Interconnection of Islanded DC microgrids

Srayashi Konar, Arindam Ghosh, *Fellow, IEEE*

Abstract – **In this paper, the interconnection of islanded DC microgrids are discussed. The interconnection increases the power supply reliability since a power shortfall in one of the microgrids can be supplied by the others. The islanded DC microgrids are interconnected through a bi-directional DC-DC converter. A high frequency transformer isolation is used in the converter. For interconnecting more than two microgrids, a multiple winding transformer is used. The interconnected system is studied for both equal and unequal capacity DC microgrids. A detail description of the interconnection technique is provided with simulation results and illustrations.**

Index Terms– DC microgrids, DC droop, Bi-directional DC-DC converter and Transformer isolation.

I. Introduction

Modern power system is expanding rapidly. This rapid expansion is increasing the complexity of the system and giving rise to several problems like, increasing the reactive power loss, affecting the power quality and stability of the system. The idea of DC system came as a possible solution to many such problems an AC power system is presently going through. DC system is not only simple in nature but also free from problems like reactive power loss and power quality issues. As a result DC system is installed extensively for bulk power transmission. The current trend is to have DC systems in the distribution levels as well.

In distribution level DC microgrids are increasingly drawing attention due to DC loads like LED lighting, computer loads and variable speed drives [1]. DC microgrids do not go through several AC/DC or DC/AC power conversion .This results in high efficiency and reliable performance [2].Because of its reliability and efficiency, DC microgrids are seen in building electrical systems, data centers and plug-in-electric-vehicles [2]. A DC microgrid is equipped with AC/DC sources, DC loads and battery storage systems [3]. Hence, it is capable of operating both in islanded and grid connected mode [2, 4]. A microgrid operates in grid connected mode to supply excess generation or to draw power from the main grid [2]. Islanding occurs due to grid disturbances, abnormalities in grid operation or to supply power to the loads, far away from the main grid [5-7].

DC microgrids are mainly integrated with renewable sources [2, 8]. Hence, a storage system may not be sufficient for uninterrupted power supply. Therefore, remotely located islanded microgrids may need to be interconnected for continuity of power supply and reliability. Microgrids are interconnected through power converters [5, 9]. DC microgrids are connected through DC-DC converters [5].

The authors thank the Australian Research Council (ARC) for the financial support for this project through the ARC Discovery Grant DP140103883.

The authors are with Department of Electrical and Computer Engineering, Curtin University, Perth, Australia.arindam.ghosh@curtin.edu.au.

As in this study DC-DC converter is used to interconnect islanded DC microgrids, the selection of the DC-DC converter is the most important task. Several DC-DC converter topologies are present in literature. Few of them are buck, boost, buck-boost, push pull, cuk, forward and flyback converter [10]. DC-DC converters can be with or without high frequency transformer isolation [10].Isolated DC-DC converters have several advantages over non-isolated converters. Isolation separates the interconnected system. It works more efficiently than non-isolated converters, if large voltage step-up or step-down is required. By adjusting the turns ratio of the transformer, the input and output voltage can be varied over a wide range. Multiple secondary windings with different number of turns can help to get multiple outputs at different voltage levels [11]. These characteristics of isolated DC-DC converters are ideal for interconnecting different capacity DC microgrids. Among different isolated DC-DC converters, flyback converter is the simplest in nature. A high output voltage is achievable with this converter which is independent of the transformer turns ratio. Multiple outputs can also be obtained by using multiple windings in the secondary of the high frequency transformer [12, 13].Due to these above advantages a flyback converter is used to interconnect DC microgrids.

In this work, a brief description of the structure of a DC microgrid and flyback converter is provided. The interconnection scheme is explained elaborately. Finally interconnection of more than two DC microgrids, through a multiple winding transformer is proposed.

