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A Stable Black-Start Strategy for a Stand-Alone DC Micro-Grid

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Abstract – Unlike an AC system, a DC system does not cause problems with synchronization, stability, reactive power, system losses, and cost. However, more research is still required for the application of DC Systems. This paper proposes a stable black-start strategy for a stand-alone DC micro-grid, which consists of an energy storage system, photovoltaic generator, wind-turbine generator, diesel generator, and DC loads. The proposed method is very important for avoiding inrush current and transient overvoltage in the power system equipment during restoration after a blackout. PSCAD/EMTDC software was used to simulate, analyze, and verify the method, which was found to be stable and applicable for a stand-alone DC micro-grid.

Keywords: LVDC, DC Distribution, DC micro-grid, Blackout, Black-start, Restoration, PSCAD/EMTDC

1. Introduction

In some areas, it is difficult to connect to the main power grid in due to geographical or economic factors, such as on islands. One method to supply power to such areas is a stand-alone micro-grid, which is a small-scale power system that is not connected to a utility grid and can supply power locally from distributed generators (DGs).

In the past, stand-alone micro-grids were supplied power by diesel generators, but recently, they have been powered by hybrid power generation systems that combine diesel generators and renewable energy sources (RES), which have been attracting interest from researchers [1-3]. However, such a setup makes it impossible to supply power to a load stably because the output power is not constant due to environmental factors such as weather. Therefore, energy storage systems (ESSs) are an essential element [4-7].

Micro-grids can be divided into AC and DC micro-grids. Unlike AC micro-grids, a DC micro-grid does not cause problems with synchronization, stability, and reactive power. It also does not require a converter for secondary power conversion, which is advantageous in terms of system efficiency and cost. In addition, the number of applications using DC power sources is increasing, and much research on DC systems is being conducted [8-10].

Power systems can have a variety of problems, such as faults, lightning strikes, and equipment failures. When a blackout occurs, it is very important to restore the power system quickly and reliably because blackout has significant impacts on every life. The restoration method depends on the fault type, voltage level, and generators [11-13]. Complete system restoration after a blackout requires appropriate restoration plans, training exercises, verification, and expert knowledge and experience [14].

There are several issues in the black-start of AC systems, such as transmission line charging. In this process, the charging current at the time of re-energizing requires sufficient reactive capability from the black-start generation due to the high capacitance of the transmission lines [15-17]. However, for DC systems, the frequency of the voltage and the current is zero, so these problems do not occur. This is additional advantage of DC systems.

This paper proposes a black-start strategy for a stand-alone DC micro-grid, which depends on the state of charge (SOC) of ESS. We had analyzed using PSCAD/EMTDC software. The rest of the paper is as follows. Section II describes the micro-grid configuration, and Section III explains the system controller. Section IV presents the proposed strategy, and the results of a simulation and analysis are described in section V.

2. Configuration of a Stand-Alone DC Micro-grid

Fig. 1 shows the configuration of a stand-alone DC micro-grid combined with an RES and ESS, which consist of a wind power (WP) generator, photovoltaic (PV) generator, diesel generator, and DC loads. To maintain the voltage of the micro-grid, the voltage of the DC bus must be maintained using the ESS, so it must operate at all times [18]. The RES is configured with an MPPT control scheme.

