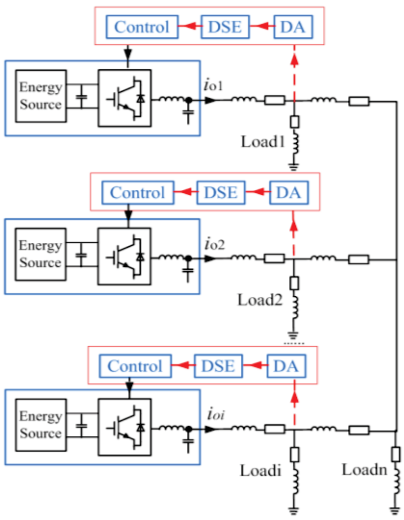


Fig.2.The proposed state estimation scheme.

The proposed state estimation scheme is based on small signal model. As shown in Fig.2, distributed state estimator (DSE) of each DG unit acquires local voltage and current from data acquisition (DA) unit and estimates system information. Further, the estimated information is used to support system analysis and control. The analysis and control procedures are out of the range of this paper. The main benefit of the proposed method is that DG units are completely independent with each other and no communication links are needed.

3.1 Small signal model of islanded microgrids

In the section, the small signal model of distributed generator (DG) is represented by a controllable voltage source, assuming current controller and voltage controller have much faster speed than power controller. Fig.3 depicts a small signal model diagram of an islanded microgrid configuration combining DG units, network and loads.

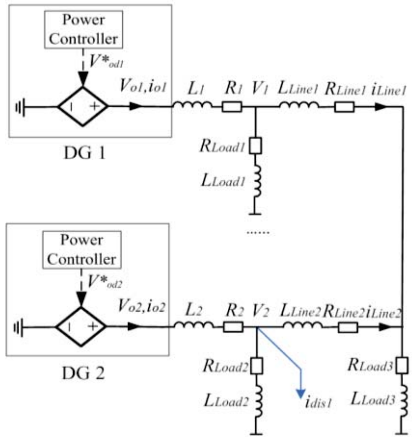


Fig.3. Small signal model of an islanded microgrid.

Small signal dynamic of each DG unit is formulated on local frame d-q, and all the DG units, network and loads dynamic are represented on DG common frame by transformation equation [8]. The average active power and reactive power are obtained separately from instantaneous powers passing one-order low-pass filters:

$$P_i = \frac{\omega_c}{s+\omega_c}(V_{odi}i_{odi} + V_{oqi}i_{oqi}) \tag{1}$$
$$Q_i = \frac{\omega_c}{s+\omega_c}(V_{odi}i_{oqi} - V_{oqi}i_{odi})$$

Further, conventional active power-frequency droop, reactive power-voltage droop control method for paralleled inverters operation [8-9] can be written as (2):

$$\omega_i = \omega^* - m_{pi}P_i \tag{2}$$
$$V_{oi} = V^* - n_{qi}Q_i$$

Then, output current of DG unit can be represented as

$$\frac{di_{odi}}{dt} = -\frac{R_i}{L_i}i_{odi} - \omega i_{oqi} + \frac{1}{L_i}V_{odi} - \frac{1}{L_i}V_{dk} \tag{3}$$
$$\frac{di_{oqi}}{dt} = -\frac{R_i}{L_i}i_{oqi} + \omega i_{odi} + \frac{1}{L_i}V_{oqi} - \frac{1}{L_i}V_{qk}$$

Small signal dynamics of individual inverter can be represented in a general standard state space form by combining and linearizing (1)-(3):

$$\Delta \dot{x}_{invi} = A_{invi}\Delta x_{invi} + B_{invi}\Delta V_j \tag{4}$$

where $\Delta x_{invi} = \left[\Delta\delta_i, \Delta P_i, \Delta Q_i, \Delta V_{odi,} \Delta i_{odi,} \Delta i_{oqi}\right]^T$, $\Delta V_j = \left[\Delta V_{dj} \quad \Delta V_{qj}\right]^T$. $i = 1,2; k = 1,2$. ω_i is rotating angle frequency of ith DG unit; V_{odqi}, i_{odqi} are output voltage and current on individual frame (d-q); P_i, Q_i are average active and reactive power; m_{pi}, n_{qi} are droop coefficient of active power and reactive power. A_{invi}, B_{invi} are parameters matrixes of individual inverter. The detail modelling procedures of DG units can be referred in [8].

