Novel Communication Method Between Power Converters for DC Micro-grid Applications

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***Abstract*— Communication between power converters is vital for high performance DC micro-grids controls. However, for residential DC micro-grid applications, using external communication link would increase the system cost, and reduce the system flexibility and reliability. This paper presents a novel method to enable the conventional DC/DC converters to transmit data via the common DC Bus. With this technology, cost-effective low bandwidth communication links between power converters can be established within a DC micro-grid, and advanced distributed control algorithms can be developed. A reliable communication with 2 kbps transmission rate has been implemented between the Boost converters through the common input DC bus.**

Keywords—DC micro-grid, power converter, communication, Discrete Fourier Transform (DFT), modulation, demodulation.

I. INTRODUCTION

Micro-grids are small scale power systems that use distributed renewable and/or non-renewable generations and energy storage systems to supply power to local loads. Most of renewable sources and energy storage devices, such as Photovoltaics (PV), fuel cells and batteries, generate DC power, and more and more electrical loads in residential houses or commercial buildings use DC power, such as laptops, LED lighting, etc. In a DC micro-grid, these sources and loads are connected directly via a common DC bus. Fig. 1 shows the structure of a typical DC micro-grid. Compared with the AC systems, DC micro-grids have the advantage of higher efficiency by eliminating the wasteful AC to DC and DC to AC conversion stages [1]. DC micro-grids hold extraordinary promise for a wide variety of situations [2], but there are still a few barriers to deploy this technology, such as the initial cost of the system, lack of standards and code of practice, etc.

To improve the system performance, the DC micro-grids must be controlled in an optimal way based on system control law. Many control methods have been proposed, and they are classified into three categories [3]:

Independent control: each power converter in the DC micro-grid operates independently. The system is low cost and reliable, but the system performance can not be optimized because each power converter does not know the operation of other power converters in the system.

Centralized control [4]: all the power converters in the DC micro-grid are controlled by a central controller through external communication links. Various control methods, such as active load sharing control, can be easily applied to the DC micro-grid, and the system performance can be optimized. However, the reliability of the system is degraded due to the whole system depends on the central controller and external communication links.

Distributed control [3, 5-7]: the DC micro-grid control is distributed to each power converter controller. The system can still function under the conditions of single or multiple power converters failure, so it has better reliability than the system under centralized control. For some distributed control methods, low bandwidth external communication link for each power converters are still needed for correct operation [5]. To remove the external communication link, DC bus signalling (DBS) based distributed control methods were proposed by several researchers [3][6][7]. In these methods, the DC bus acts as a communication link between the power converters. During the operation, different DC bus voltage levels indicate different system operation modes. All the power converters respond to the level of the DC bus voltage, and they also can change the level of the DC bus voltage to control other converters in the

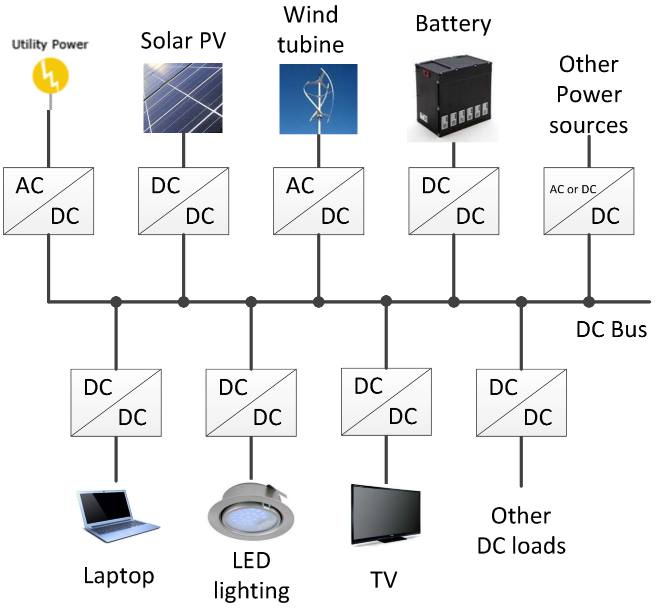

Fig. 1. A typical DC micro-grid

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system [3]. However, with DBS based control schemes, only very limited information can be exchanged between the power converters, therefore, the system performance optimization is still limited and it is more suitable for simple structured DC micro-grids.