The WP generator consists of a permanent magnet

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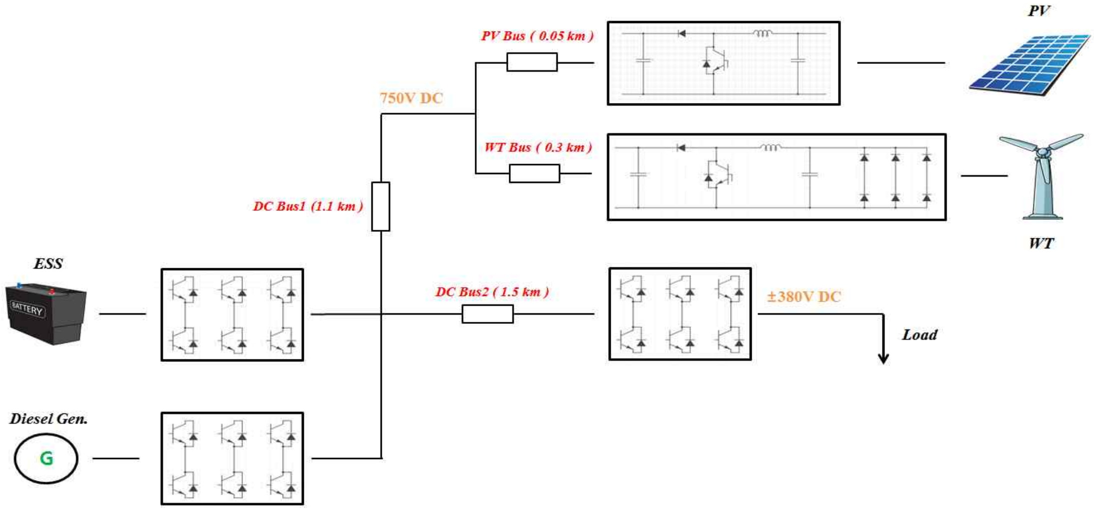


Fig. 1. Concept of stand-alone DC micro-grid

synchronous generator (PMSG) that is capable of variable speed control for different wind speeds. The PV generator has a DC/DC boost converter that controls the MPPT current. The diesel generator is configured to operate only when the demand is more than the supply of the DG, or when the battery needs charging but other RESs don't provide enough power because of weather condition. The ESS has a bidirectional three-phase interleaved DC/DC converter, and a constant DC bus voltage should be maintained in both charging and discharging operation modes.

3. System Controller

3.1 Diesel generator controller

In general, synchronous generator has power control mode when supply power to DC system. But in this system the diesel generator has two modes: active power control mode and voltage control mode, which is connected to the DC bus. The controller structure is shown in Fig. 2. Because the ESS maintains the voltage of the DC bus, the diesel generator normally operates in only the active power mode when the power supply to the load or the state of charge of the battery becomes insufficient. However, if a fault in the ESS prevents the DC bus voltage from being maintained, the converter must operate in voltage control mode to supply power to the load.

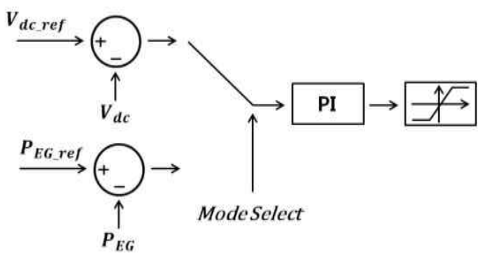


Fig. 2. Voltage and active power controller for diesel

3.2 PV controller

DC/DC converters are generally applied to PV systems to supply appropriate DC voltage amplitude to a system input terminal. When the number of modules is small, the input voltage is low and it is difficult to attain the reference voltage. Therefore, a high DC voltage is required to maintain a stable reference voltage. In this model, the controller is designed as in Fig. 3, which shows the switching of the DC/DC converter to transfer maximum power through current control instead of simple voltage boosting control.

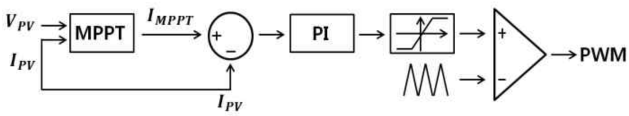


Fig. 3. Current controller for a PV system

3.3 WT controller

The WT Generator is connected to the DC Bus via a three-phase rectifier and DC/DC boost converter. The mechanical energy produced by the blades can be modeled as a current controller, as shown in Fig. 4.

