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Improving Control Performance in DC Micro-Grids with Distributed Generations

Weilin Li*, Huimin Li, Min Luo*, Yunfei Zhang*****
*E.ON Energy Research Center, RWTH Aachen University
**Departement of Electrical Engineering, University of South Carolina
*******Departement of Mechanical Engineering, University of British Columbia

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ABSTRACT

DC micro-grids are attracting more and more attention due to their capability to lead to more efficient integration of distributed generation compared with traditional AC micro-grids. In this paper, a hierarchical control architecture is proposed to improve the control performance of DC micro-grid with distributed generations (DGs), which utilize a global controller (GC) to optimize the overall process and a number of distributed local controllers (LCs) associated with each subsystem. The measurement reliability of each LC is guaranteed by an associated measurement validation module which is developed based on Polynomial Chaos Theory (PCT). The system efficiency and robust is counted in the design of GC, where synergetic control theory is adopted. Numerical simulations have been done to verify the proposed method, and the simulation results show good consistency with theoretical analysis.

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Corresponding Author:

Weilin Li,
Departement of Electrical Engineering and Information Technology,
RWTH Aachen University,
Kastanieweg 27, 52074, Aachen, Germany.
Email: wli@eonerc.rwth-aachen.de

1. INTRODUCTION

Recently, there has been a significant increase in the research, development, and use of distributed generations (DGs) in the electric power system at the distribution level [1]. The prospect of generating power from clean energy sources and local power generation near consumers has fundamentally changed the way of thinking with regard to the conventional centralized, large generation-based power systems. Power systems composed of small-scale distributed energy resources, such as wind turbines, fuel cells, photovoltaic, storage devices, etc. can be stand alone and grid connected. Many of these generation sources directly produce either dc or variable frequency/voltage ac outputs and, thus, prolific challenges exist in integrating increasing levels of distributed energy resources into the grid. Isolating some portions of the grid as self-regulating micro-grid has been proposed as one promising approach [2]. A working definition of micro-grid is a distribution level network of generators and electrical and thermal loads that can exchange power with other networks, each through a single gateway.

DC micro-grids are attracting more attention because they can lead to more efficient integration of distributed generation compared with traditional AC micro-grids. They will enable distributed energy resources usage worldwide at various levels of power delivery and increase the efficiency with which multiple renewable energy sources such as photo-voltaic cells, fuel cells and wind turbines can provide aggregate power to a group of loads. Because both loads and sources can be interfaced to a common DC bus with fewer redundant stages of power conversion, the result is less waste heat and potentially lower cost than AC based implementations [3]. Other key advantages are the ease with which multiple sources can be parallel connected to a single bus without increasing the circuit and control complexity, allowing for a more robust de-centralized approach to power flow management using voltage droop, and an improved ride-through capability when energy sources drop off of the bus [4][5]. To connect an energy source to a dc system only the voltage has to be controlled, as opposed to the ac system where voltage magnitude, frequency and phase must be matched [6].

According to previous literatures, control of DC micro-grids has been studied regarding its stability, grid connection, voltage control and power flow. However, one of the main assumptions in all the previous proposed control algorithms is the instantaneous recognition of the disturbances or changes in the system without considering measurement failure in the systems.

In order to solve the above mentioned problem and achieve the targeted benefits of DC micro-grids, incremental efforts are made in this paper. A hierarchical control architecture is proposed with one global controller (GC) that optimizes the overall process and a distributed number of local controllers (LCs) associated with each source of the DC micro-grid to make the control more efficient and also more easier. In the LC, polynomial chaos theory (PCT) based method is used to realize the sensor validation (SV) and information rebuilding, which further guarantees the assumption that all the measured data is right when we apply the control algorithms in DC micro-grids, and thus leads to a robust control performance. On the other hand, the GC has the capability to apply coordinative control to maximize the system efficiency.

In this work, SV module in LC includes measurement diagnosis, measurement failure detection and isolation, and bad data reconstruction. An observer based on PCT model of the system is adopted to achieve the goal for SV. The advantage of using PCT instead of conventional Monte Carlo method to build the system model is that Monte Carlo methods do not represent a viable option for on line operation. Moreover, PCT is a fast stochastic method [7]-[9]. It enables fast computation of the boundaries of the distribution of each variable, given a known probability distribution function (PDF). The dynamically yielded boundaries [10] can be used to generate thresholds that represent the limit reasonable value of a variable for validating actual measurements. Using dynamically computed, instead of pre-determined thresholds makes the measurement validation method here advantageous over other work in the literatures.