II. System Description

A. Structure of a DC microgrid

In this study first two islanded DC microgrids are interconnected through a bi-directional DC-DC converter. As shown in Fig.1. It has been assumed that each DC microgrid consists of several DC, AC sources and DC loads. The load power is shared among generators based on the following droop equations [7].

$$V_{dcn} = V_{ref} - m_n I_n \tag{1}$$

Where, n=1, 2, 3….k. In (1), V_{dc} is the generator voltage. V_{ref} is the reference voltage. I is the generator current. This reference voltage V_{ref} is nearly equal to the DC bus voltage. m is the droop gain and it depends on the generation capacity of each generator. This implies that m dictates the ratio of the power sharing amongst generators. n is the generator number, participating in the power sharing and k is the number of generators.

B. Interconnection of two islanded DC microgrids

During the time of power shortfall in a microgrid it can be connected to a neighboring microgrid that has a power surplus. These two interconnected microgrids can be of different capacity and they can be operating at different voltage levels. For example in this work the voltage levels of the two interconnected microgrids (microgrid-1 and microgrid-2) are at 500V and 600V, respectively (Fig.2).

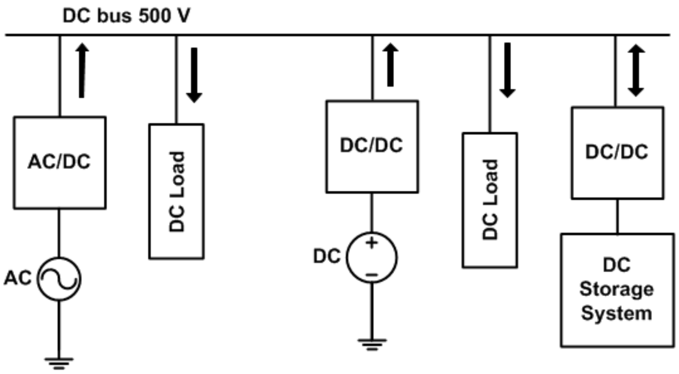

Fig.1. A DC microgrid.

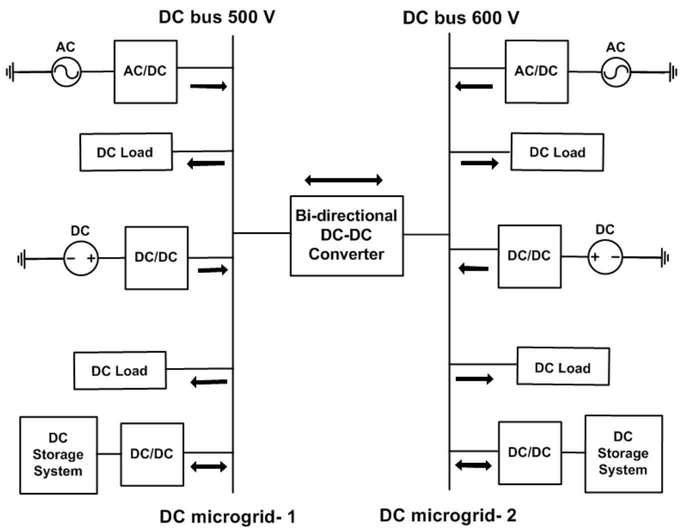

Fig.2. Interconnection of islanded DC microgrids.

C. Bi-directional DC-DC converter [14, 15]

A bi-directional flyback converter is used to interconnect the DC microgrids.

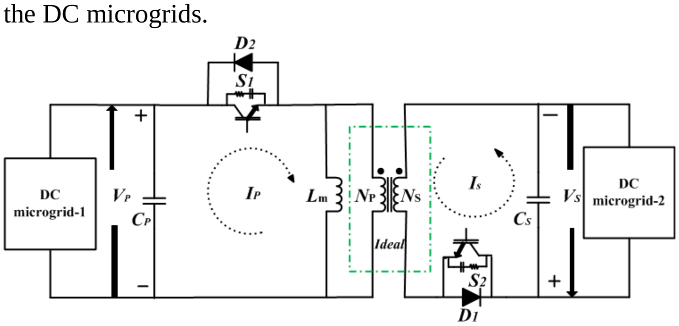

Fig.3. Interconnection of islanded DC microgrids through a flyback converter.