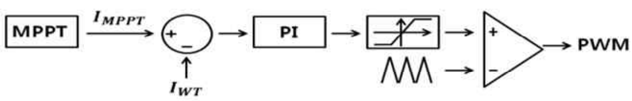


Fig. 4. Current controller for WT generator

3.4 ESS controller

The voltage of the DC bus must be controlled by the

ESS, and when the generated power is smaller than the load power, it operates in discharge mode and transfers the power stored in the battery to the load. When the generated power is greater than the load power, the system operates in a charging mode to store surplus power in the battery such that the power is transmitted in both directions. Fig. 5 presents the control structure of the ESS.

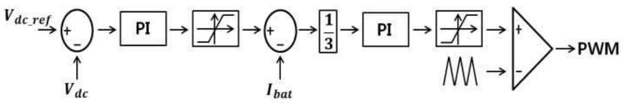


Fig. 5. Controller for the ESS

4. Black-Start Strategy for a Stand-Alone DC Micro-Grid

In the proposed black-start strategy, except when SOC is greater than maximum SOC rate, the diesel generator should operate in voltage control mode to set the initial DC bus voltage. Next, the ESS is connected to perform voltage control of the DC Bus, and the diesel generator changes to active power control or stop according SOC of ESS. The PV, WT, and load are then connected in that order. If SOC is greater than maximum SOC rate, only ESS operates. The flowchart of such a blackstart strategy is presented in Fig. 6. The procedure of the blackstart strategy as the following:

Step 1. Check if the DC bus voltage is zero
Step 2. If the SOC is greater than SOC_{max} rate go to Step 3, If not go to Step 4
Step 3. Connect the ESS, which performs voltage control of the DC bus and manages the power
Step 4. Diesel generator starts operating and performing constant voltage control mode
Step 5. Check the SOC of the ESS to determine whether the PV and WT can be connected, and determine the operation mode of the diesel generator
Step 6. Check for the following condition to connect the load:

$$P_{Load} \le P_{PV} + P_{WT} + P_{EG} + P_{ESS}$$

where P_{Load} is the load that satisfies blackstart, P_{PV} is PV output, P_{WT} WT output, P_{EG} is diesel generator output, and P_{ESS} is ESS output. Only the load that satisfies the above condition can be connected.
Step 7. End

5. Simulation Results and Analysis

To verify the proposed strategy, a simulation was carried out for three cases using PSCAD/EMTDC software. Table 1 shows the configurations, and Table 2

Table 1. Specifications of stand-alone DC micro-grid for verification

Index	Parameters	Value	Remarks
Battery DC/DC converter	Input cap.	6 [uF]	
	Output cap.	10000 [uF]	
	Reactor	0.01 [mH]	
Diesel AC/DC converter	DC-link cap.	10000 [uF]	250 [kW]
	AC reactor	1 [mH]	
	AC filter cap.	50 [uF]	
	Tr.	290/380 Y/D	
RES DC/DC converter	Input cap.	1220 [uF]	PV = 200[kW] WT = 100 [kW]
	Output cap.	1220 [uF]	
	Reactor	0.104 [mH]	