For the global controller design, we use synergetic control theory, which is based on ideas of self-organization [11] [12]. The theory allows designers to derive analytical control laws for nonlinear, high-dimensional, and multi-connected systems. We illustrate the capability of the synergetic control to maximize the system efficiency by means of coordinative control that changes the number of operating converters. And to show overall flexibility and efficiency of application of synergetic control theory for DC/DC converter control design.

The rest of the paper is divided into four parts. The configuration of the proposed DC micro-grid is presented in Section II. The general control structure is introduced in Section III. In section IV, the local controller design together with the application of PCT is provided. Section V gives the detailed design of global controller with synergetic control theory. Simulation results are given in section VI. Conclusion is made in section VII.

2. STUDIED DC MICRO-GRID MODEL

The proposed configuration of DC micro-grid integrates the following subsystems with separate control units and a grid connected voltage source converter (G-VSC), as shown in Figure 1.

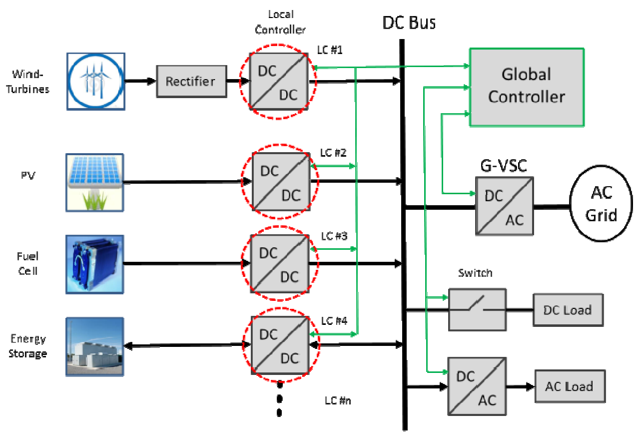

Figure 1. Investigated DC micro-grid configuration

All the energy systems are connected in parallel to a common DC bus line through DC/DC boost converters.

Photovoltaic (PV) systems are becoming increasingly important as renewable energy sources since they offer many advantages such as, incurring no fuel costs, no pollution, requiring little maintenance, and emitting no noise, among others.

The fuel cell (FC) is an electrochemical device that converts the chemical energy of fuel directly into electric energy. Water and heat are the only byproducts if the fuel is pure hydrogen.

PV arrays and FCs produce DC voltage and, therefore, are suitable to be connected to the DC bus via a DC/DC converter. With respect to DC/DC converter topologies, the boost converter is considered the most advantageous in this application because of its simplicity, low cost and high efficiency.

Similarly, wind-turbine generators are also preferred due to the fact that their energy sources are free and sustainable, produce voltage with varying frequency. To connect the wind turbine to a DC bus, a rectifier together with a DC/DC boost converter is used.

The availability or the transient response of the above mentioned DGs require them to be combined with other energy sources or energy storage. Furthermore, energy storage (ES) can be used for power-quality (PQ) improvement, load leveling, or emergency power supply. They are connected to the dc bus with a bidirectional DC/DC converter.

Through the use and the control of G-VSC, the DC micro-grid can achieve DC bus voltage regulation/stabilization at the input of the inverter if one or more energy sources are diminished. This leads to increased robustness and high power quality of the electric power injected to the grid from the VSC.

3. GENERAL CONTROL STRUCTURE

The proposed control architecture consists of a GC that optimizes the overall process and a distributed number of LCs associated with each subsystem in DC micro-grid (as shown in Figure 1).

The LC is responsible for each of the subsystem inside DC micro-grid. In the LC, PCT based method is presented to realize the sensor validation and information rebuilding, which further guarantees the measured data is right when we apply the control algorithms in DC micro-grids, and leads to a robust control performance.

The GC coordinates the outputs of the subsystems in order to obtain the optimal efficiency of the whole system. Synergetic control theory, which is based on ideas of self-organization, is adopted in the GC. The commands from GC definitely have higher priority than those from LCs.

4. LOCAL CONTROLLER DESIGN

The LC is an agent that has a direct access to local measurements like information on the DG’s bus or DG’s operating status. This capability enables it to have immediate knowledge of any changes or events happened in the local system. The architecture of a LC is shown in Figure 2. As we can see, all the local measurements are fed to the sensor validation module before they arrive at the execution controller.

