DC-Voltage Regulation for Solar-Variable Speed Hybrid System

Gedeon Niyitegeka¹, Kyungkyu Lee¹, Jaeho Choi†, and Yujin Song²

Abstract

Recently, the interest in DC systems to achieve more efficient connection with renewable energy sources, energy storage systems, and DC loads has been growing extensively. DC systems are more advantageous than AC systems because of their low conversion losses. However, the DC-link voltage is variable during operation because of different random effects. This study focuses on DC voltage stabilization applied in stand-alone DC microgrids by means of voltage ranges, power management, and coordination scheme. The quality and stability of the entire system are improved by keeping the voltage within acceptable limits. In terms of optimized control, the maximum power should be tracked from renewable resources during different operating modes of the system. The ESS and VSDG cover the power shortage after all available renewable energy is consumed. Keeping the state of charge of the ESS within the allowed bands is the key role of the control system. Load shedding or power generation curtailment should automatically occur if the maximum tolerable voltage variation is exceeded. PSIM-based simulation results are presented to evaluate the performance of the proposed control measures.

Key words: DC microgrid, State of charge, DC voltage regulation, Variable speed diesel generator, Voltage variation.

1. Introduction

Renewable energy integration in today's power production system has been considered as a feasible solution in microgrid technology[1]. As the central controlled microgrid needs a real time feedback based on communication from the entire system to the central controller, it needs a high speed data exchange. But it is not preferable in stand-alone DC microgrid (DCMG) because it may result to the reduction of system reliability due to possible communication errors and delay time. Contrarily, the voltage droop control can be utilized so that all units may be controlled autonomously using real time data detected locally[2,3].

DCMG control system has to make sure that some changes can occur in the system[4], for example one source, energy storage system (ESS) or some loads may be removed from or added to the system anytime depending on present circumstances. It should also be capable to assure the optimum power flow balance, and finally to enable the ESS to compensate the possible voltage fluctuation and to support the system to reduce or rise the power surplus or deficit.
In principle, as previously studied\cite{7}, the diesel generator must be designed to meet the average load. The use of variable speed diesel generator (VSDG) in a stand-alone DCMG results to the improvement of energy efficiency\cite{8} and the fuel consumption reduction compared to the constant speed diesel generator (CSDG) and this increases the reliability of whole system.

Various reports about DCMG control and its applications have been published, such optimal control strategies\cite{9}, droop control\cite{10}-\cite{12}, supervisory control for energy cost management\cite{13}, Fuzzy control and Gain-scheduling technique\cite{14}, etc...

The decoupling of low and high frequency power components based method which used battery’s current error component to control the super-capacitors (SC) was proposed\cite{15}. The combined energy storage (batteries and SC) with high energy and power density to stabilize the power flow in the system was studied\cite{16}.

Many frameworks on AC/DC microgrids were reported. The operational mode classification of the hybrid AC/DC microgrid according to the power flow was discussed\cite{17,18}. The comparison between AC and DC microgrids with distributed energy resources was studied\cite{19}. This comparison reveals that DCMG systems will be the right candidates for the energy systems in the future with the influence of the electrical system projected to increase the number of DC powered components for residential and industrial application.

Therefore, to maintain the DC voltage of grid, the description of designing a controller that based on the combination of current mode control (CMC) and linear quadratic regulator (LQR) control method was studied\cite{20}.

This paper discusses a method to regulate DC voltage that follows a proposed operating scheme of power management and power sharing priorities in DCMG, as well as coordinating its components using well-designed controllers that present high performance with constant power loads (CPLs). Fig. 1 shows the configuration of DCMG to consider in this paper.

Furthermore, this paper is organised as follows: Section II presents the operation modes and control methods to achieve a voltage regulation. Section III contains the simulation results of the system in different cases. The conclusion is made in section IV.

2. Proposed operation and control strategies

2.1 Operation system

Fig. 2 shows the proposed operation ranges of DCMG system. It can be divided into three operation ranges that operate in two modes (VSDG ON or OFF).

