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Design for Low Voltage DC Distribution Network Testbed

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Abstract: A Low Voltage DC (LVDC) distribution network is gaining popularity as the next generation distribution network. However, LVDC network test environments are limited. A full-scale environment for LVDC distribution network test is preferable to evaluate various operation characteristics. However, it has limitations in implementation cost and operation methodologies. In this study, a 48 V DC-based down-scale LVDC distribution network testbed is developed to enable the reproduction and observation of various phenomena of DC distribution networks. The proposed testbed provides flexible configuration capability by introducing S and T-connector modules that can be controlled remotely and real-time monitoring functions by using a data acquisition system connected to the nodes. Each connector can measure voltage and current with up to 250 kHz sampling frequency. The frequency analysis is also supported based on the collected data to evaluate power quality and characteristics of the distribution network. Complicated phenomena of DC distribution systems can be easily implemented using the developed LVDC distribution network testbed.

Key words: LVDC, DC distribution network, testbed, power quality, monitoring, configuration capability, implementation cost

INTRODUCTION

Low Voltage DC (LVDC) distribution network technology is gaining popularity as the next generation distribution network due to its improved features such as the freedom of synchronization and the efficiency of power conversion. LVDC distribution networks, unlike the conventional AC distribution networks have different characteristics in voltage by having no base frequency. Many studies have been conducted on the adoption of the LVDC distribution mostly focusing on improved distribution efficiency of electricity, high Power Quality (PQ) and reliability (Lana *et al*., 2015; Lee, 2015). The PQ is one of the important parameters in the distribution of LVDC systems but studies on this subject are limited. Furthermore, some of the existing PQ measurement standards for AC systems are not appropriate to describe the PQ of DC systems. This study reviews the PQ measurement standard designed for AC distribution networks to apply LVDC distribution networks. Based on the results, the major measurement parameters for PQ in LVDC distribution networks are selected. LVDC distribution network is designed to support flexible configuration with remotely controlled switch nodes that are called as S and T-connectors. A real-time monitoring system is attached to collect voltage and current data from the nodes with the maximum sampling speed of 250 kHz. To observe the effect on PQ, frequency analysis is performed using the collected data.

Power quality of LVDC distribution network: PQ refers to the electrical changes that cause errors or faults in the final adoption equipment. In AC systems, the standardized definition such as IEC 61000-4-30/4-15, IEEE1159/1549 and EN50160 are used to manage the power quality (Baskar, 2015; Mariprasath and Kirubakaran, 2016). The indices for the major PQ by the afore-mentioned standard can be categorized as transient, interruption, sag/under-voltage, swell/overvoltage, distortion, voltage fluctuation and frequency variation. In general, some PQ measurement parameters used in the AC

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Table 1: Major measurement parameters for PQ in LVDC distribution network

Types	Measurements	Details/Reasons
Volt (V)		
Interruption	O	System error and protection equipment operation, etc.
Dip/sag, swell	O	Operation or stoppage of heavy loads
Variations	O	Damage or shortened lifespan of electrical-equipment
Current (A)	O	Common parameter
Phase (deg.)	X	AC only measurement parameter
Fundamentals	X	AC only measurement parameter
Crest factor	X	AC only measurement parameter
Form factor	X	AC only measurement parameter
Watt (W)	O	Common parameter
Volt-Amps Reactive (VAR)	X	AC only measurement parameter
Volt-Amps (VA)	X	Common parameter
Power factor (%)	X	Power factor generated by harmonics
Unbalance	O	Lack of equilibrium in the lines and loads
Flicker	O	Transformer tap change, motor start, intermittent load, etc.
Transient	O	Utility switching operations, changes of heavy loads
Harmonics	Δ	Substituted by frequency analysis
Total Harmonic Distortion (THD)	Δ	Substituted by frequency analysis
Telephone Influence Factor (TIF)	Δ	Substituted by frequency analysis
Total Rated-Current Distortion (TRD)	Δ	Substituted by frequency analysis
Total Demand Distortion (TDD)	Δ	Substituted by frequency analysis
EMI	Δ	Substituted by frequency analysis
Inrush current	O	Operation and stoppage of heavy loads