Fig.3 shows the diagram of a flyback converter, interconnecting two DC microgrids. V_P and V_S are the voltage levels of microgrid 1 and 2, respectively. N_P and N_S are the number of turns in the primary and secondary winding of the transformer, respectively. I_P and I_S are the current through the primary and the secondary winding of the transformer, respectively. L_m is the transformer magnetizing inductance.

$$V_S = \frac{N_S}{N_P} \times V_P \times \frac{d}{1-d} \tag{2}$$

Here, d is the duty ratio of the flyback converter.

$$P_1 = V_P \times I_P \times d \tag{3}$$

P_1 is the average input power, (over a cycle) of the flyback converter. (Let, power is flowing from microgrid 1 to 2)

$$\Delta I_P = \frac{V_P \times dT}{L_m} \tag{4}$$

T is the time period. T=1/f, f is the switching frequency of the flyback converter and the base frequency of the transformer. ΔI_P is the peak to peak ripple of the current I_P.

$$K_r = \frac{\Delta I_P}{2 I_P} \tag{5}$$

K_r is the ripple factor. Hence, from (3), (4) and (5) we get

$$L_m = \frac{{V_P}^2 \times d^2}{2 \times K_r \times f \times P_1} \tag{6}$$

To avoid saturation of the transformer magnetic core, the value of L_m is calculated for maximum value of d (d_{max}), maximum value of P_1 (P_{1max}) and minimum value of V_P/V_s (depending on the direction of power flow). The specifications of the transformer are given in the Table I in the Appendix.

Active switch S_1 and diode D_1 are turned on in a complementary manner when microgrid-2 draws power from microgrid -1. Similarly, active switch S_2 and diode D_2 are turned on in a complementary manner when microgrid-1 draws power from microgrid -2. A detail description of the power exchange scheme is provided in the next section (Sec III).

III. Interconnection Strategy

As stated before, if a microgrid has a power shortfall, it will be connected to the other microgrid, provided that it has a power surplus. Let us denote the power demand in a microgrid by P_{dc}(2), while its generation capacity by P^*_{dc}. A reference voltage signal V^* is generated to draw the required power from the other microgrid as

$$\begin{aligned} e_{dc} &= P^*_{dc} - P_{dc} \\ V^* &= K_P e_{dc} + K_I \int e_{dc}\, dt \end{aligned} \tag{7}$$

Assume there is a power shortfall in microgrid-1(Fig.3).This microgrid will generate a reference voltage signal V^* depending on its power requirement (7).This voltage is used as the reference voltage signal to control the voltage across the capacitor C_P (Fig.3).and the error signal is send to a PI controller, as shown in Fig.4. In Fig.4, V_P is the voltage across the capacitor C_P. The output of the PI controller is compared to a 10 kHz saw tooth waveform. The output signal of the comparator is used to fire the active switch S_2.

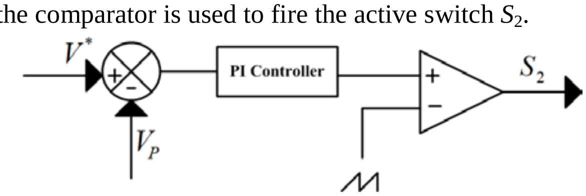

Fig.4.Firing signal for active switch S_2.

In the similar manner to draw power from microgrid-1 to supply microgrid-2, the voltage across the capacitor C_S, i.e. V_S

(Fig.3) is regulated and the active switch $S_1$is fired. Three case studies are performed, which are discussed below.