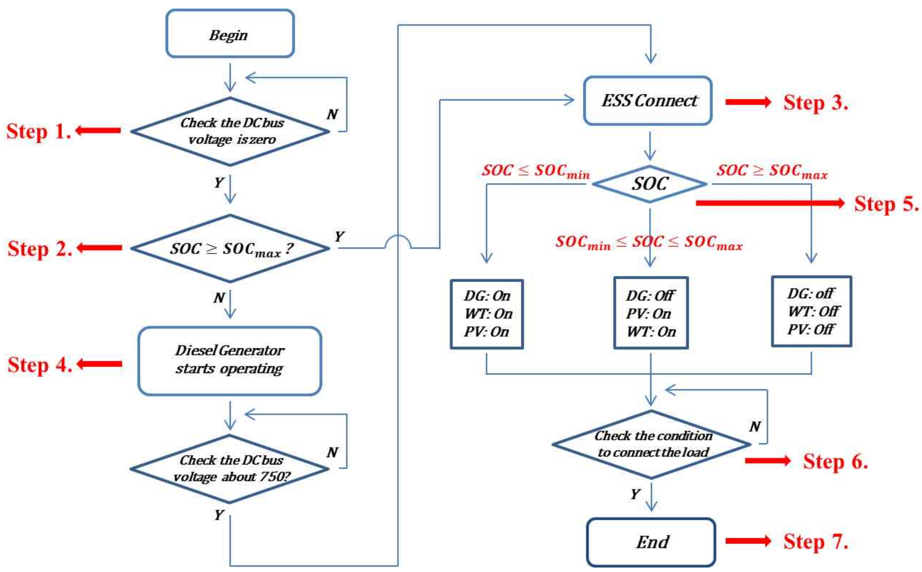


Fig. 6. Flowchart of the Black-Start Strategy

Table 2. Parameters of each line cable

Index	Length	Parameter
Bus 1	1.1 [km]	R = 0.169 [Ω/km], L = 0.7452 [mH/km]
Bus 2	1.5 [km]	
PV	0.05 [km]	
WT	0.3 [km]	

shows the parameters of each line cable.

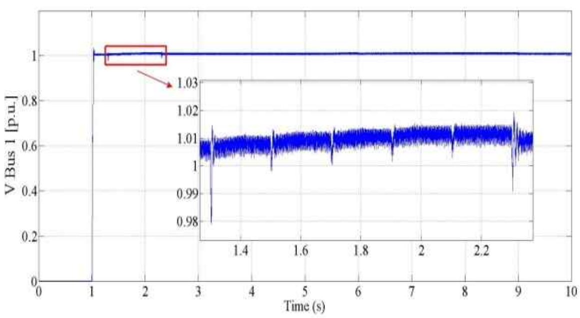
5.1 Case 1: SOC≤SOC_{min}

Fig. 7 shows the simulation results for Case 1, in which the SOC of the ESS is lower than the minimum SOC rate. The operating scenario in the simulation is scheduled in terms of the intervals of cases and times listed in Table 3. Figs. 7(a) and (b) show the p.u. values of the DC bus voltage and load side voltage, which are maintained within ±2%.

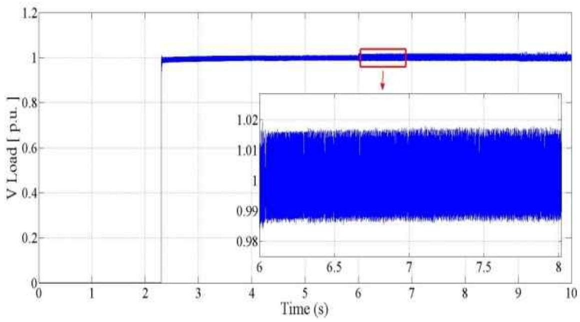
Table 3. Operation scenario of Case 1

Time (s)	0	1	2	3	4	5	6	7	8	9	10
DG											
ESS											
PV											
WT											
Load											
Load Power [kW]			60	60	60	60	80	80	80	100	100

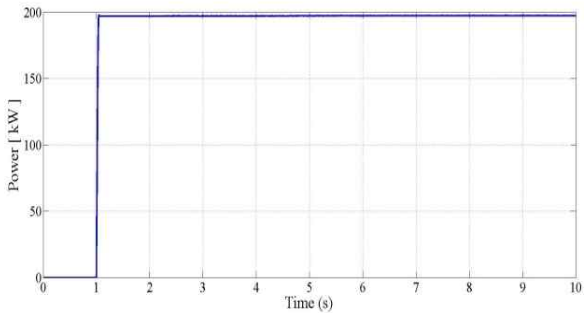
At this case all systems are operating. First, the diesel generator operates to set the DC bus voltage, Next the ESS is connected. Then the PV generators are connected in order and the wind generators are connected. When all generators are connected to the DC bus, the DC loads are connected.