The idea of using DC bus as a communication link in the DBS methods is similar to the power line communication (PLC) technology, which is able to use the power line for communication. PLC technology has been widely investigated, and it has been proved as a reliable method for communication in many applications. However, conventional PLC requires independent circuits for injecting, amplifying and processing the communication signal, which increases the system costs and volume, and is not suitable for residential DC micro-grids applications, where the system cost is the key.

Pulse Width Modulation (PWM) is the most popular strategy employed in the power converter controls, and it is also a technique used to encode a message into a pulsing signal. There are two modulation methods to carry information by PWM signals: the frequency-shift keying (FSK) method which modulates the PWM carrier frequency, and the phase-shift keying (PSK) method which modulates the phase of the PWM signals. This paper focuses on PWM/FSK modulation.

A power converter switching frequency modulation method for communication purposes has been proposed [8]. By changing the PWM carrier frequency and detecting the switching signal on the DC bus, power converters are able to communicate to each other via a common DC bus. The communication signal is inherently generated by the PWM of DC/DC converters, so no additional circuit is needed for injecting the communication signal on the DC bus. However, there are several limitations to this method. The switching noise was used to detect the switching frequency on the DC bus, therefore, the signal processing is complicated, and extra analog peak detector circuits and high order digital filters are needed. In addition, the number of the DC/DC converters can be connected to the DC bus and the communication speed are limited. The proposed method has a high bit error rate at bit rate of 2 kbps.

In this paper, a novel switching frequency detection method is proposed for the communication between power converters via a common DC bus link. Using TI's latest low cost Piccolo Microcontroller, discrete Fourier transform (DFT) algorithm can be applied to analyse the harmonic spectrum of the DC bus voltage directly. The proposed method only requires a simple filter and amplifier circuit for DC bus voltage signal processing. By integrating the data modulation/demodulation algorithms into the power converter control loop, the power converters can communicate between each other via the common DC Bus without external communication link. Compared to the method used in [8], the proposed method has simpler analog signal processing circuits, and it allows more DC/DC converters to be connected the common DC bus and with higher communication speed. The proposed method can be used in DC micro-grid applications, providing a low cost communication link for the DC micro-grids distributed control algorithms.

II. WORKING PRINCIPLE

For PWM controlled DC/DC power converters, both the input voltage and the output voltage have the voltage ripple at the PWM carrier frequency, i.e. switching frequency. The voltage ripple is a function of the switching frequency f_{sw}, the inductor ripple current $I_{L\text{-}pp}$, the input or output capacitance C and its effective series resistance (ESR) R.

For a synchronous Boost converter, the input current is continuous, and the input voltage ripple V_{pp} can be approximately calculated as [11]:

$$V_{pp} = \frac{I_{L-pp}}{8Cf_{sw}} + I_{L-pp}R \tag{1}$$

When the switching frequency is high or the DC bus capacitor ESR is high, equation (1) can be simplified as:

$$V_{pp} = I_{L-pp}R \tag{2}$$

Equation (2) shows for a synchronous Boost converter, the input voltage ripple is independent on the load conditions.

For a synchronous Buck converter, the input current is discontinuous, and the input voltage ripple is dependent on the load condition. The voltage ripple has a minimum value when the load is zero, and the minimum value can be calculated using equation (2).

Fig. 2 shows a DC system including three Boost converters with a common input DC Bus. Assume all the converters have two working switching frequencies, 20 kHz and 30 kHz. When all the converters work at the switching frequency of 20 kHz, the common DC Bus voltage ripple will not have 30 kHz component (as shown in fig 3.a). If the converter A changes the switching frequency to 30 kHz, the common DC bus voltage ripple will have 30 kHz component (as shown in fig 3.b). If the converter B and C can detect weather the DC bus voltage has a harmonic component at 30 kHz, then they will know if the converter A is working at 20 kHz or 30 kHz. So the data can be sent from the converter A to the converter B or C by changing the switching frequency of the converter A: The converter A working at 20 kHz for sending data of 0, or working at 30 kHz for sending data of 1. The same method can be used for the converter B or C to send data to the other converters.