**Operation range A:**

In this range, the system operates properly at a regulated voltage which equals to the DC-reference bus voltage $V_{bus}^*$ and the total available power meets the load demand in a coordinated way as described by flowcharts shown in Fig. 3 and Fig. 4. The ESS is operated to eliminate the voltage fluctuations from the system, so it can be charging or discharging in order to maintain the bus voltage constant.

In mode 1 (VSDG OFF), the PV power $P_{PV}$ and the ESS power $P_{ESS}$ together meet the load demand. The ESS may be in charging or discharging mode but the main concern in this range is that the voltage variation stays approximately zero ($\Delta V \approx 0$).
In mode 2 (VSDG ON), the voltage variation keeps being approximately zero: firstly, after the generator power $P_G$ is increased or added to the system, and/or after the load shedding is applied on the system when the voltage variation $\Delta V$ gets under the minimum tolerable voltage degradation ($\Delta V < -\Delta V_{\text{max}}$). Secondly, after the generator power is decreased or removed from the system, and/or after the PV power is curtailed when the voltage variation $\Delta V$ gets over the maximum tolerable voltage degradation ($\Delta V > \Delta V_{\text{max}}$). In this case, the ESS may be in charging or discharging mode.

$$P_{PV} + P_{ESS} = P_{Load}$$  \hspace{1cm} (1)

$$P_{PV} + P_G + P_{ESS} = P_{Load}$$  \hspace{1cm} (2)

**Operation range B:**

The system is said to be operating in range B if the total output power (PV power, generator power, and ESS power) is lower than the load demand under the condition that $-\Delta V_{\text{max}} \leq \Delta V < 0$. In such conditions, the ESS stays in discharging mode and its power is noted $P_{ESS_d}$.

In mode 1, the photovoltaic power $P_{PV}$ and the ESS discharging power $P_{ESS_d}$ both cannot satisfy the load demand. The voltage variation $\Delta V$ remains lower than zero and greater than or equal to the minimum tolerable voltage degradation.

$$P_{PV} + P_{ESS_d} < P_{Load}$$  \hspace{1cm} (3)

In mode 2, the same condition may occur even when the VSDG runs at any speed if a negative $\Delta V$ is still greater than or equal to $-\Delta V_{\text{max}}$.

$$P_{PV} + P_G + P_{ESS_d} < P_{Load}$$  \hspace{1cm} (4)

**Operation range C:**

The voltage variation is caused by the power flow unbalance due to the lower load demand or the higher power production. In this range, the voltage variation condition is $0 < \Delta V \leq \Delta V_{\text{max}}$. The ESS keeps the charging mode in this conditions and its power is noted $P_{ESS_c}$.

In mode 1, the photovoltaic power $P_{PV}$ is much higher than the load demand, so the ESS charging power $P_{ESS_c}$ cannot remove all excessive power from the system. Depending on the power surplus amount, the voltage variation $\Delta V$ varies between zero and $\Delta V_{\text{max}}$ as defined above.

$$P_{PV} + P_{ESS_c} > P_{Load}$$  \hspace{1cm} (5)

In mode 2, this situation may occur when VSDG is running. If the voltage variation keeps being in the range C’s band at any speed of the generator, (even at the minimum speed), in this case, the system is said to be in the range C of mode 2.

$$P_{PV} + P_G + P_{ESS_c} > P_{Load}$$  \hspace{1cm} (6)

**2.2 Control system**

**2.2.1 Droop control for DC microgrid**

Consider two parallel sources sharing a common load as shown in Fig. 5. Any voltage difference
2.2.2 Storage control

In storage control system as shown in Fig. 6, the ESS output voltage \( V_{ESS} \) is compared to the reference bus voltage \( V_{bus} \) and the error is sent to the PI controller to find the reference current of the storage system \( i_{ESS}^* \). The current limiter is added to assure the ESS protection by limiting \( i_{ESS}^* \) in \([-i_{max}; i_{max}]\) interval. Then the difference between \( i_{ESS}^* \) and the storage current \( i_{ESS} \) is sent to the next PI controller to generate the PWM signal.