3.2 The proposed small signal network model

First, network and loads dynamic can be linearized and represented on common frame (DQ) according to KCL as (5):

$$\begin{bmatrix} \Delta \dot{i}_{LineDQ} \\ \Delta \dot{i}_{LoadDQ} \end{bmatrix} = A_{net}\begin{bmatrix} \Delta i_{LineDQ} \\ \Delta i_{LoadDQ} \end{bmatrix} + B_{net1}\left[\Delta i_{oDQ}\right] + B_{net2}\left[\Delta \dot{i}_{oDQ}\right] + B_{net3}\Delta i_{disDQ} \tag{5}$$

To avoid the negative influence of virtual resistor defining network voltages in [8], the network voltages are expressed as linear combination of system states according to KCL as (6), shown in Fig.3.

$$\begin{aligned} V_1 &= R_{Load1}(i_{o1} + i_{Line1}) + L_{Load1}\frac{d(i_{o1} + i_{Line1})}{dt} \\ V_2 &= R_{Load2}(i_{o2} + i_{Line2} - i_{dis1}) + L_{Load2}\frac{d(i_{o2} + i_{Line2} - i_{dis1})}{dt} \\ V_3 &= R_{Load3}(-i_{Line1} - i_{Line2}) + L_{Load3}\frac{d(-i_{Line1} - i_{Line2})}{dt} \end{aligned} \tag{6}$$

Now, the small signal voltage equations can be obtained as (7) by transforming (6) on common frame (DQ) and combining (4),(5) and (6):

$$V_{bDQ} = C_1\left[x_{inv}\right] + C_2\begin{bmatrix} \Delta i_{LineDQ} \\ \Delta i_{LoadDQ} \end{bmatrix} + C_3\left[i_{disDQ}\right] \tag{7}$$

C_1, C_2, C_3 are voltages parameter matrixes. A_{net} , B_{net1} , B_{net2} , B_{net3} are lines and loads parameters matrixes; i_{disDQ} are unknown disturbances, which depicts the influence of disturbances on equilibrium state of an islanded microgrid.

Finally, an overall model including inverters, loads, network by combining (4),(5) and (7) can be rewritten as

$$\begin{aligned} \Delta \dot{x} &= A\Delta x + B\Delta i_{dis} \\ \Delta y &= C\Delta x + D\Delta i_{dis} \end{aligned} \tag{8}$$

where Δx is overall state vector of whole microgrid, $\Delta x = \left[\Delta x_{inv1} \cdots \Delta x_{invn}, \Delta i_{line1} \cdots \Delta i_{linei}, \Delta i_{load1} \cdots \Delta i_{loadi}\right]$, A, B, C, D are system parameters matrixes. To allow a simpler representation, sign Δ in small signal model is omitted in the following contents.

3.3 The proposed Kalman-Filter-based state estimation

System dynamic responses under load disturbances can be described in a discrete state space form according to (8) as follows:

$$x(k+1) = A_d x(k) + B_d i_{dis}(k) \tag{9}$$

$$y_m(k) = C_m x(k) + D_d i_{dis}(k) + D_m n\ (k) \tag{10}$$

$$y_{um}(k) = C_{um} x(k) + D_d i_{dis}(k) \tag{11}$$

where (9) is an extended model combining plant of microgrid with disturbance model and measurement noises. (9)-(11) is well-established relationship between measured output $y_m(k)$, system states $x(k)$, disturbance inputs $i_{dis}(k)$ and measurement noise $n(k)$, where $n(k)$ is added to measured output for imitating sensor noise and environment disturbance.

In fact, internal states contain adequate operation information of the whole system, which provides possibility to reconstruct desired states according to the measured states. State estimation equation is given by [14]

$$x(k|k) = x(k|k-1) + K(y_m(k) - y_m(k|k-1)) \tag{12}$$

K is the Kalman gain, which is the solution of Ricatti matrix equation. Estimated output and state update equation are given as (13) and (14):

$$y_m(k|k-1) = C_m x(k|k-1) \tag{13}$$

$$x(k+1|k) = Ax(k|k) \tag{14}$$

These estimated states are updated continuously via update of measured output voltage and current of each DG unit. Then, state estimation equations of each DG unit can be obtained by combing (12), (13) and (14) as follows:

$$x(k+1|k) = A_o x(k|k-1) + B_o y_m(k) \tag{15}$$

$$y_m(k+1|k) = C_{om} x(k+1|k) \tag{16}$$

$$y_{um}(k+1|k) = C_{oum} x(k+1|k) \tag{17}$$

where $A_o = A - A*K*C_m$, $B_o = A*K$. C_{om}, C_{oum} are measured and unmeasured output matrixes, respectively.