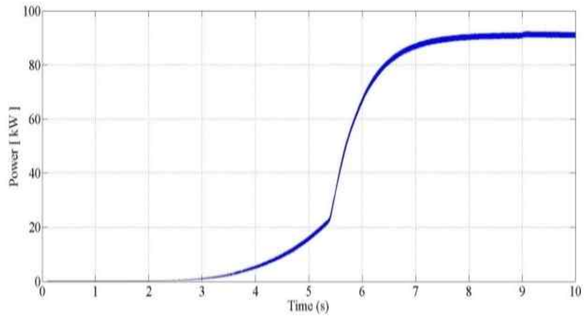
(a) DC bus voltage (p.u.)



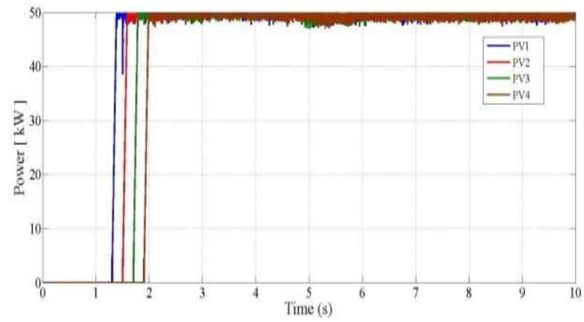
(b) Load side voltage (p.u.)



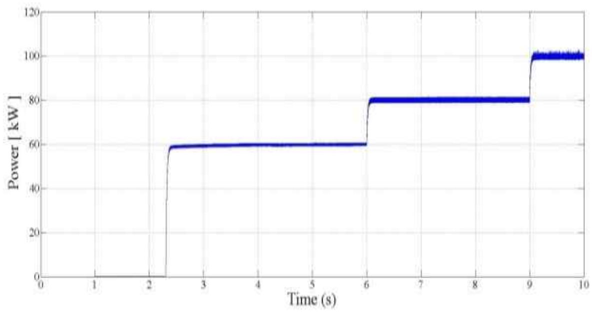
(c) Output Power of diesel generator



(d) Output power of wind turbine



(e) Output power of photovoltaics



(f) Power of DC loads

Fig. 7. Simulation results for Case 1: (a) DC bus voltage (p.u.); (b) load side voltage (p.u.); (c) output power of diesel generator; (d) output power of wind turbine; (e) output power of photovoltaic; (f) power of DC loads

5.2 Case 2: $SOC_{min} \leq SOC \leq SOC_{max}$

Case 2, the SOC is in the steady state range. The simulation results are illustrated in Fig. 8, and Table 4 shows the operating scenario.

In Case 2, the diesel generator operates for stability of the initial start although the SOC is in a steady state. When the ESS is connected and the DC bus voltage is maintained, the diesel generator stops operating, and the connection method of the remaining generators is the same as Case 1. Like Case 1, the black-start result of Case 2 also indicates that the DC bus voltage and load side voltage are well maintained within ±2%.