distribution network are still required even in the LVDC distribution network although some other parameters are only related to AC systems. The fundamental frequency that is usually 50 or 60 Hz only holds meaning in AC networks. LVDC distribution network consists of various power conversion devices that use power switching devices such as a converter, switching power supply and battery charger. Therefore, the effects of disturbance such as the inrush current, harmonics and Electro Magnetic Interference (EMI) appear to be high. And these disturbances need to be considered as a major PQ measurement parameters in LVDC distribution networks (Nuutinen *et al*., 2014; McGrath and Holmes, 2009; Graham, 2012). Table 1 shows the list of major PQ types and their necessity to measure for LVDC monitoring.

MATERIALS AND METHODS

Design for LVDC distribution network testbed: In this study, an LVDC distribution network testbed is developed to replay and monitor various phenomena in DC distribution systems. The LVDC distribution network testbed uses 48 VDC downscale voltage and consists of up/down power convertors, S and T-connectors. S-connectors serve as the switches of the distribution network allowing topology changes. T-connectors play the role of the branches of the distribution network and links of the distribution line to power convertors connecting loads and generators. The measurement of the distribution network is performed using the voltage and current sensors embedded in S and T-connectors. The current sensors are designed to measure the current of all branches including the ground. The measured values of voltage and current of the distribution network are collected through RS-485 with 250 kHz sampling rates by using a 128 channel data acquisition (DAQ) board. The collected data are transmitted through TCP/IP to the Main Data Collection unit (mDCU). Table 2 shows major design specifications of the designed testbed. Figure 1 shows the schematic diagram and real image of the LVDC distribution network testbed, respectively. Each component is modularized for later ease of configuration changes and expandability.

Table 2: Major design specifications of the LVDC Distribution Network

Categories	Details
Operation voltage/maximum current	48 V/10 A
Consisting equipment	
Up converter	Input:12 V, 20 A Output: 48 V, 5 A
Down converter	Input: 48 V 5, 5 A Output:12 V 10,20 A
T-connector	3 line connection 2 voltage sensor 6 current sensor (GND included)
S-connector	2 line connection 1 voltage sensor 2 current sensor (GND included)
Data collection specifications	Max 250kHz/128 (sample/node) channel RS 485 and TCP/IP communication

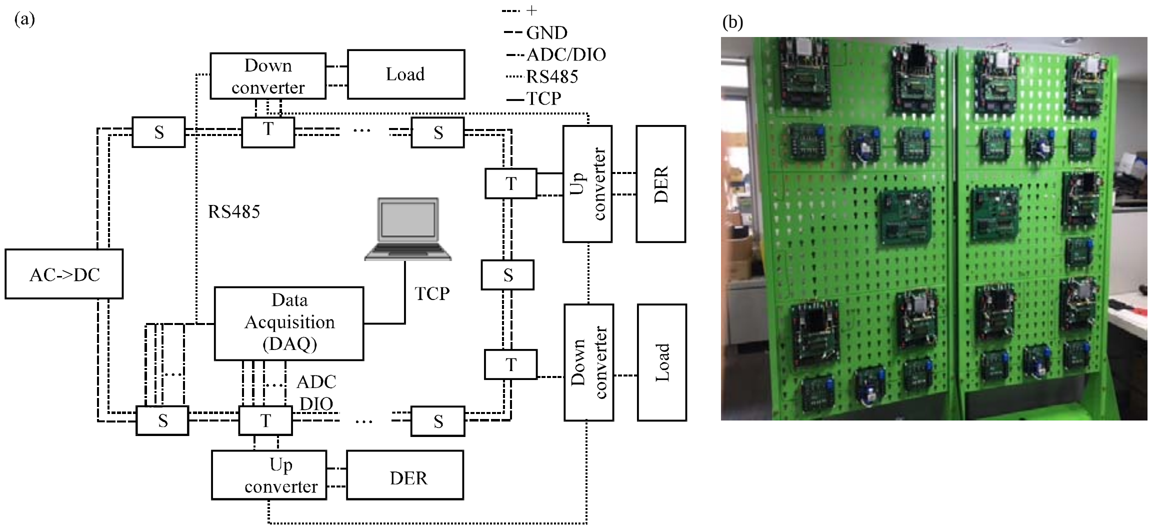

Fig. 1: Schematic diagram and real-image of the LVDC distribution network testbed: a) Schematic diagram and b) Real image of the testbed