Regulated power exchange between two interconnected microgrids is studied. It is assumed that microgrid-1 and microgrid-2 are operating at different voltage levels, 500V and 600 V, respectively. The capacity of microgrid-1 and microgrid-2 are also different, 45 kW and 40 kW, respectively. Microgrid-1 consists of three generators, *Pg11*, *Pg21* and*Pg31*. The capacities of these three generators are 10kW, 20kW and 15kW, respectively. Microgrid-2 also consists of three generators, *Pg12*, *Pg22* and *Pg32*, having capacity of 5kW, 20kW and 15kW, respectively. The system data used are listed in Table II in the appendix.

A. Case-1: Islanded mode of operation: Prior to study an interconnected system, a brief study is carried out with the islanded micrograms, where the load demand of each microgrid is supplied by its generators following DC droop line. The results are shown in Figs. 5 to 7. In Fig. 5, *PL1* is the load demand inmicrogrid-1, which is nearly 41 kW. This demand is shared among all three generators according to their droop coefficients. The power generated by the three generators is 9.1 kW, 18.3 kW and 13.6 kW, respectively.

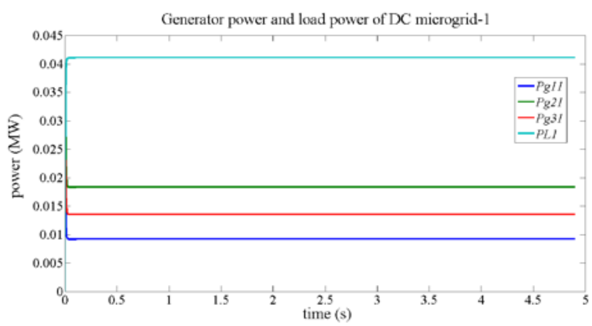

Fig.5. Generator power and load power in DC microgrid-1.

In Fig.6, *PL*2 is the load demand in the microgrid-2, which is nearly29 kW. This demand is shared among all three generators, which are supplying nearly 3.6kW, 14.5 kW and 11 kW, respectively as per their droop gains.The voltages of the two islanded microgrids, 1 and 2 are 410 V and 530 V, respectively.

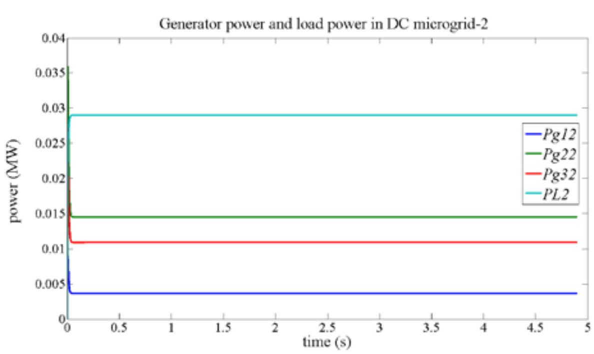

Fig.6. Generator power and load power in DC microgrid-2.

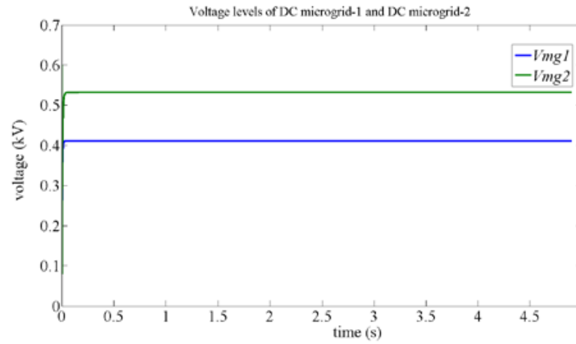

Fig.7. Voltage levels of DC microgrid-1 and DC microgrid-2.