\[
V_{droop_2}^* = V_{ref} - r_{v_2} i_2
\]  
\hspace{1cm} (8)

2.2.3 PV control

The solar generator is controlled to meet the maximum power point tracking (MPPT). The PV voltage \( V_{PV} \) and PV current \( i_{PV} \) are checked by MPPT to obtain the reference PV voltage \( V_{PV}^* \) and this later is compared to \( V_{PV} \). The error undergoes PI control to find an appropriate duty ratio for PWM so that \( V_{PV} \) may be regulated. The PV control block diagram is shown in Fig. 7.

\[
\begin{align*}
P_{PV} + P_G + P_{ESS} & < P_{Load} \text{; then (9) and (10) are valid:} \\
P_{Load} - P_{PV} + P_G + P_{ESS} & = \Delta P \hspace{1cm} (9) \\
\text{Generator output power} & = P_G + \Delta P \hspace{1cm} (10)
\end{align*}
\]

As the second case, if \( P_{PV} + P_G + P_{ESS} > P_{Load} \), then (11) and (12) are valid:

\[
\begin{align*}
P_{PV} + P_G + P_{ESS} - P_{Load} & = -\Delta P \hspace{1cm} (11) \\
\text{Generator output power} & = P_G - \Delta P \hspace{1cm} (12)
\end{align*}
\]

Generally, the VSDG output power varies on the range \([P_{G_{min}}, P_{G_{max}}]\) where,

\[
P_{G_{min}} \leq (P_G - \Delta P) < P_G < (P_G + \Delta P) \leq P_{G_{max}}
\]
3. Simulation results

PSiM simulator is used as a tool to test and validate a proposed standalone DCMG system operation. The simulated photovoltaic power is averaged to be 1200W and the rated power of VSDG is 1500W. The capacity of storage system is 750W and the load power varies from 500W to 1000W. The DC-link voltage for this study is 200V, and the maximum tolerable voltage variation $\Delta V_{\text{max}}$ equals 5% of the DC voltage link which is 10V.

Fig. 8(a) shows a stable DCMG, where the voltage remains regulated in given conditions, no matter what change in load, $\Delta V \approx 0$. The PV and ESS powers alone are enough for any load condition.

In Fig. 8(b), the behavior of the system is represented. From 0s to 0.8s, the system is balanced for different load changes. The DC-link voltage stays at a regulated value following the reference DC voltage that equals to 200V and the system operates in range A as previously defined. As the ESS stays in charging mode from 0.55s, the battery reaches the maximum state of charge, (SOC) at 0.8s. Then the charging power becomes zero, the DC voltage goes up around 204V and the system operates in range C ($\Delta V \approx 4V$).

In Fig. 8(c), the PV power is weakened from 0.2s. From 0.25s, the ESS starts the discharging mode to help PV to cover the load demand as the PV power keeping being lowered. From 0.28s, ESS and PV output powers are no longer able to satisfy the load demand as the load increases and the ESS power reaches its maximum capacity, then the system operates in range B. At 0.4s the voltage degradation tends to go out of boundaries ($\Delta V = \Delta V_{\text{max}}$), but the VSDG starts automatically to cover the power shortage and regulates the DC voltage to follow the reference DC voltage.

In Fig. 8(d), the voltage is regulated from the beginning till 0.4s when the PV power raises its power production from 600W to 1000W. At that time, the voltage tends to vary but the ESS changes quickly from discharging mode to charging one to stabilize the system, and then keeps eliminating fluctuations. At 0.55s, the radiation on PV cell is increased and the PV power generation changes from 1000W to 1200W, and DC voltage goes up to 202V. As the ESS is not able to consume all surplus power but the VSDG responds immediately to decrease its input power from 1200W to 800W and returns the DC voltage back to 200V. At 0.75s, the SOC upper limit was detected and the voltage starts to increase. The system operates in range B until the 0.8th second where the VSDG is turned off due to the voltage variation that is about to pass the boundaries.