RESULTS AND DISCUSSION

The effect of a load change is monitored and analyzed to evaluate the developed LVDC distribution network testbed. The average load attached to the DC distribution network via. a dc/dc converter is varied to change the distribution network current from 0~2 A to verify the phenomena that occur in the distribution network by the load changes. The distribution network voltage varies between 47.1~49.4 V as shown in Fig. 2. The voltage changes would be reduced with the additional voltage control algorithms later.

An LVDC distribution network usually includes the switching power devices for electric power conversion such as converters and inverters. Electromagnetic waves are generated due to high-frequency components in the band of 30 MHz or less by the operation of the switching device. Nuutinen *et al*. (2014) suggest the need to analyze signals up to 150 kHz for EMI consideration because of the power switching devices. In addition, the effect of an electromagnetic wave due to the arc discharge may appear in the frequency band higher than 30 MHz. This electromagnetic noise can cause malfunctions and interferences with the wireless service such as a control device and an electric and electronic equipment. Therefore, the LVDC distribution network testbed environment requires a variety frequency analysis. This study conducts the frequency analysis for 100 Hz~25 kHz and 100 Hz~100 MHz bands. Figure 3 shows the voltage FFT analysis result for the load variations over time increasing the DC distribution

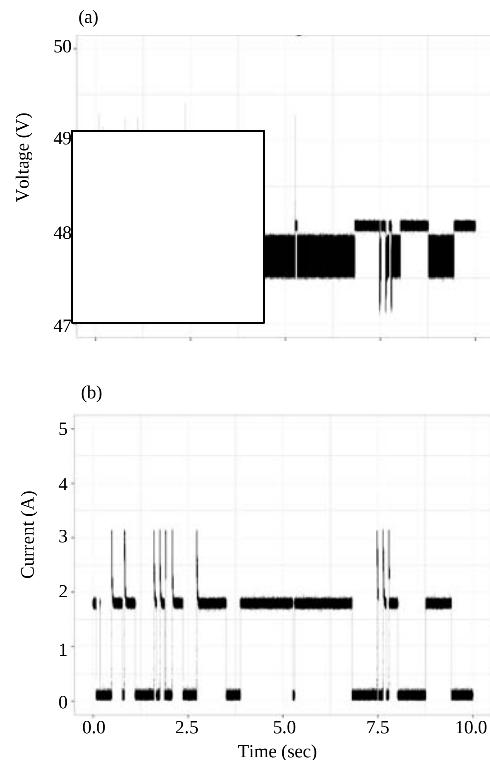

Fig. 2: Voltage measurement results obtained from the LVDC distribution network testbed

network current from 0-2 A by increasing loads attached to the network. According to the FFT analysis on the voltage, the main frequency components are observed in