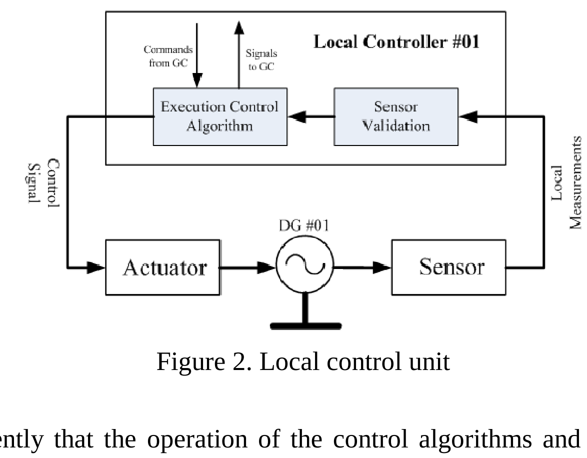

Figure 2. Local control unit

It is quite apparently that the operation of the control algorithms and the choice of the operating mode of devices rely upon one assumption that all the local measurements from the sensors are reliable. In this situation a failed sensor may have catastrophic consequences on the whole system. Measurement from the failed sensors may present in various ways. For instance, a sudden change of the values which is caused by bad connection or damage of the sensors, a drift of the measured quantities due to the aging of the sensors, to name a few. In any faulty situation, these bad measures should be isolated from LC and rebuilt data should replace the bad ones. Otherwise, the LC will deliver wrong control signals to the controlled objectives even though the real system is still in good condition. Aiming to solve this issue, in this paper the LC is designed to have extra capability to reject the bad measurements and reconstruct the measurements based on PCT theory.

4.1. Brief introduction of PCT theory

PCT concept was first introduced by Wiener in 1938 as “Homogeneous Chaos” [13] in 1938. It was spanned from Hermite polynomials of a Gaussion process. PCT expansion is a method that uses a polynomial based stochastic space to represent the evolution of the uncertainty propagation into the system [14]-[16].

The detailed procedure of PCT expansion of the system with uncertainties is given in [16]. Thus, in the following of this paper, only a brief introduction of this procedure will be presented. Consider the state space model of a general system given by a set of differential equations as in (1):

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) \\ y(t) &= Cx(t) + Du(t) \end{aligned} \tag{1}$$

Where,

$x(t) \in R^n$ system state vector;

$u(t) \in R^r$ input vector;

$y(t) \in R^n$ output vector;

A, *B*, *C*,*D* system metrices with appropriate dimensions.

The corresponding stochastic model of this system can be represented in PCT expanded form (examples of this procedure are available in [16]). Assume that the general PCT form of equation (1) is written as:

$$\begin{aligned} \dot{x}_{pct}(t) &= A_{pct}x_{pct}(t) + B_{pct}u_{pct}(t) \\ y_{pct}(t) &= C_{pct}x(t) + D_{pct}u_{pct}(t) \end{aligned} \tag{2}$$

Where,

$x_{pct}(t) \in R^{npct}$ system state vector;

$u_{pct}(t) \in R^{rpct}$ input vector;

$y_{pct}(t) \in R^{npct}$ output vector;

A_{pct}, B_{pct}, C_{pct}, D_{pct} system metrices with appropriate dimensions.

The expression of PCT expanded variables for any arbitrary variable *y* of the system, including the states *x* and parameters, can be represented, as:

$$y = \sum_{n=0}^{P} y_n \Psi_n(\xi_1, \xi_2, \cdots, \xi_{n_v}) \tag{3}$$

The representation of the time dependence of *y* and y_n is omitted for brevity, and:

P: truncation of the expansion

y_n: coefficients of the expansion;

Ψ_n: functions of the selected polynomial basis;

ξ_i: random variable associated to uncertainties with known PDF;

n_v: rank of $\boldsymbol{p}_u$ in equation (2) .

Finally, if the power system under consideration is fully observable, a Polynomial Chaos Observer (PCO) based on the stochastic PCT model was built to dynamically calculate the thresholds. The equation of the PCO is:

$$\frac{d\hat{\mathbf{x}}_{\mathbf{pct}}(t)}{dt} = \mathbf{A}_{\mathbf{pct}}\hat{\mathbf{x}}_{\mathbf{pct}}(t) + \mathbf{B}_{\mathbf{upct}}\mathbf{u}(t) + \mathbf{B}_{\mathbf{wpct}}\mathbf{w}(t) + \mathbf{G}_{\mathbf{pct}}[\mathbf{m}(t) - \hat{\mathbf{m}}(t)] \tag{4}$$

Where:

$\hat{x}_{pct}(t)$: estimated uncertain states in PCT form;

m(t): available measurements;

$\hat{m}(t)$: expected values of the estimated values of measured variables.

G_{pct}: gain matrix.

A_{pct}, B_{upct}, B_{wpct}: system matrices with appropriate dimensions after expansion.