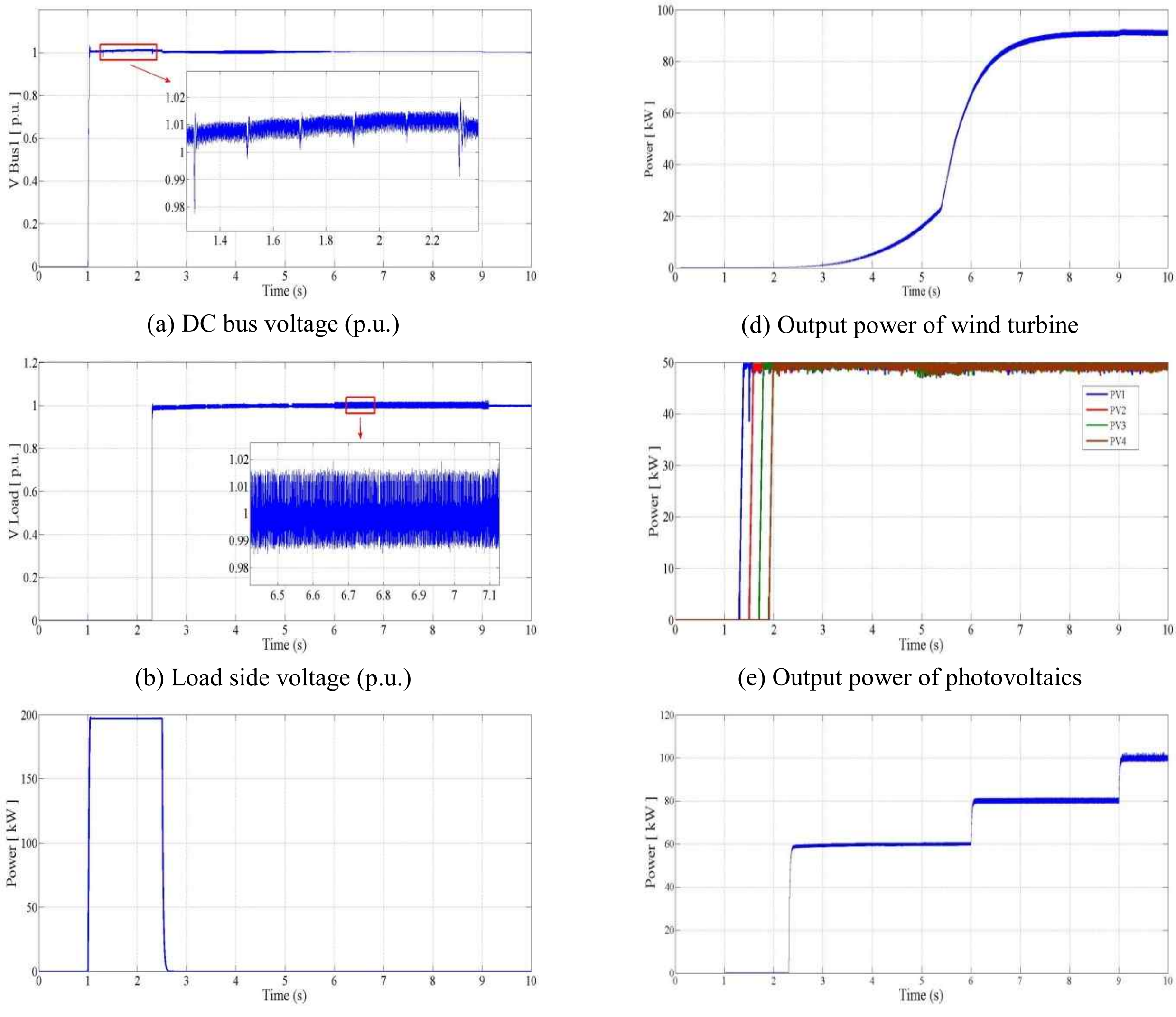
Table 4. Operation scenario of Case 2

Time (s)	0	1	2	3	4	5	6	7	8	9	10
DG		—	—								
ESS		—	—	—	—	—	—	—	—	—	—
PV		—	—	—	—	—	—	—	—	—	—
WT			—	—	—	—	—	—	—	—	—
Load			—	—	—	—	—	—	—	—	—
Load Power [kW]			60	60	60	60	80	80	80	100	100

5.3 Case 3: $SOC \geq SOC_{max}$

In Case 3, the SOC of the ESS is higher than the SOC maximum rate, and the results are shown in Fig. 9. Table 5 shows the operating scenario.

In Case 3, unlike Case 1 and Case 2, all generators do not operate. Only ESS is connected to DC bus to maintain voltage and supply power to the load. The DC bus voltage and load side voltage are maintained within ±3%.



(a) DC bus voltage (p.u.)