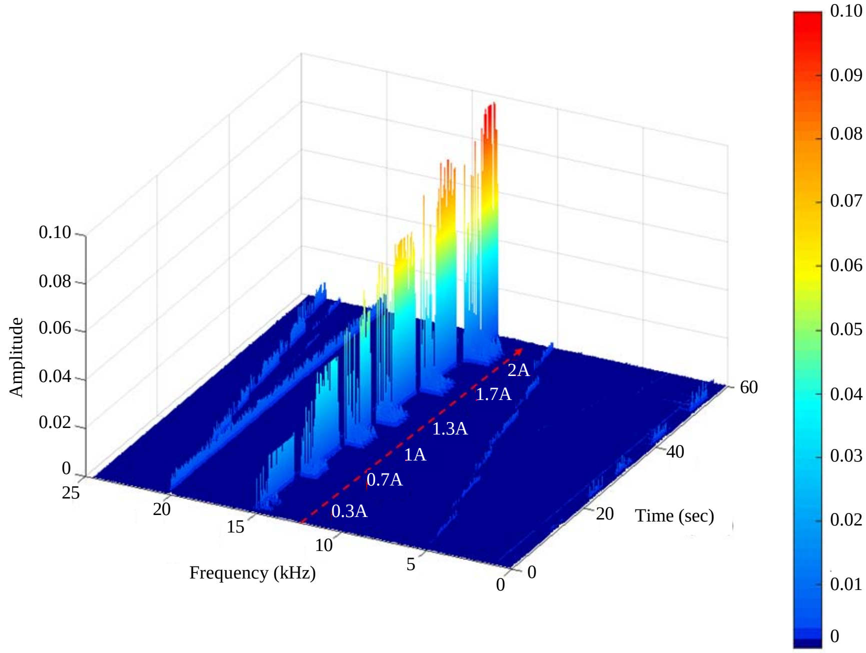

Fig. 3: Frequency domain analysis result of voltage for the load variations (100 Hz~25 kHz)

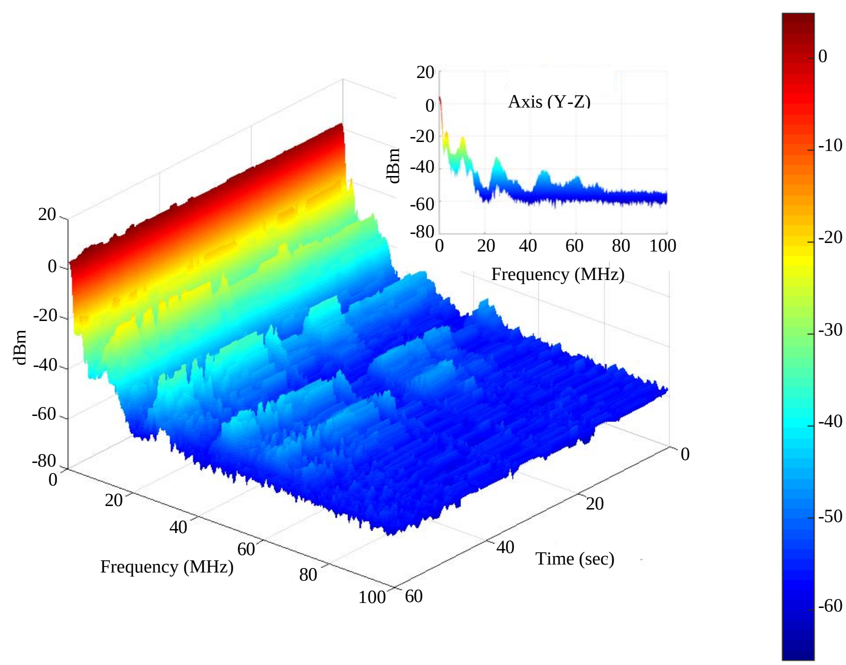

Fig. 4: Frequency analysis result of voltage for the load variations (100 Hz~100MHz)

15 and 20 kHz. Especially, the amount of the frequency component at 15 kHz increases as the load increases showing the characteristics of PCS attached to the load.

Figure 4 shows the frequency analysis result of the voltage signal in 100 Hz~100 MHz band by using a spectrum analyzer. The result can be seen that the noise generates up to 70 MHz band. Therefore, it may be necessary to observe up to 70 MHz signals in the LVDC distribution network testbed environment to understand the DC distribution network phenomena at high-frequency such as EMI with additional equipment.

CONCLUSION

In this study, an LVDC distribution network testbed is developed to provide flexible and expandable test environment by adopting remotely controller S and T-connectors. The testbed supports real-time monitoring with the maximum 250 kHz sampling speed. Frequency analysis is also performed to observe PQ changes while the load changes. The testbed can be used to provide insight into the phenomena that occur in DC distribution networks. Although, the testbed has a limitation in the high-frequency analysis for EMI it can be compensated with additional equipment such as a spectrum analyzer.

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