B. Power shortfall in microgrid-1: In this section interconnected microgrids are studied during power shortfall in microgrid-1. Microgrid-2 will supply the demand of the interconnected system. Microgrids will be disconnected as soon as the demand comes back within the generation capacity of microgrid-1. The results are shown in Figs. 8 to 10. The load demand in microgrid-1 increases at 1 s to a level, which is beyond the cumulative power generation capacity of its generators. This is shown in Fig. 8. As can be seen from this figure, at 1 s, the power supplied by all the generators reaches their respective peak values. However the load demand in this microgrid causes a power shortfall of nearly 10 kW. The power demand reduces to the previous level at 4 s.

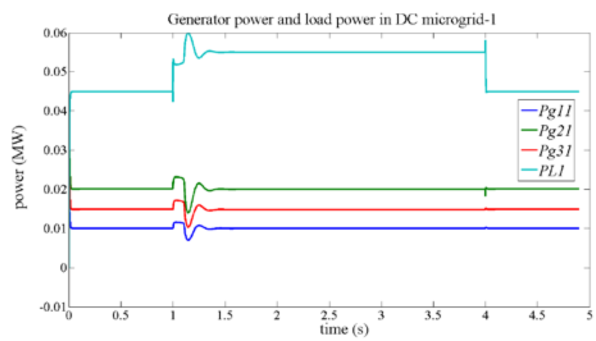

Fig.8. Generator power and load power in DC microgrid-1.

To supply the 10 kW demand of microgrid-1, microgrid-2 is connected to it at 1 s and gets disconnected at4 s. The power flow in microgrid-2 is shown in Fig. 9. Nominally the three generators in this microgrid are supplying 2.5kW, 10kW and 7.5 kW. Once, this microgrid gets connected with the other, the supply power increases to 3.7 kW, 15 kW and 11 kW. The load demand in this microgrid remain almost constant, albeit a slight drop due to the drop in the voltage, as can be seen from Fig. 10 (a). Fig. 10 (b) shows the duty ratio of the flyback converter. Nominally this is zero. Only when the power exchange takes place between the microgrids, this becomes nonzero.

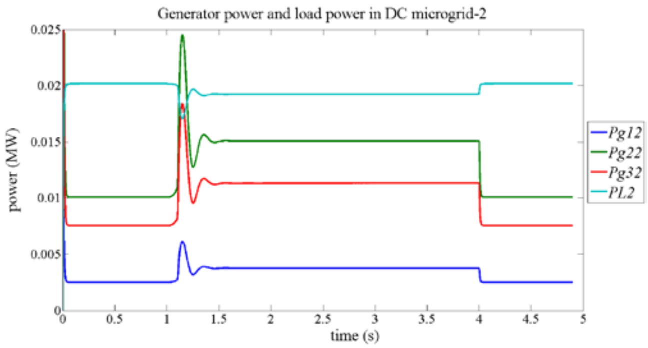

Fig.9. Generator power and load power in DC microgrid-2.

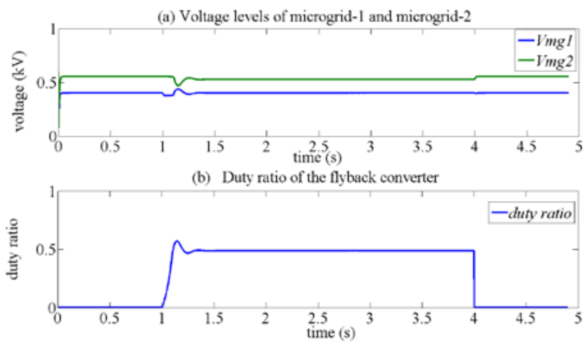

Fig.10. (a) Voltage levels of DC microgrid-1 and DC microgrid-2.(b) Duty ratio of the flyback converter.

C. Power shortfall in the DC microgrid-2: In this section the power shortfall study described before is repeated for microgrid-2. This study is carried out to validate the bi-directional nature of the flyback converter. The load demand in microgrid-2 increases at 1 s and comes back to its nominal value at 4 s. The power through the two microgrids is shown in Fig. 11.