The interval z_t representing the possible values of an arbitrary measured variable is defined through its boundaries as:

$$z_t = [z_L , z_U] \quad (5)$$

Where,

$z_L = f(\hat{\mathbf{x}}_{npct}, \hat{\mathbf{x}}_{0\,pct})$: Lower Threshold

$z_U = f(\hat{\mathbf{x}}_{npct}, \hat{\mathbf{x}}_{0\,pct})$: Upper Threshold

$\hat{\mathbf{x}}_{0\,pct}$: mean value of the estimated uncertain states

$\hat{\mathbf{x}}_{npct}$: tail value of the estimated uncertain states

f: function based on circuit laws.

4.2. Sensor validation algorithm

As a result of the PCT approach, a reasonable interval, zt, as expressed in Equation (5), can be determined for each measured variable. The diagnosis of the measured data then becomes a decision making process based on the fact that the measured value belongs or not to the continuously evolving interval zt. The sensor diagnosis (SD) algorithm proposed in this paper detects a failure when the measured value of a given variable exceeds the thresholds, which are the boundary values that the variable can take due to normal variability. The logic of operation of SD and bad data reconstruction (BDR) can be summarized as follows:

If measurement is within the uncertainty thresholds,
Sensor is healthy;
Else, sensor is faulty. SD identifies and isolates the faulty sensor; BDR reconstructs the bad data.

Failure isolation is realized by permanently locking the sensor's status at "Failed" if and only if a sensor has been diagnosed to be "Failed" by SD. In this way data from such nodes will be blocked. The simplified logic of reconstructing missing data is portrayed in

Figure *3*. The sensor status diagnosed by SD acts as the trigger of the data reconstruction of BDR [18]-[20]:

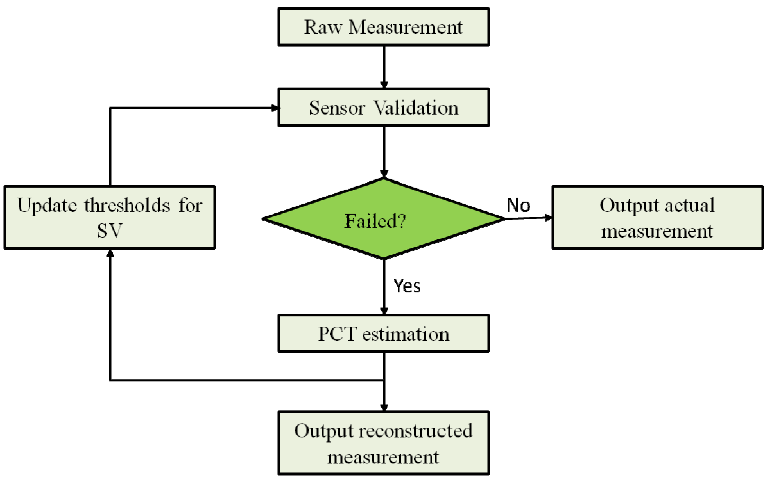

Figure 3. Missing data reconstruction algorithm

4.3. Local controller design

The controlled devices of the LCs are the DC/DC converters that are used to connect DGs to the DC bus of the micro-grid. As shown in Figure 4, two control loops are used in the LC, which are the external voltage feedback loop and the internal current feedback loop. The voltage control loop is realized with a proportional integral (PI) controller that provides a feedback control signal which is a reference value for the current control loop. The voltage control loop assures maintenance of the rated voltage in every normal and non-faulty situation. The current control loop is also realized with a PI controller. Sensor validation modules are developed and inserted between the controller and the instruments. The purpose is to make the local controller capable to survive from malfunction of the measurement devices.

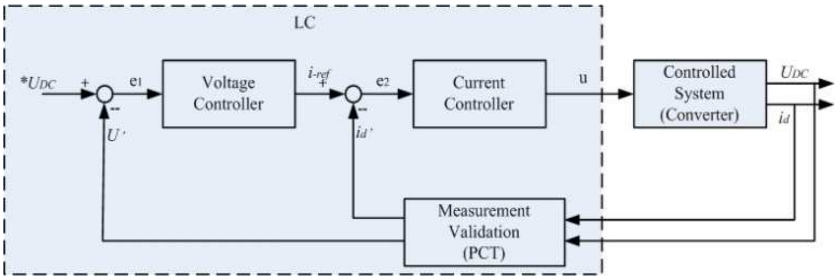

Figure 4. Local controller design

As stated above, sensor validation module is developed based on PCT. The linear time-invariant system model of the converter is considered in this paper. For the sake of simplicity, we assume that the resistances that are associated with the inductor and capacitor are null, as in the case of an ideal lossless converter. The average model of the converter can be written as:

$$\frac{di(t)}{dt} = -\frac{v(t)}{L}(1-u) + \frac{v_{cc}}{L}$$
$$\frac{dv(t)}{dt} = \frac{i(t)}{C}(1-u) - \frac{GX_2}{C} \quad (6)$$