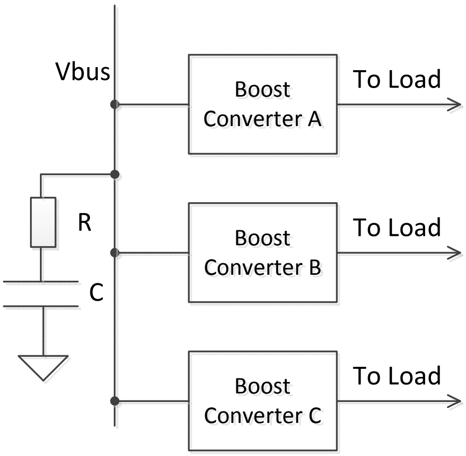


Fig. 2 Three Boost converters with a common input DC bus

Fig 4 shows the block diagram of the modulation for power converters to sending data by changing the PWM carrier frequency. The power converter can work at two switching frequencies, f_1 and f_2 ($f_1 < f_2$). It works at frequency of f_1 when sending data 0 or not sending data, and works at frequency of f_2 when sending data 1.

Fig. 5 shows the block diagram of the signal processing for demodulation.

For most of power electronics designs, the magnitude of the DC bus voltage ripple is usually small. An analog ripple sensing circuit [9] is therefore used to detect the DC bus voltage ripple, which includes a band pass filter and an amplifier. The band pass filter is used to remove the DC component, low frequency components and the high frequency switching noise of the DC bus voltage.

The digital signal processing consists of: 1) an analog to digital converter (ADC) with a high sampling rate, 2) a discrete Fourier transform (DFT) session to identify the harmonic components of the DC bus voltage at specific frequencies, and 3) a comparator to generate digital signals.

The ADC sample rate f_s should comply with the Nyquist–Shannon sampling theorem, which is:

$$f_s > 2 \times f_2 \tag{3}$$

where f_2 is the higher working switching frequency of the power converters.

To detect if any power converters on the DC bus working at switching frequency of f_2 (sending data 1), only the harmonic component at the switching frequency f_2 needs to be identified. To calculate the harmonic component at f_2 accurately using Fourier transform method, the switching frequencies f_1 and f_2 should be orthogonal in the Fourier transform period:

$$f_2 = K f_F, and\ f_2 = M f_F \tag{4}$$

where K *and* M are an integers, and f_F is the Fourier transform frequency.

Assume there are N sampling points in a Fourier transform period. The N-point complex DFT of a discrete-time signal *x(n)* is:

$$X_N(k) = \sum_{n=0}^{N-1} x(n) W_N^{kn}, k = 0, 1, 2, \cdots, N-1 \tag{5}$$

where $W_N = e^{-j\left(\frac{2\pi}{N}\right)}$.

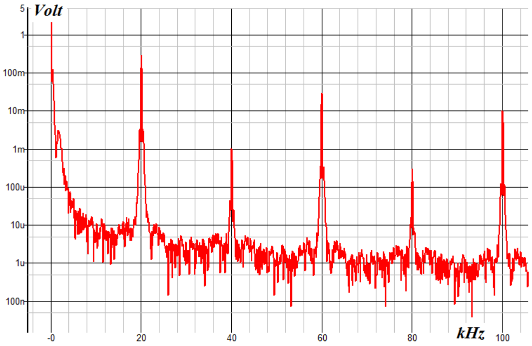
Replace k with M in equation (5), the harmonic component at f_2 can be calculated:

$$X_N(M) = \sum_{n=0}^{N-1} x(n) W_N^{nM} \tag{6}$$

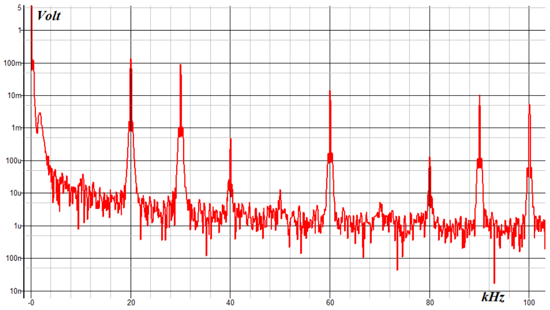
To reduce the calculation time, the sliding DFT algorithm [10] is applied.