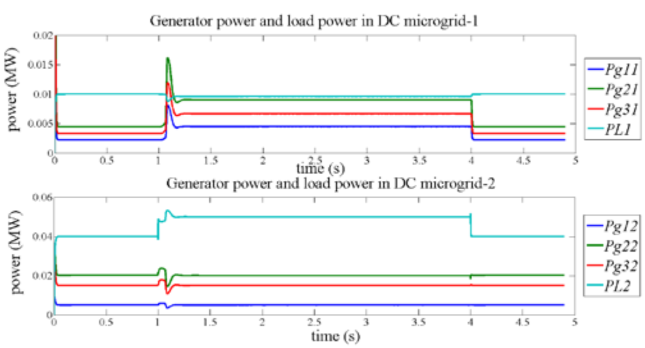

Fig.11.(a) Generator power and load power in DC microgrid-1.(b)Generator power and load power in DC microgrid-2.

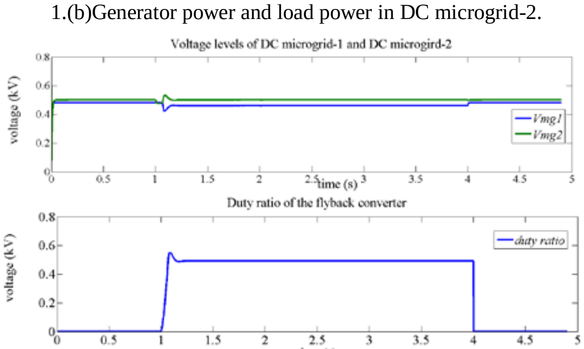

Fig.12. (a) Voltage levels of DC microgrid-1 and DC microgrid-2.(b) Duty ratio of the flyback converter.

The behavior in this case is similar to the previous case, where the generators in microgrid-2 supplies their maximum rated power, while the rest of the power is supplied by microgrid-1. The voltage levels of the two microgrids and the duty ratio of the flyback converter is shown in Fig. 12.

The studies made in this section validate the bi-directional power transfer capability of the DC-DC converter. It also shows that the excess power generated by a microgrid is shared among its generators following their capacity. Moreover, this study proposes a regulated power exchange scheme between the interconnected microgrids.

IV. Interconnectionof Multiple DC Microgrids

In this section more than two islanded DC microgrids are interconnected through a flyback converter. A multi-output flyback converter is used for this interconnection, as shown in Fig.13. It is assumed that microgrid 1 is supplying power to both microgrids 2 and 3. The flyback converter contains a three winding transformer with N_1, N_2 and N_3 number of turns. Then from mmf balance we get [14]

$$N_1 \times i_1 + N_2 \times i_2 + N_3 \times i_3 = 0 \tag{8}$$

which implies

$$N_1 \times i_1 = -N_2 \times i_2 - N_3 \times i_3 \tag{9}$$

where, i_1, i_2 and i_3 , respectively are the current supplied by microgrid-1 and current drawn by microgrid-2 and microgrid-3 that flow through the transformer windings. For this study we have considered that all three microgrids are operating at the same voltage level (600 V). Therefore

$$N_1 : N_2 : N_3 = 1:1:1 \tag{10}$$

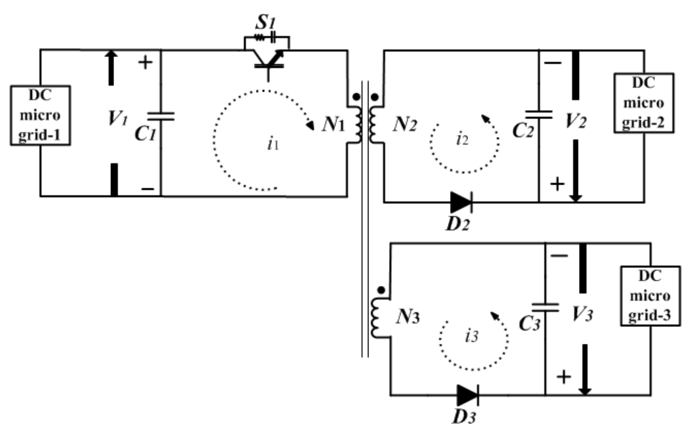

Fig.13.Multi-output flyback converter.