The meanings of the symbols in the above equations are detailed in Appendix. Assuming that a single parameter and its PDF is given, the above equation can be expanded using PCT with a covenient polynomial basis that is chosen based on that PDF. In this specific case, uncertainties in the load are taken as the major uncertain sources to expand the determinstic model into PCT domain. The PDF of the load conductance, G, is assumed to be uniform here with an interval of 8% of the central value. A first-order polynomial (n_p=1) is adopted. The PCT expansion of all the uncertain variables is given as:

$$G = \sum_{a=0}^{P} G_a \Phi_a(\xi)$$
$$i(t) = \sum_{b=0}^{P} i_b(t)\Phi_b(\xi) \quad (7)$$
$$v(t) = \sum_{c=0}^{P} v_c(t)\Phi_c(\xi)$$

Then the calculation and development of the sensor validation modular will follow the instructions briefly introduced in Part A of this section. For further reference, a detailed description of the whole precess was provided in [17].

5. GLOBAL CONTROLLER DESIGN

5.1. General functions of global control unit

The goals of the designed global control unit are summarized as follows:

- It is robust to the change of the number of DGs connected to the DC bus of micro-grids. In other words, the performance of the system is practically independent of the number of paralleled DGs. Thus, we can design the global controller based on a fixed number of inverters and use it in a system with a variable number of inverters without re-designing.
- It has the capability to optimize the efficiency of the whole system by changing the number of DGs connected to the grid.

Synergetic control theory is adopted in this paper for its capability to maximize the system efficiency by means of coordinative control that changes the number of operating converters. The synergetic control design procedure consists of four steps:

- Development of augmented (extended) model of the system by including models of the influencing disturbances.

- Selection of macro-variables and a proper functional equation for control design ensuring the specified behavior of the closed loop system.
- Derivation of feedback by solving a system of functional equations.
- Definition of constrains on macro-variable components to ensure stable behavior of the closed system on the manifolds and at an equilibrium point.

5.2. Global controller design

The equivalent circuit of the proposed DC micro-grid is shown in Figure 5 [11][12]. The problem of the global control then becomes the control of parallel connected converters. Synergetic control method is applied in GC to optimize the efficiency of the system. The state space averaged model of the system presented here can be derived as follows [21]-[23]:

$$\begin{cases} \dfrac{dv_0}{dt} = \dfrac{1}{C}\sum_{j=1}^{m} u_j i_j - \dfrac{v_0}{R_{ext}C} - \dfrac{M}{C} \\ \dfrac{di_1}{dt} = \dfrac{E_1}{L_1} - \dfrac{v_0}{L_1}u_1 \\ \dots \\ \dfrac{di_m}{dt} = \dfrac{E_m}{L_m} - \dfrac{v_0}{L_m}u_m \\ \dfrac{dM}{dt} = \eta v_0 \end{cases} \tag{8}$$

Where

u_i=1-d_i

v_0: capacitor voltage;

i_{Li}: inductor current;

M(t): impact of the load and parameter's changes;

t: time constant

For a mathematical standpoint, synergetic control design [12] is based on a new method for generating control laws $\Phi_i=\Phi_i(i_1, i_2,\dots,i_m,v)$ or feedbacks that direct the system from arbitrary initial conditions into a vicinity of manifolds $\Phi_i(i_1, i_2,\dots,i_m,v)=0$ and then ensure asymptotically stable motion along these manifolds toward the end attractors. On these attractors the desired properties of the controlled system are guaranteed.

In short, the tenet of synergetic control design is the use of macro-variables to define the laws of interaction among the system components. These macro-variables define the properties of the motion of the extended system to the equilibrium state. The number of macro-variables in the set equals the number of control channels. The switching-macro-variable defined in this paper is as follows:

$$\phi_i = c_i\left[\sum_{j=1}^{m} a_{i,j} i_j + a_{i,m+1}v + a_{i,m+2}M(t)\right]; i=\overline{i,m} \tag{9}$$

Where $a_{i,j}$ are selected to ensure the existence of the manifolds intersection. c_i represents the coordinative control inputs, it is assumed that coefficient c_i can only take values 0 and 1. As a result, when $c_i=0$ the converter is switched off and for $c_i=1$ it is switched on.