(d) Output power of wind turbine

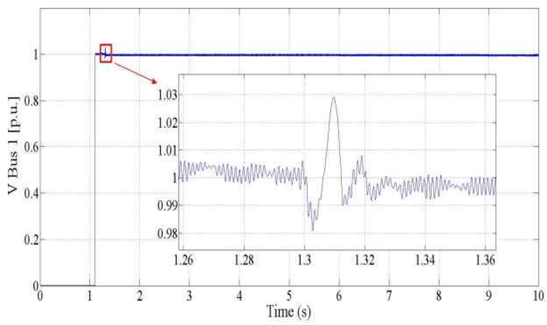
(b) Load side voltage (p.u.)

(e) Output power of photovoltaics

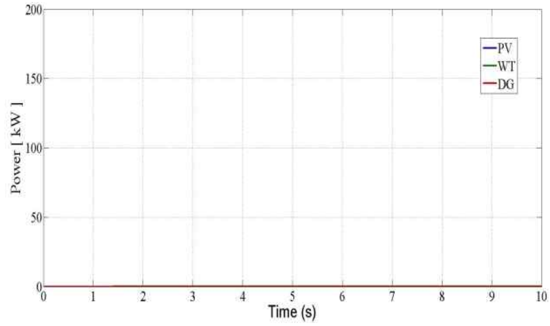
(c) Output power of diesel generator

(f) Power of DC loads

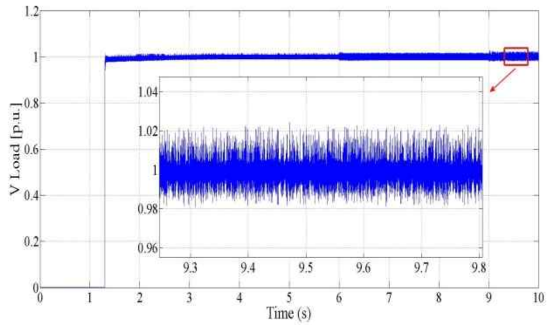
Fig. 8. Simulation results of Case 2: (a) DC bus voltage (p.u.); (b) load side voltage (p.u.); (c) output power of diesel generator; (d) output power of wind turbine; (e) output power of photovoltaic; (f) power of DC loads



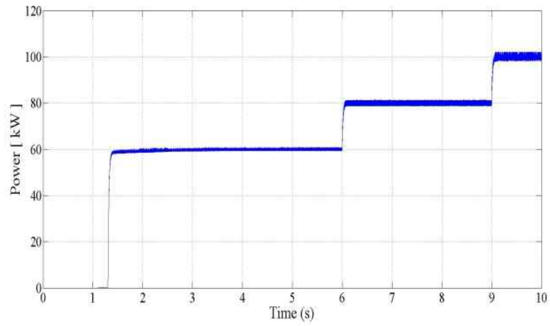
(a) DC bus voltage (p.u.)



(c) Output power of DGs



(b) Load side voltage (p.u.)



(d) Power of DC loads

Fig. 9. Simulation results of the Case 3: (a) DC bus voltage (p.u.); (b) load side voltage (p.u.); (c) output power of DGs; (d) power of DC Loads

Table 5. Operation scenario of Case 3

Time (s)	0	1	2	3	4	5	6	7	8	9	10
DG											
ESS											
PV											
WT											
Load											
Load Power [kW]		60	60	60	60	60	80	80	80	100	100

6. Conclusion

In the event of blackouts, it is very important to restore the power system both quickly and stably. The simulation results of the proposed method met the relevant requirements in all the three cases. In the future, this method could be used to restore systems in a stable manner when blackouts occur or initial start in a stand-alone DC microgrid.

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References

[1] Chad Abbey, Wei Li and Geza Joos, “An Online Control Algorithm for Application of a Hybrid ESS to a Wind-Diesel System”, *IEEE Transactions on Industrial Electronics*, vol. 57, no. 12, Dec. 2010.