(1) DG units state estimation.

To be exact, for ith DG unit, local states vector $y_m(k) = \left[V_{odi}, i_{odi}, i_{oqi}\right]$ is defined as measured output, while other units' state vector $y_{um}(k) = \left[V_{odj}, i_{odj}, i_{oqj}\right](j \neq i)$ is defined as unmeasured output. The principle of DG unit estimator is shown in Fig.4.

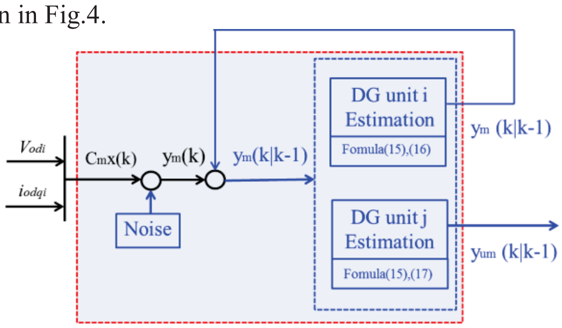


Fig.4. The proposed DG units estimator

(2) Network voltage estimation.

Similarly, network voltages also can be estimated by the proposed method. For ith DG, local state vector $y_m(k) = \left[V_{odi}, i_{odi}, i_{oqi}\right]$ is still viewed as measured output, while network voltages $y(k) = \left[V_1, V_2, \cdots, V_j\right]$ is selected as unmeasured output. The principle of network voltage estimator is shown in Fig.5. And voltage estimation output equation can be represented as (18)

$$y_{um}(k|k-1) = \begin{bmatrix} V_1(k|k-1) \\ V_2(k|k-1) \\ \vdots \\ V_j(k|k-1) \end{bmatrix} = \begin{bmatrix} C_{b1} \\ C_{b2} \\ \vdots \\ C_{bj} \end{bmatrix} x(k|k-1) \tag{18}$$

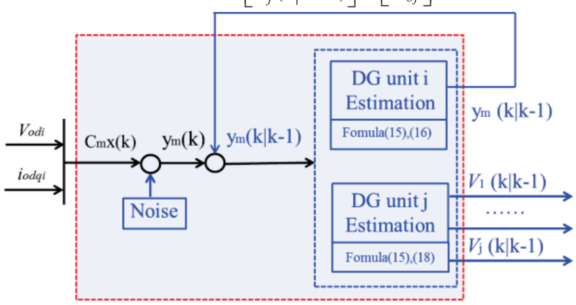


Fig.5. The proposed network voltages estimator

Then, DG units can dynamically estimate system information just by local voltage and current itself.

4 Simulation and Experimental Verification

To verify correctness and effectiveness of the proposed small signal model and state estimation method, the simulations in MATLAB/SIMULINK and experiments have been carried out respectively on a three phase 50Hz prototype islanded microgrid. As depicted in Fig.6, the experiment setup is composed of two inverters in parallel operation, three RL loads and a RL disturbance load. Also, the photograph of the laboratory setup is shown in Fig.7.