The desired dynamic evolution of the macro-variables is

$$T_i\dot{\phi}_i + \phi_i = 0, T_i \rangle 0, i=\overline{1,m} \tag{10}$$

Where T_i is a design parameter which specifying the convergence speed to the manifold specified by the macro-variable.

Solving jointly the system of the functional equations (10) with the system model (8) and with the set of the macro-variables (9), the synergetic control variable *u* for the system can be found.

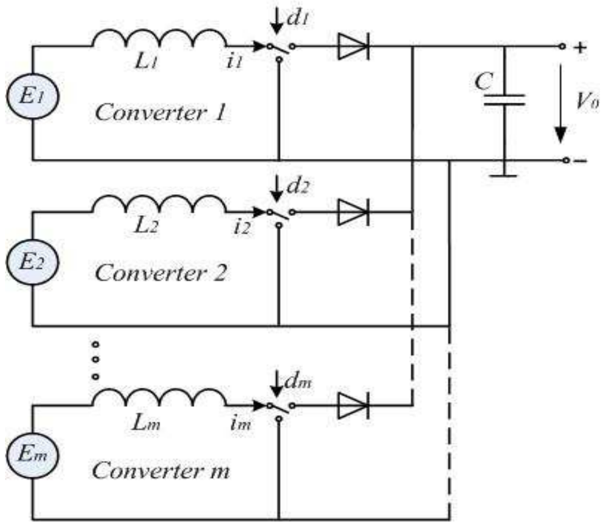

Figure 5. Equivalent global control circuit

The optimization of the system efficiency is made by changing a number of operating converters in accordance with the power consumed by the load. A transition from one system configuration to another can be made using switching function (9). By changing the number of operating converters, it is possible to improve the efficiency of the system with various loads. An algorithm defining possible behavior of the coordinative switching function is shown in Figure 6. It takes power demand *P-ref* as input. The algorithm compares *P-ref* with threshold values *Pj* and changes switching function accordingly.

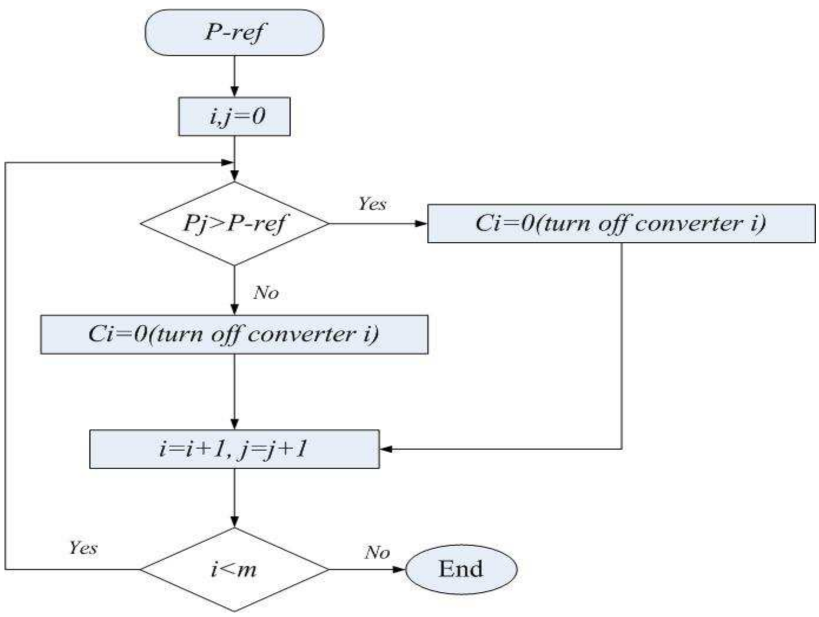

Figure 6. Algorithm of the operation switching function

6. SIMULATION RESULTS

Preliminary simulation results are provided and analyzed in this section to verify the performance of the proposed methods.

6.1. Simulation results of the local controller

This simulation case shows the consequences that defective current sensors, whose measurements are used by the local controller, can cause if no sensor validation action is taken. And the improvements that have been achieved with the application of the proposed PCT methods.

Figure *7* shows that at 0.6s a failure of the measurement is detected.

Figure *8* shows the difference in converter output current in case incorrect measurements are used as they are (left side of

Figure *8*). Notice that, following a failure of the current sensor, even without resuming to data reconstruction, the DC bus voltage that directly feeds the load may stay rather constant (bottom of the left side

Figure *8*). However, current tends to increase unlimitedly (top left side

Figure *8*), since the local controllers take actions based on both voltage and current at the output points of the converter. As a result, the current may keep increasing till the converter is damaged. However, when the incorrect measurements are replaced with reconstructed data, the situation is mitigated (right side of

Figure *8*).