Assume $X_M(n)$ is the current DFT value based on the sequence of $\{x(n-N+1), x(n-n+2), \cdots, x(n)\}$, and $X_M(n+1)$ is the next DFT value based on the sequence of $\{x(n-N+2), x(n-n+3), \cdots, x(n+1)\}$, then based on the sliding DFT algorithm:

$$X_M(n+1) = [X_M(n) - x(n-N+1) + x(n+1)]W^{-M} \tag{7}$$



(a) All converters work at 20 kHz



(b) Converter A works at 30 kHz, converter B and C work at 20 kHz

Fig. 3 Harmonic spectrum of the DC bus voltage

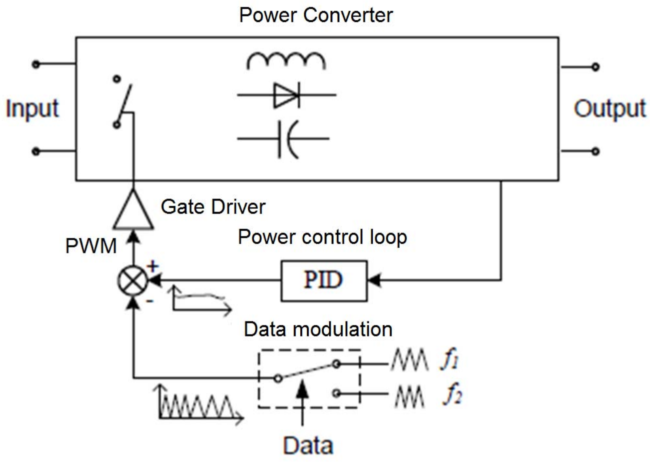


Fig. 4 Block diagram of PWM/FSK modulation

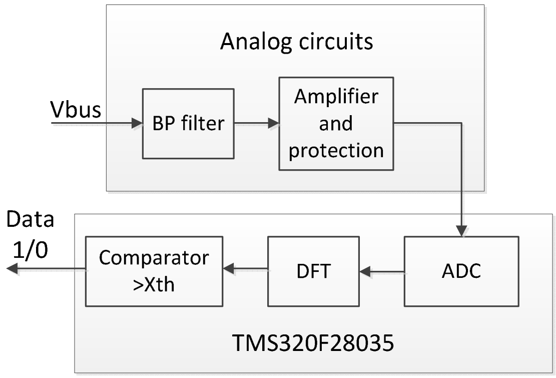


Fig. 5 Block diagram of the signal processing for demodulation

Equation (7) only has two addition operations and one multiply operation of complex numbers, so the total calculation time will be short.

A constant threshold X_{th} is set to identify the useful communication signal from noise. It is compared with the DFT result X_M to discriminate data 0 and 1:

$$D = \begin{cases} 0 & \text{if } |X_M| \le X_{th} \\ 1 & \text{if } |X_M| > X_{th} \end{cases} \qquad (8)$$

III. IMPLEMENTAION AND EXPERIMENTAL RESULTS

An experimental setup has been built to verify the proposed method. As shown in fig.2, three synchronous Boost converters are connected to a common input DC Bus. The common input DC bus voltage V_{Bus} is 12V, and the DC bus capacitor C is 14 μF.

Three Boost converters are all identical, and fig. 6 shows the block diagram of one Boost converter. The output voltage is 20V, and the output current is 1A. The inductor is 300 μH.

The output voltage and the inductor current are sampled at the switching frequency for closed loop power control, and the input DC bus voltage after the analog amplifier is sampled at 500 kHz for data demodulation.

The closed loop power control and the data modulation/demodulation are both implemented with a single TI's Piccolo Microcontroller TMS320F28035.

TMS320F28035 is a low cost and low pin-count micro-processor device, and it combines the power of the C28x core and a control law accelerator (CLA) [11]. CLA is an independent and fully programmable 32-bit floating-point math accelerator that runs in parallel with the main CPU. The sliding DFT algorithm using equation (7) is implemented in the CLA, and the calculation time is less than 1 μs. Therefore, the DC bus voltage ripple sampling rate was selected as 500 kHz (2 μs) with some safety margin.

The DFT frequency was set as 16.67 kHz (60 μs), so there are 30 sampling points in one DFT period. Based on equation (4), the PWM carrier frequencies of the Boost converter are selected as 100 kHz (for sending data 1) and 83.33 kHz (for sending data 0 or not sending data).