4. Conclusion

This paper presents an idea of regulating the DC voltage in standalone DCMG. It proposes the way to manage the solar source, ESS and VSDG source by means of voltage ranges using a power management scheme. The droop control method can be one of the safest means to achieve the best performance of the system. The proposed operation system is verified by PSIM simulation results that shows a good performance of the system.

Acknowledgement

This work was conducted under the framework of Research and Development Program of the Korea Institute of Energy Research (KIER) (B4–2411).

References

[1] H. Zeng, H. Zhao, and Q. Yang, “Coordinated energy management in autonomous hybrid AC/DC microgrids,” in Conf. Rec. of IEEE POWERCON’2014, no. CP1915, pp. 3186–3193, 2014.
[2] D. Chen, L. Xu, and L. Yao, “DC voltage variation based autonomous control of DC microgrids,” IEEE Trans. Power Delivery, Vol. 28, No. 2, pp. 637–648, 2013.
[3] R. S. Balog, W. W. Weaver, and P. T. Krein, “The load as an energy asset in a distributed DC smartgrid architecture,” IEEE Trans. Smart Grid, Vol. 3, No. 1, pp. 253–260, 2012.
[4] Y. Wang, K. T. Tan, and P. L. So, “Coordinated control of battery energy storage system in microgrid,” in Conf. Rec. of IEEE APEEC’2013, pp. 1–6, 2013.
[5] P. C. Loh, D. Li, Y. K. Chai, and F. Blaabjerg, “Autonomous operation of hybrid microgrid with AC and DC subgrids,” IEEE Trans. Power Electronics, Vol. 28, No. 5, pp. 2214–2223, 2013.
[6] D. Chen and L. Xu, “Autonomous DC voltage control of a DC microgrid with multiple slack terminals,” IEEE Trans. Power Systems, Vol. 27, No. 4, pp. 1887–1905, 2012.
[7] T. Theubou, R. Wamkeue, and I. Kamwa, “Dynamic model of DG set for hybrid wind-diesel small grids applications,” in Conf. Rec. of IEEE CCECE’2012, pp. 1–4, 2012.
Fig. 8. Simulation results for power flow and voltage behavior: (a) Normal operation test, (b) SOC response test, (c) Emergency generation test by VSDG, (d) Fuel consumption and energy cost reduction test.
[8] P. Y. Lim, and C. V. Nayar, “Photovoltaic–variable speed diesel generator hybrid energy system for remote area application,” in Conf. Rec. of IEEE AUPEC’2010, pp. 1–5, 2010.

[9] A. Bracle, P. Caramia, G. Carpinelli, E. Mancini, and F. Mottala, “Optimal control strategy of DC microgrid,” Int. J. of Electrical Power and Energy Systems, Vol. 67, pp. 25–38, 2015.

[10] W. W. Weaver, R. D. Robinett III, G. G. Parker, and D. G. Wilson, “Energy storage requirements of DC microgrids with high penetration renewable under droop control,” Int. J. of Electrical Power and Energy Systems, Vol. 68, pp. 203–209, 2015.

[11] H. J. Kim, Y. S. Lee, J. H. Kim, and B. M. Han, “Coordinated droop control for stand-alone DC Micro-grid,” J. Electr. Eng. Technol. Vol. 9, No. 3 pp. 1072–1079, 2014.

[12] F. Cingoz, A. Elrayyah, and Y. Sozer, “Optimized droop control parameters for effective load sharing and voltage regulation in DC microgrids,” Int. J. of Electric Power Components and Systems, Vol. 43, No. 8–10, pp. 879–889, 2015.

[13] M. Sechilariu, B. C. Wang, and F. Locment, “Supervision control for optimal energy cost management in DC microgrid: Desing and simulation,” Int. J. of Electrical Power and Energy Systems, Vol. 58, pp. 140–149, 2014.