This measurement fault is a potential threat to the converter that directly feeds the DC bus, and it may also result in unpredictable damage of other components in the power system. On the contrary, the situation is mitigated or even avoided with reconstructed data obtained through PCT based observer.

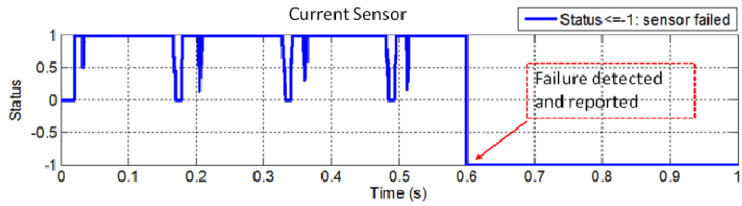

Figure 7. Current Sensor Status Monitoring of the Converter

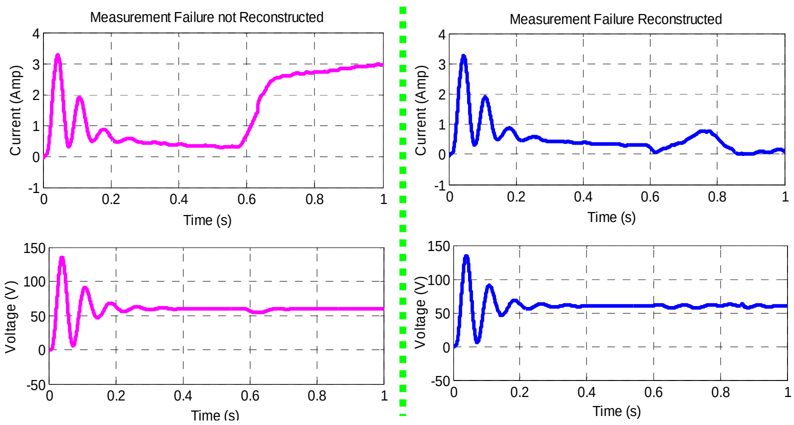

Figure 8. Impact of the Measurement Failures on the Vital Load Bus

6.2. Simulation results of the global controller

This simulation section is to evaluate the efficiency optimization capability of the global controller for DC micro-grid system with four paralleled subsystems. Each DC/DC converter in the subsystem is rated at 50 kW. The converter efficiency curve against power output is shown in

Figure 9. The global control task is to optimize the system's efficiency by proper choice of the coordinative control function c_i that put corresponding converter online if $c_i=1$ and offline if $c_i=0$. In other words, power levels thresholds Pj are to be chosen to maximize the system efficiency, as shown in Table 1.