Combining (9) and (10), we get

$$i_1 = -i_2 - i_3 \tag{11}$$

Assume that the capacity of a microgrid is P^*_d, while its demand is P_d. Then in case of a power shortfall in this microgrid, the following PI controller is used.

$$\begin{aligned} e_d &= P_d^* - P_d \\ i^* &= K_{PD}\, e_d + K_{ID} \int e_d \, dt \end{aligned} \tag{12}$$

Where, K_{PD} and K_{ID} are the proportional gain and the integral gain of the PI controller, respectively. The quantity i^* (12) is the reference for the current the microgrid is required to draw when $P_d > P^*_d$. Now assume that microgrid-1 needs to supply both microgrids 2 and 3. Then the reference current of this microgrid needs to compute from the sum total of the reference currents of the other two microgrids, i.e.

$$i_1^* = -i_2^* - i_3^* \quad (13)$$

This reference signal i^*_1 is compared to i_1 and the error signal is send to another PI controller. The controller output is compared to the sawtooth pulse train of 10 kHz frequency. The output of the comparator is used to switch the active switch S_1 of the flyback converter. This is shown in Fig. 14.

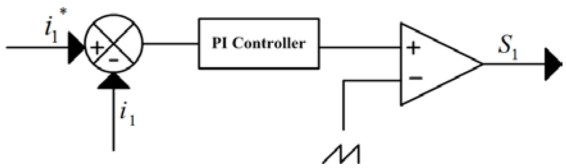

Fig.14. Firing signal for active switch S_1.

To verify the three microgrid connection, it is assumed that initially all three microgrids are operating in islanded mode. At 1s, there is a sudden power shortfall in both microgrids 2 and 3. As a result, at that time microgrid-1 is connected to the other microgrids through the flyback converter. The simulation result is shown in Fig. 15. It shows that before 1s, there is no power exchange between the microgrids. At 1 s, the power shortfalls in microgrids 2 and 3 are 5.8 kW and 8 kW respectively. Therefore microgrid-1 supplies nearly 16 kW power to these two microgrids.

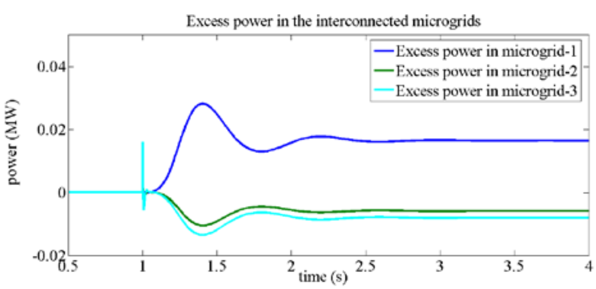

Fig.15. Excess power in microgrid-1, microgrid-2 and microgrid-3.

V. Conclusions

In this work, interconnection of DC microgrids is studied, where 2 or 3 neighboring microgrids can be connected together. For power sharing between two remotely located microgrids, they are interconnected through an isolated bi-directional DC-DC converter. It is found that this interconnection does not affect the power sharing among generators inside the microgrid. This work includes the regulated power flow scheme among interconnected DC microgrids of different capacity, operating at different voltages. This study also concludes that more than two microgrids can be interconnected for controlled power exchange, through a multi-output DC-DC converter.

References

[1] N. Nayanar, N. Kumaresan, N. A. Gounden, "A Single Sensor Based MPPT Controller for Wind-Driven Induction Generators Supplying DC Microgrid," *IEEE Transactions on Power Electronics,* vol. PP, no.99, pp.1, April. 2015.