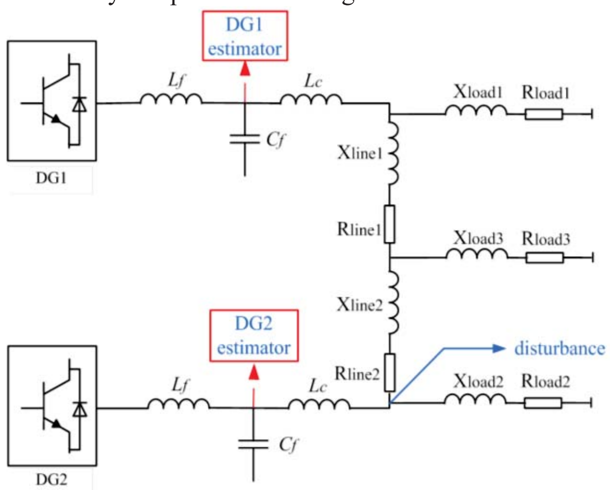


Fig.6. The simulation and experiment setup

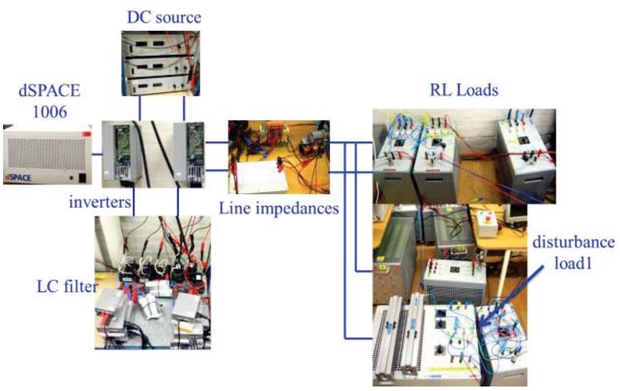


Fig.7 The photograph of experiment setup.

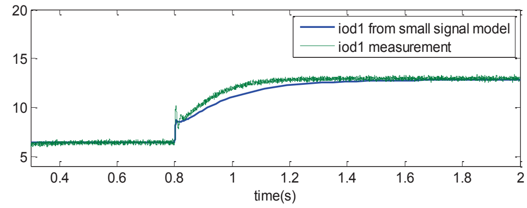
TABLE I

PARAMETERS FOR SIMULATION AND EXPERIMENT

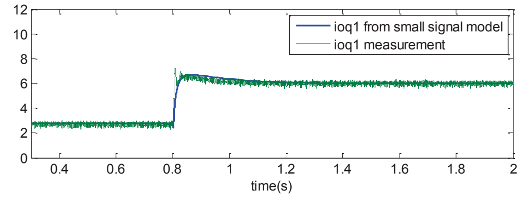
Parameters	Value	Parameters	Value
inverter rate	11kVA/5kVA	L_c	1.8mH
f_s	10k	$R_{line1}+jX_{line1}$	0.2+j0.565
L_f	1.5mH	$R_{line2}+jX_{line2}$	0.2+j0.565
C_f	25μF	$R_{load1}+jX_{load1}$	64.5+j48.67
mp1/mp2	2.5e-5/1e-4	$R_{load2}+jX_{load2}$	64+j48.98
nq1/nq2	1e-3/1e-3	$R_{load3}+jX_{load3}$	80+j76.93

4.1 Small signal model considering voltage dynamic.

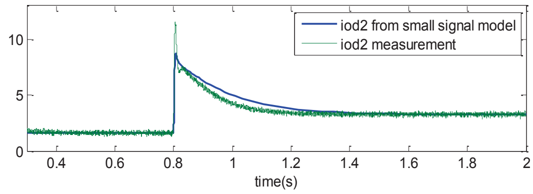
To validate the proposed small signal model, a disturbance load(R=10Ω, L=50mH) is exerted at bus2 as shown in Fig.6. The simulation results are illustrated in Fig.8 and Fig.9.



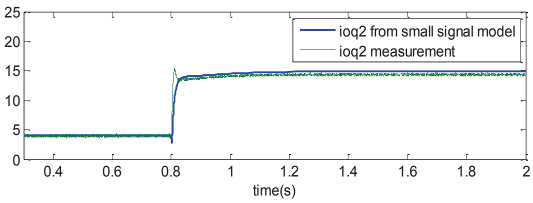
(a)



(b)

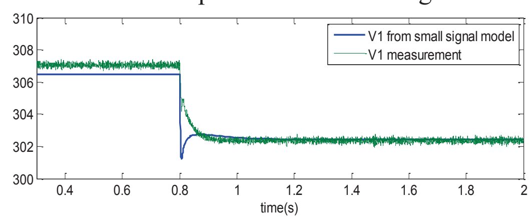


(c)

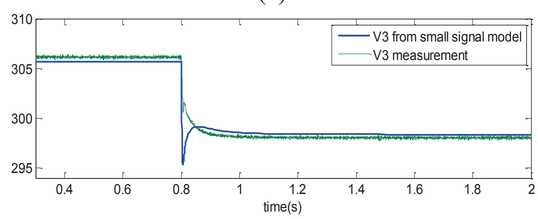


(d)

Fig.8.The currents responses from small signal model.



(a)



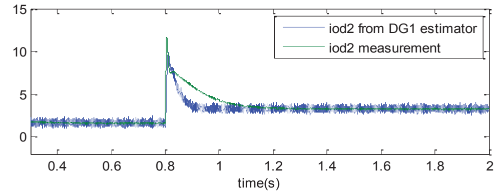
(b)

Fig.9. Network voltages responses from small signal model.