Table 1. Power Threshold Level

Threshold number	Level, kW

P1	*45*
P2	*84*
P3	*120*

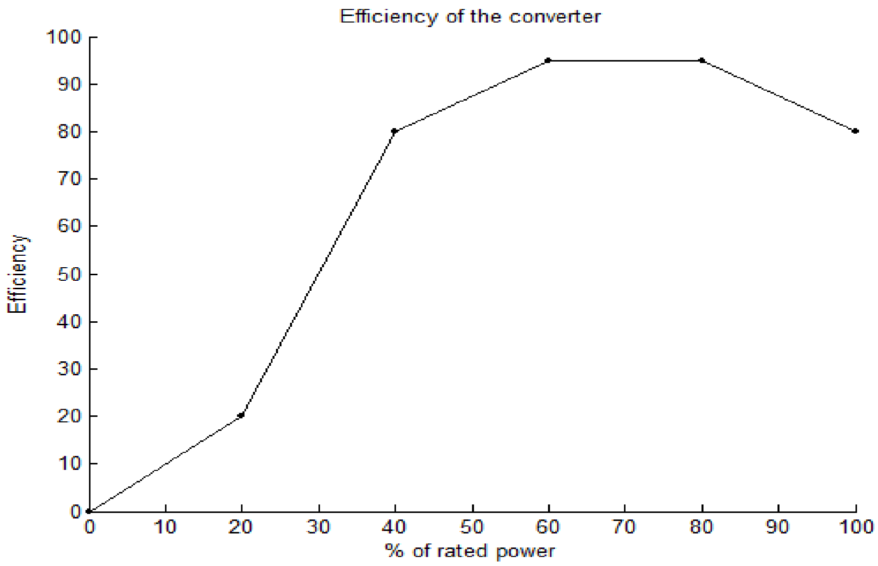

Figure 9. Efficiency of the converters

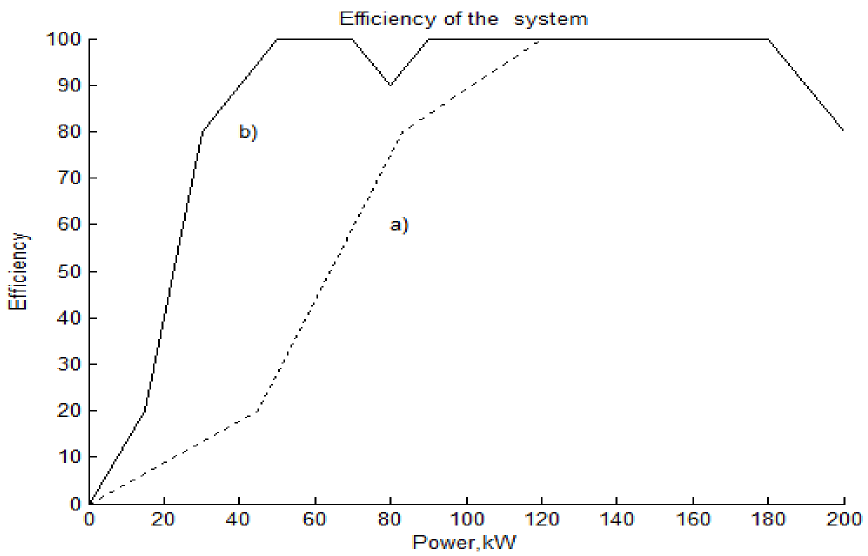

Figure 10. System efficiency (a) without coordination and (b) with coordination

The simulation results in

Figure *10* show the efficiency of the proposed DC micro-grids both when the system operates without global coordinative control and with global coordinative control that use the switching thresholds as shown in TABLE 1. It can be seen that the proposed global control algorithm provides substantial improvement of the system power efficiency at the very beginning of the system operation.

7. CONCLUSION

The proposed two-level hierarchical control method in this paper aims at an overall control performance improvement for this kind of DC micro-grids with DGs. By the implication of sensor failure detection and information rebuilding method using PCT in the local controller, bad data is able to be rejected and rebuilt to avoid a catastrophic malfunction during the system operation. The global control unit is designed to be robust to the change of number of DGs, it also has the capability to optimize the system efficiency. Numerical simulation results show that significant improvements of the control performance have been achieved.

APPENDIX

Parameter values of the converters:

R= 10Ω;
L= 5e-2H;
C= 4e-5F;

Meanings of the symbols in Equation (6):

L	Value of the inductor
C	Value of the capacitor
G	Value of the load conductance
i(t)	Current through the inductor
v(t)	Voltage across the capacitor
V_{cc}	Supply voltage
d	Applied duty cycle

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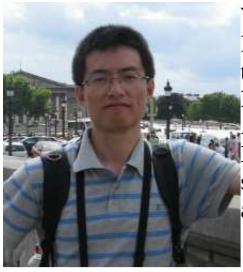
BIOGRAPHIES OF AUTHORS



Weilin Li received the B.S. and M.S. degrees in electrical engineering from Northwestern Polytechnical University, Xi'an, China, in 2007 and 2009, respectively. He is currently working toward the Ph.D degree in electrical engineering with the Institute for Automation of Complex Power Systems, E.ON Energy Research Center, Rheinisch-Westfälische Technische Hochschule Aachen University, Aachen, Germany.
His research interests are fault detection and protection in medium voltage DC (MVDC) power systems, integrated simulation, and smart grid. Mr. Li is a student member of the IEEE Power and Energy Society, and IEEE Power Electronics Society.

Huimin Li received the B.S and M.S. degrees in electrical engineering from Hefei University of Technology (Hefei, Anhui, China in 2002) and Donghua University (Shanghai, China, in 2005) respectively. She obtained the Ph.D degree in electrical engineering with the department of Electrical Enginnering in University of South Carolina (Columbia, SC, USA, 2010).
Her research interests include wind power conversion, advanced protection of power system such as self-healing, sensor failure detection and information rebuilding, advanced ac motor drives, etc.

Min Luo received the B.S degree in electrical engineering from Tsinghua University, Beijing, China, in 2009. He is currently working toward the M.S. degree in electrical engineering at RWTH Aachen University, Aachen, Germany.

Yunfei Zhang received the B.S. degree from Qingdao University of Science& Technology, Qingdao, China, in 2006, and the M.S. degree from Shanghai Jiao Tong University, Shanghai, China, in 2010.
He is currently a Ph.D candidate in the Industrial Automation Laboratory, Department of Mechanical Engineering, University of British Columbia.
His current research interests include robotics, machine learning, controls and automation.