[2] D. Wu, F. Tang, T. Dragicevic, J.M. Guerrero, J.C. Vasquez, "Coordinated Control Based on Bus-Signaling and Virtual Inertia for Islanded DC Microgrids," *IEEE Transactions on Smart Grid,* vol. PP, no.99, pp.1, Jan. 2015.

[3] J. Lee, B. Han, N. Choi "DC micro-grid operational analysis with detailed simulation model for distributed generation," *IEEE Energy Conversion Congress and Exposition (ECCE), 2010*, vol. 3153, no. 3160, pp.12-16, Sept.2010.

[4] R. H. Lasseter, "Micro Grids," *Power Engineering Society Winter Meeting, 2002. IEEE*, vol.1, no.1, pp.305, 308, 2002.

[5] M. Kumar, S.C. Srivastava, S.N.Singh, M. Ramamoorty, "Development of a control strategy for interconnection of islanded direct current microgrids," *IET Renewable Power Generation,*vol.9, no.3, pp.284,296. 2015.

[6] T.L. Vandoorn, B. Meersman, L. Degroote, B. Renders, L. Vandevelde, "A Control Strategy for Islanded Microgrids With DC-Link Voltage Control," *IEEE Transactions on Power Delivery,* vol.26, no.2, pp.703,713, April 2011.

[7] K. Kurohane, T. Senjyu, A. Yona, N. Urasaki, T. Goya, T. Funabashi, "A Hybrid Smart AC/DC Power System," *IEEE Transactions on Smart Grid*, vol.1, no.2, pp.199, 204, Sept. 2010.

[8] A.P.N. Tahim, D. J. Pagano, E. Lenz, V. Stramosk, "Modeling and Stability Analysis of Islanded DC Microgrids Under Droop Control," *IEEE Transactions on Power Electronics,* vol.30, no.8, pp.4597, 4607, Aug. 2015.

[9] A.A.A. Radwan, Y.A -R. I. Mohamed,. "Bidirectional power management in hybrid AC-DC islanded microgrid system," *IEEE PES General Meeting Conference & Exposition, 2014* vol. 1, no. 5, pp., 27-31 July 2014.

[10] N.U. Mohan, M. R. Tore, P. Williams, “Power electronics, converters, applications and design,” New York, US, Willey, p 802, 1995.

[11] J. Zeng, W. Qiao, L. Qu, "A single-switch isolated DC-DC converter for photovoltaic systems," *IEEE Energy Conversion Congress and Exposition (ECCE), 2012*, vol. 3446, no. 3452, pp.15-20, Sept. 2012.

[12] K. Creel, “Expedite Transformer Calculations for Flybacks ,” Romoland, Calif, Fuji Electric Device Technology America,Inc.USA.[Online].Available:http://www.powerelectronics.com.

[13] S. Raghunathan,”Isolated Multiple Output Flyback Converter Design Using TL494,” Texas Instruments, Tech. Rep.SLVA666, April - 2014.

[14] R. W. Erikson, D. Maksimovic, “Fundamentals of Power Electronics,” New York, Kluwer Academic Publishers, 2004.

[15] H.S. Choi, “Design Guidelines for Offline Flyback Converters Using Fairchild Power Switch (FPS),”Fairchild Semiconductor, Tech.Rep.AN4137.

Appendix

TABLE I TRANSFORMER SPECIFICATION

V_P	500± 20% V
V_S	600 ±20% V
d_{max}	0.5
P_{1max}	10 kW
K_r	0.2
L_m(secondary)	1.44 mH
f	10 kHZ

TABLE II GENERATOR DATA

Generator	Capacity (kW)	Droop Gain
Pg11	10	4
Pg21	20	2
Pg31	15	2.7
Pg12	5	10
Pg22	20	2.5
Pg32	15	3.33