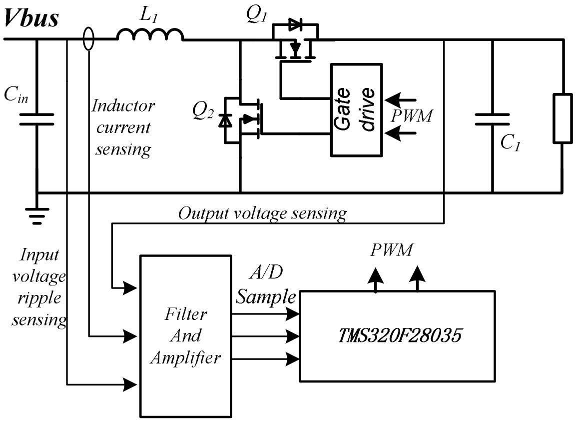


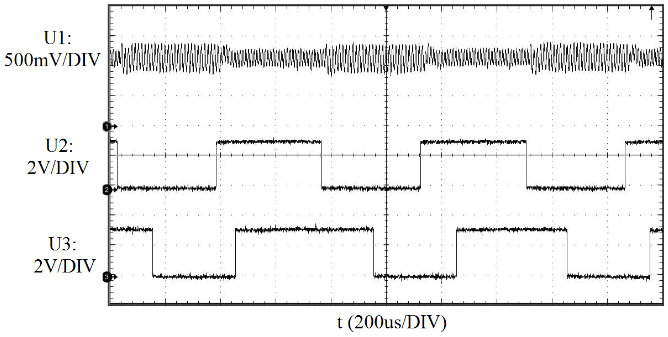
Fig. 6 Block diagram of the Boost converter

A reliable communication with 2 kbps transmission rate has been implemented between the Boost converters via the common input DC bus. Experimental results are shown in fig. 7. Fig. 7(a) shows the result when only one Boost converter is connected to the DC bus, and fig. 7 (b) shows the result when three Boost converters are connected to the DC bus. U1 is the DC bus voltage ripple after analog amplifier circuit, U2 is the data sent to the DC bus by one Boost converter, and U3 is the data received by one Boost converter.

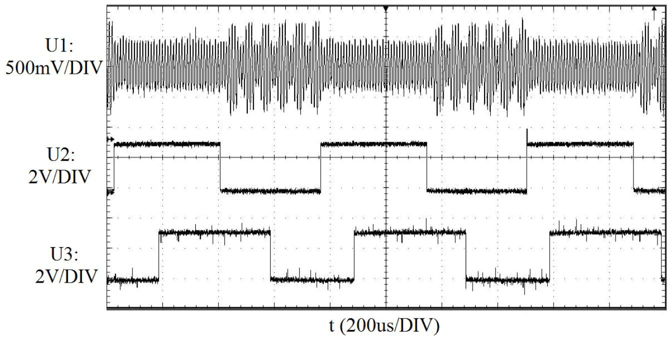
In fig. 7, it shows there is a delay between the data received (U3) and data out (U2). The delay time is due to the calculation of DFT algorithm, which is not a constant, but is close to a DFT period (60 μs). Therefore, the communication speed is upto a few kbps, making it suitable for applications that require low speed communication, such as providing communication link for the DC micro-grid distributed control.

In the experiment, it has been found that the DC bus voltage harmonic component at frequency f_2 is reduced when more DC/DC converters are connected to the common input DC bus. It is because the ESR of the DC bus capacitance is reduced (see equation 2). Therefore, the number of the DC/DC converters that can be connected to the system is mainly limited by the ESR of the DC bus capacitance.

Based on the equation (2), the voltage ripple is proportional to the ESR of the DC bus capacitance. A system with higher DC bus ESR will allow more DC/DC converters connect to the DC bus, but the system efficiency will be lower. Therefore, the proposed communication method is more suitable for low power rating DC micro-grid applications.



(a) One Boost converter on the DC bus



(b) Three Boost converters on the DC bus

Fig. 7 Experimental waveforms of the signal modulation and demodulation

IV. DC MICRO-GRIDS APPLICATION

As discussed in section I, communications between power converters are vital for high performance distributed control of DC micro-grids. However, for residential DC micro-grids, external communication link would increase the system cost, reduce the system flexibility and reliability. The work has presented in this paper could provide a cost-effective communication method for this application.

This paper mainly focuses on the physical layer of the communication method, and introduced the means of transmitting raw bits between the power converters in a DC micro-grid. To apply the proposed communication method in the application of DC micro-grids distributed control, more research work need to be done, which includes the design of the data link layer and application layer of the communication. The data link layer and the application layer design are currently under research by the authors in some funded projects.