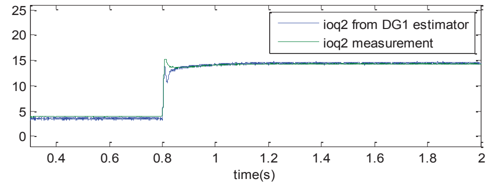
It can be observed that active and reactive power currents of DG units increase to track power demand for the load disturbance, shown in Fig.8.(a)-(d). Results from small signal model almost match with counterparts of time simulation. Fig.9.(a)-(b) depicts network voltages responses at different bus for the load disturbance. It can be seen that voltages decrease at each bus due to inherent droop control effect. Voltage response results at bus1 and bus3 from small signal model nearly match with counterparts of time simulation.

4.2 The proposed state estimation for DG units.

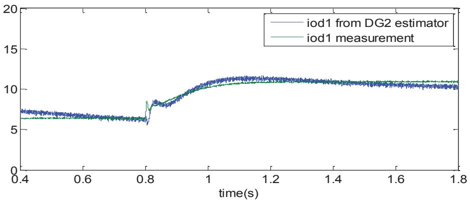
To validate the proposed network voltage estimator, disturbance load (R=10, L=50mH) is exerted at bus2 at 0.8s. In accompanying experiment, the system is disturbed deliberately by load (R=10, L=110mH) at bus2 at 3s.



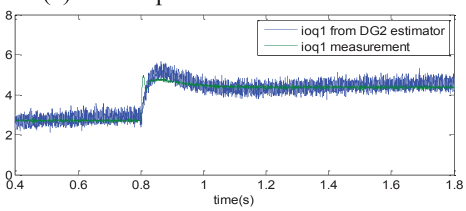
(a) Active power current of DG2



(b) Reactive power current of DG2

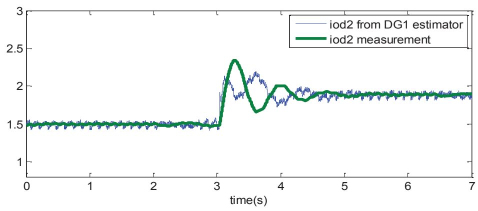


(c) Active power current of DG1

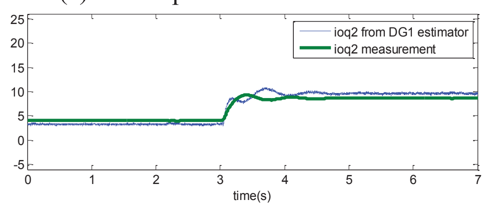


(d) Reactive power current of DG1

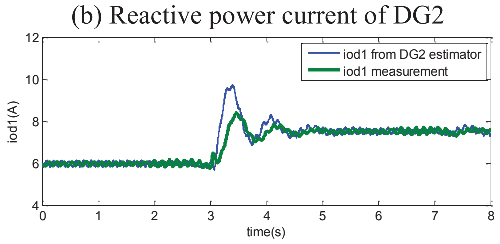
Fig.10. The simulation results for DG unit state estimation.



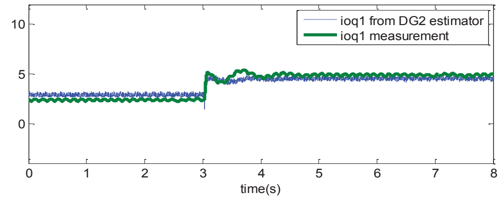
(a) Active power current of DG2



(b) Reactive power current of DG2



(c) Active power current of DG1



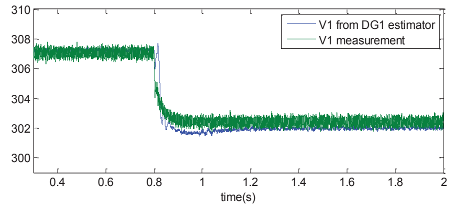
(d) Reactive power current of DG1

Fig.11. The experimental results for DG unit state estimation.