[14] H. Kakigano, Y. Miura, and T. Ise, “Distribution voltage control for DC microgrids using fuzzy control and gain-scheduling technique,” IEEE Trans. Power Electronics, Vol. 28, No. 5, pp. 2246–2258, 2013.

[15] S. K. Kallimalla, M. K. Mishra, and N. L. Narasamma, “Design and analysis of novel control strategy for battery and supercapacitor storage system,” IEEE Trans. Sustainable Energy, Vol. 5, No. 4, pp. 1137–1144, 2014.

[16] R. Sathishkumar, S. K. Kollimalla, and M. K. Mishra, “Dynamic energy managements of microgrids using battery supercapacitor combined storage,” in Conf. Rec. of IEEE INDICON’2012, pp. 1078–1083, 2012.

[17] G. Ding, F. Gao, S. Zhang, P. C. Loh, and F. Blaabjerg, “Control of hybrid AC/DC microgrid under islanding operational conditions,” J. of Modern Power Syst. Clean Energy, Vol. 2, No. 3, pp. 223–232, 2014.

[18] R. B. U. S. B. K. Ram, and M. V. G. Rao, “Performance of a hybrid AC/DC microgrid using RES and supercapacitor in gridconnected and islanded mode,” in Conf. Rec. of IEEE ISEB’2014, pp. 1–6, 2014.

[19] J. J. Justo, F. Mwasili, J. Lee, and J. W. Jung, “AC-microgrids versus DC-microgrids with distributed energy resources: A review,” Renewable and Sustainable Energy Reviews, Vol. 24, pp. 387–405, 2013.

[20] M. A. Abdullah, A. H. M. Yatim, C. W. Tam, and A. S. Samosir, “Control of a bidirection converter to interface ultracapacitor with renewable energy sources,” in Conf. Rec. of IEEE ICFIT’2013, pp. 673–678, 2013.

[21] K. Lee, B. An, M. W. Hadi, J. Choi, and Y. Song, “Optimized control strategy for hybrid energy system,” in Conf. Rec. of IEEE ICOPE’2015-ECCE Asia, pp. 2495–2500, 2015.

Niyitegeka Gedeon
He was born on 1st January, 1991. He received the B.S. degree in Electrical Engineering from National University of Rwanda, Huye, Rwanda in 2013. He is currently working toward the M.S. degree in Electrical Engineering at Chungbuk National University, Cheongju, South Korea.

Kyungkyu Lee
He was born on 17th September, 1987. He received the B.S. and M.S. degrees in Electrical Engineering from Chungbuk National University, Cheongju, South Korea in 2014 and 2016 respectively. Currently, he is a researcher at Dawon Universe, R&D team.

JaeHo Choi
He was born on 27th September, 1955. He received the B.S., M.S. and Ph.D. degrees in Electrical Engineering from Seoul National University, Seoul, South Korea in 1979, 1981 and 1989 respectively. From 1981 to 1983, he worked at Jungkyung Technical College, Daejeon, South Korea, as a full-time lecturer. Currently he is a Full Professor in the School of Electrical Engineering, Chungbuk National University, Cheongju, South Korea. In 1993, 1998, 2003, and 2009, he was a visiting professor at University of Toronto, Canada. In 2000 he was a visiting professor at Aalborg University Danfoss, Denmark. His current interests include power electronics, power quality problems and solutions, energy storage systems, renewable energy and microgrid systems. He is currently an active member of KIEE, KIPE, and IEEE. He was the Editor-in-chief of the JPE and the President of the KIPE.

Yujin Song
Yujin Song received his B.S. and M.S. degrees in electrical engineering from Yonsei University, Seoul, Korea in 1988 and 1991, and Ph.D degree in electrical engineering from Texas A&M University at College Station, Texas in 2004. He has been a principal engineer at Korea Institute of Energy Research since 2004. His research interests are primarily in advanced power electronics applied to distributed power generation system and microgrid.