For a DC micro-grid, data only need to be transferred locally, therefore, only data link layer need to be designed, which is the protocol layer that transfer data between power converters. As shown in fig 1, a DC micro-grid is a multiple access network that incorporates a shared medium (common DC bus), therefore, it is necessary to exploit a Multiple Access Control (MAC) protocol for this application. Some common MAC communication methods, such as master/slave polling arrangement and carrier sense multiple access with collision avoidance (CSMA/CA), etc. are currently under evaluation.

The application layer defines the data that should be sent and received for each type of power converters. A system level optimized control scheme will be proposed based on a list of criteria, such as overall system efficiency, system stability, etc. and then the data that needed for each type of power converters will be obtained. As discussed in the experimental results, the communication speed is limited, therefore, the above data will be assigned a priority weight, and the most important data will have the high priority to be transmitted. Advanced distributed control algorithms for DC micro-grids, such as enhanced current sharing control [5] or Multi-Agent System (MAS) based distributed control method [12], could be implemented without external communication links.

V. CONCLUSIONS

This paper presented a novel communication method between power converters via a common DC bus. PWM/FSK modulation method is used to carry information by PWM signals. To demodulate the signal, discrete Fourier transform algorithm is applied to analyse the DC bus voltage harmonics directly. A reliable communication with 2 kbps transmission rate has been implemented between the Boost converters via the common input DC bus. The proposed method could provide cost-effective low bandwidth communication links for low power rating DC micro-grid applications to develop various distributed control algorithms.

REFERENCES

[1] H. Kakigano, M. Nomura, and T. Ise, “Loss evaluation of DC distribution for residential houses compared with AC system”, IEEE The 2010 International Power Electronics Conference (IPEC), June 2010, pp. 480-486

[2] R. Singh and K. Shenai, “DC Microgrids and the Virtues of Local Electricity", IEEE Spectrum, Feb 2014

[3] J. Schonberger, R. Duke, and S. D. Round, “DC-Bus signalling: A distributed control strategy for a hybrid renewable nanogrid”, IEEE Trans. on Industrial Electronics, Vol. 53, No. 5, October 2006, pp. 1453 - 1460

[4] W. Dalbon, M. Roscia, and D. Zaninelli, “Hybrid photovoltaic system control for enhancing sustainable energy”, IEEE 2002 Power Engineering Society Summer Meeting, July 2002, pp. 134-139

[5] X. Lu, J. M. Guerrero, K. Sun, and J. C. Vasquez, “An improved droop control method for DC microgrids based on low bandwidth communication with DC bus voltage restoration and enhanced current sharing accuracy”, IEEE Trans. on Power Electronics, Vol. 29, No. 4, April 2014, pp. 1800 - 1812.

[6] Y. Gu, X. Xiang, W. Li, and X, He, “Mode-Adaptive Decentralized Control for Renewable DC microgrid with Enhanced Reliability and Flexibility”, IEEE Trans. on Power Electronics, Vol. 29, No. 9, September 2014, pp. 5072 - 5080

[7] K. Sun, L. Zhang, Y. Xing, and J. M. Guerrero, “A distributed control strategy based on DC Bus signalling for modular photovoltaic generation systems with battery energy storage”, IEEE Trans. on Power electronics, Vol. 26, No. 10, October 2011, pp. 3032 – 3045

[8] W. Stefanutti, S. Saggini, P. Mattavelli, and M. Ghioni, “Power line communication in digitally controlled dc–dc converters using switching frequency modulation,” IEEE Trans. on Industrial Electronics, Vol. 55, No. 4, April 2008, pp. 1509– 1518.

[9] S. Chae, Y. Song, S. Park, and H. Jeong, “Digital current sharing method for parallel interleaved DC-DC converters using input ripple voltage”, IEEE Trans. on Industrial Informatics, Vol. 8, No. 3, August 2012, pp. 536 – 544

[10] E. Jacobsen and R. Lyons, “The sliding DFT,” IEEE Signal Processing Magazine, Vol. 20, No. 2, March 2003, pp. 74–80.

[11] Texas Instruments Incorporated, "Output ripple voltage for buck switching regulator", SLVA630A, January 2014, [Online]. Available: http://www.ti.com/lit/an/slva630a/slva630a.pdf

[12] Y. S. F. Eddy, H. B. Gooi, and S. X. Chen, “Multi-Agent system for distributed managmene tof microgrids”, IEEE Trans. on Power Systems, Vol. 30, No. 1, January 2015, pp. 24 - 34