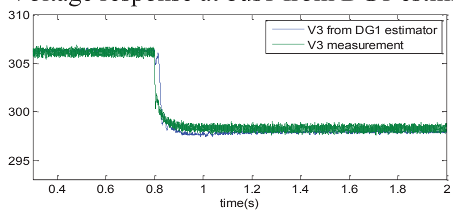
Fig.10.(a)-(b) shows simulation results about active power current and reactive power current responses of DG2 from DG1 estimator, and Fig.11.(a)-(b) depicts experimental results about current responses of DG2 from DG1 estimator. Similarly, Fig.10.(c)-(d) depicts estimated states of DG1 from DG2 estimator, and experimental results about estimated currents responses of DG1 are given in Fig.11.(c)-(d). It can be seen obviously that the currents responses of DG1 and DG2 from estimators nearly match with real counterparts in both simulations and experiments. The tight correspondence between simulated and experimental results can be noted. Hence, the correctness and effectiveness of the proposed DG estimators is confirmed.

4.3 The proposed network voltage estimator.

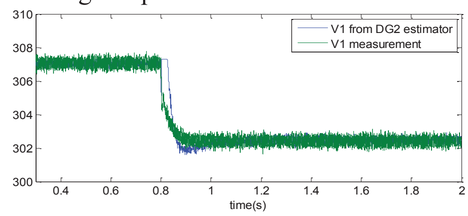
To validate the proposed network voltage estimator, disturbance load (R=10, L=50mH) is exerted at bus2 at 0.8s. In accompanying experiment, the system is disturbed by the load (R=10, L=110mH) at 4s.



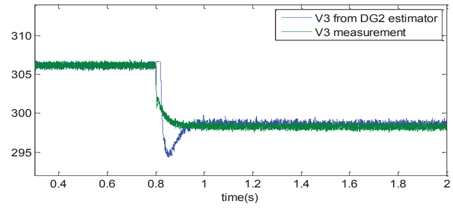
(a) Voltage response at bus1 from DG1 estimator



(b) Voltage response at bus3 from DG1 estimator

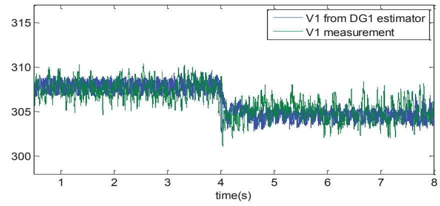


(c) Voltage response at bus1 from DG2 estimator

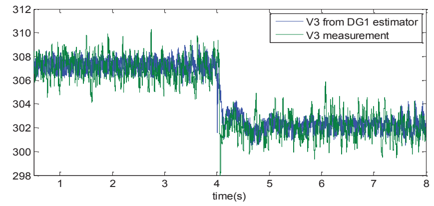


(d) Voltage response at bus3 from DG2 estimator

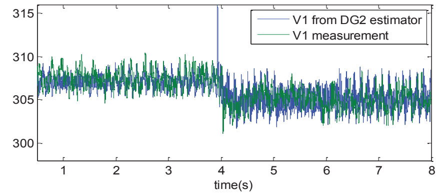
Fig.12.The simulation results for network voltage estimation.



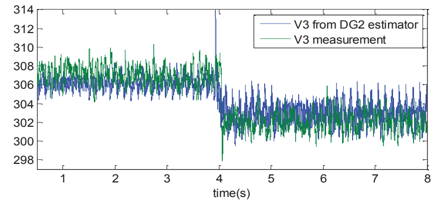
(a) Voltage response at bus1 from DG1 estimator



(b) Voltage response at bus3 from DG1 estimator



(c) Voltage response at bus1 from DG2 estimator



(d) Voltage response at bus3 from DG2 estimator

Fig.13. Experimental results for network voltage estimator.

Fig.12.(a)-(b) and Fig.13.(a)-(b) depicts simulation and experimental results about voltages responses from DG1 estimator, respectively. Similarly, simulation and experimental results from DG2 estimator are shown in Fig.12.(c)-(d) and Fig.13.(c)-(d). It can be seen that the proposed estimators can estimate network voltages change effectively at bus1 and bus3.Simulation and experimental results shows that the proposed DG estimator and network voltage estimator is able to estimate system dynamic responses effectively and thus perform information exchange without communication facilities.

5 Conclusion

In this paper, a Kalman-Filter-Based state estimation method for an islanded microgrid is presented, which is able to perform information exchange without any communication facilities. First, a small signal model considering voltage performance is developed. Then, a Kalman-Filter-Based state estimation method is exploited to preform information estimation. The local estimator of each DG unit can obtain dynamically voltage and current of all the DG units as well as network voltages information. Simulation and experimental results shows that (1) the proposed small signal model is correct and effective to represent system dynamic responses; (2) the proposed estimators can estimate system responses effectively and thus provide information exchange for supporting system operation.

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