[2] Tapas Kumar Saha and Debaprasad Kastha, “Design Optimization and Dynamic Performance Analysis of a Stand-Alone Hybrid Wind-Diesel Electrical Power Generation System”, *IEEE Trans. Energy Conversion*, vol. 25, no. 4, pp. 1209-1217, Dec. 2010

[3] Woo-Kyu Chae, et.al., “Design and Field Tests of an Inverted Based Remote MicroGrid on a Korean Island” Energies, pp. 8193-8210, Aug. 2015.

[4] Frede Blaabjerg, Fellow, Remus Teodorescu, “Over-view of Control and Grid Synchronization for Distributed Power Generation Systems”, *IEEE Trans. On Industrial Electronics*, vol. 53, no. 5, Oct. 2006.

[5] Zhe Chen, Josep M. Guerrero, Frede Blaabjerg, “A Review of the State of the Art of Power Electronics for Wind Turbines”, *IEEE Trans. On Power Elec-*

tronics, vol. 24, no. 8, Aug. 2009.
[6] Serim Heo et.al., "Simulation Analysis of a Renewable Energy Based Micro-grid using RTDS", *KIEE Trans*. vol. 60, no. 12, Dec. 2011.
[7] Eun-Sik Choi, Heung-Kwan Choi, Jin-Hong Jeon and Jong-Bo Ahn, "A Study on Simulation of Dynamic Characteristic in Prototype Micro-grid", *KIEE Trans*. vol. 59, no. 12, Dec. 2010.
[8] D. Salomonsson, L. Sode, A. Sannino, "An Adaptive Control System for a DC Microgrid for Data Centers", *IEEE Transactions on Industry Applications*, vol. 44, no. 6, pp. 1910-1917, Nov. 2008.
[9] P. Biczel, "Power Electronic Converters in DC Micro-grid", IEEE CPE'07 (Compatibility in Power Electronics 2007), Gdynia, Poland, May 29-Jun 01, 2007.
[10] H. Kakigano, Y. Miura, T. Ise, R. Uchida "DC Micro-grid for Super High Quality Distribution System Configuration and Control of Distributed Generation and Energy Sotrage Devices-", *IEEE PESC '06*, June 18-22, 2006.
[11] E. Mariani, F. Mastroianni and V. Romano, "Field Experiences In Reenergization of Electrical Networks From Thermal And Hydro Unit," *IEEE Trans. On PAS*, vol. 103, no. 7, pp. 1707-1713, July 1984.
[12] M. Adibi, P. Clelland, L. Fink, H. Happ, R. Kafka, J. Raing, D. Scheurer and F. Trefny, "Power System Restoration – A Task Force Report," *IEEE Trans. On PWRS*, vol. 2, no. 2, pp. 271-277, May 1987.
[13] M. M. Adibi et al., "Power System Restoration Issues," *IEEE Computer Applications in Power*, vol. 4, no. 2, pp. 19-24, April 1991.
[14] B. Kirkby, E. Hirst, "New Blackstart Standards Need for Competitive Markets," *IEEE Power Engineering Reveiew*, vol. 19, pp. 9-11, 1999.
[15] M. M. Adibi and R. W. Alexander, "Overvoltage Control during Restoration (Power System Restoration Working Group Report)," *IEEE Trans. On PWRS*, vol. 7, no. 4, pp. 1464-1470, Nov. 1992.
[16] M. M. Adibi et al., "Special Consideration in Power System Restoration the Second Working Group Report," *IEEE Trans. On PWRS*, vol. 9, no. 1, pp. 15-21, Feb. 1994.
[17] M. M. Adibi et al., "Reactive Capability Limitation of Synchronous Machines," *IEEE Trans. On PWRS*, vol. 9, no. 1, pp. 29-40, Feb. 1994.
[18] Kollimalla, S. Kumar, and M. K. Mishra, "A New Control Strategy for Interfacing Battery Supercapacitor Storage Systems for PV Systems," *IEEE Students' Conference on Electrical*, pp. 1-6, 2014.

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