Low Voltage DC Distribution System

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Abstract–AC distribution is conventional and its future is now under threat with its major competitor DC distribution. Transformer voltage conversion can be replaced completely by DC-DC converter in DC distribution with voltage and current regulation. DC energy and energy saving as the distribution match well with the recent technology in renewables, energy storage, computer and control electronics, modern lightings and electric mobility which are all DC based. Using DC, the AC-DC and DC-AC conversions will no longer be needed. The higher processing efficiency, simple control in power quality, easy voltage source connection and material reduction are the obvious advantages. The paper discusses the recent development of DC distribution and its technology. The work in voltage level, soft-switching, safety and protection are the area of recent development. Power Electronics is a driving force to realize this future power distribution. Analyses on the voltage and efficiency are also complemented with the description. It is expected that the DC distribution demonstrates a power innovation in the world and open a new chapter for energy saving and power utilization.

Keywords–DC distribution, AC distribution, energy storage, DC-Dc converter, inverter

I. Introduction

AC distribution has been used for more than a century. Today most of the home, office and industrial appliances or equipment are using AC. The AC distribution allows simple voltage conversion using conversion transformer. Therefore it is still being used widely everywhere [1- 6]. There are a number of disadvantages using AC distribution. The voltage conversion uses power transformer that is based on silicon iron core. They operate under low frequency which is 50Hz. The overall size is large and it needs a lot of materials. The size of the associated components are also many. The AC distribution also suffers from AC loss. Therefore the cross-section of the AC cable is usually larger than DC cable. The harmonic current, power factor and many power quality problems exist in the AC system. It also imposes drawbacks in using the AC system [7-13]. The more important issue is incompatible with the existing technologies. Today almost all the electrical and electronics systems need only DC power [14-19]. This includes the lighting – all LEDs and electronic ballast,; motor driver – all uses DC powered inverters; Entertainment – All amplifier and AV equipment are DC operated; Energy storage – Battery and super-capacitor are DC operated[20]; Renewable energy – Solar panel is DC, wind generator can directly output DC[21-29]; Control and computer- All control electronics and computers are DC operated [30-36]. Power electronics DC conversion technology has been developed and used in DC distribution system extensionally [37-41]. Many apparatus sets are of structure as shown in Fig 1. There is a rectifier that converts AC into DC. The resultant DC of the rectifier is then converted to other DC voltages for different electronic circuits or electrical units. If DC is used directly, the rectifier sub-circuit can be eliminated. The materials can be reduced and the efficiency can be increased. Table I summaries the equipment using DC.

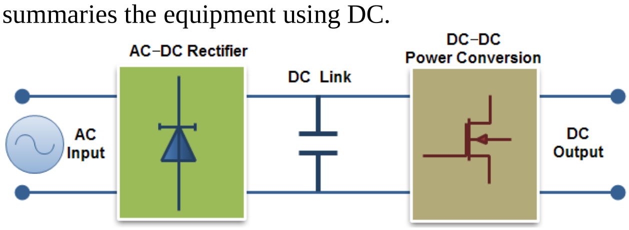

Fig.1: A typical structure of the power supply of an apparatus or equipment.

Table 1: Summary of the appliances using DC

Catalog	Applications
Consumer products	Amplifier, Television set
	Personnel computer
	Blender
	Fans
	Fluorescent lamps and its electronic ballast
	Compact fluorescent lamps and its electronic ballast
	Mobile phone, Home apparatus Charger
	Microwave oven, Induction cooker
Buildings	Ventilation
	Lift, Escalator
	Pump
	UPS, Voltage dip restorer
	VAR compensator, high frequency
	Lighting, LED
Automotive	Traction and train
	Battery charger
	Motion control
Industrial	Motor drives
	Sewing machines
	Pump
	Seawater water maker
	Electric plating
Medical	Wheel-chair, robot
	Functional electrical stimulator (FES)
	Most medical monitoring systems
	MRI

It can be seen that Table 1 cover most of the common electrical and electronic system. Most of them can actually DC connected or directly driven by DC.

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Table 2: Units used AC or DC

Units uses AC or DC	In the future
Incandescent light bulb	Replaced by compact fluorescent lamp, can use DC directly
Constant speed motor such as fans,	Replaced by inverter drives.
Thermal units of filament	Can use DC directly
Simple pump or motor such as aquarium applications	Replaced by DC motors
AC generator	DC generator using DC line power control

Table 3: Comparisons of DC/AC System

	Size Decrement	Energy Saving
Electronic Ballast	30%	5%
Motor Driver	30%	4%
Renewable Energy System	40%	5%
Transmission	50%	2%
Charger	20%	10%
TV/HiFi	10%	10%
Computer	15%	8%
Average	25%	4.5%

Many systems that are originally used in AC can also be used in DC which is shown in Table II. Typical efficiency for the power supply unit for small power electric system is 80% in which the rectifier accounts for 1/3 of the loss. Therefore it will provide 7% of energy saving if DC is used. For high power unit, the rectifier unit accounts for 5%. The saving together with equipment itself and other distribution network, the total loss using DC could be reduced by 50%. Table III summarizes the advantages.

The above discussion clearly shows that DC should be used in the electrical system rather than AC. Presently, all the AC networks are converted to DC firstly before it is connected to the appliances or equipment, either externally or internally. Therefore it is beneficial to use DC to reduce the number of stages of power conversion and reduce the materials used in power conversion, hence to increase the efficiency, simplify the power conversion, improve the reliability, simplify summation or parallel of voltage and load, and simplify the power quality circuit. Today the technology of power electronics is mature. High frequency DC-DC power conversion is simple, low cost, high efficiency and readily available to be used for this duty. All the above can be realized by DC power conversion technology.

II. Structure and DC bus voltage levels

A.DC layer structure

DC distribution power system (DPS) can be an alternative method to deliver the power to the end of the user. The driving force comes from the rapid evolution of power electronic device, the cost, stability, safety and efficiency requirement, the integration and modularize requirement of the system. And the most importance is the emerging need for DC power supply for all electric and electrical products that most of them have power electronics circuits. DC distribution method allows the incorporation of recent improvement in power electronics, and obtains significant improvement in design and manufacturing process. A typical DC distributed power system is shown in Fig. 2. The main structure of the DPS contains power sources which are commonly parallel connected and delivers power to the intermediate bus, the voltage level in this system is 310V dc and also several load converters to convert the specified voltage to the customer. In Fig. 2, the power sources include renewable resources such as wind power, photovoltaic generation, and also battery backup which power the loads when the two main power sources fail to supply electricity in a short period and a redundancy generator activates when wind power and photovoltaic fail in a long period.

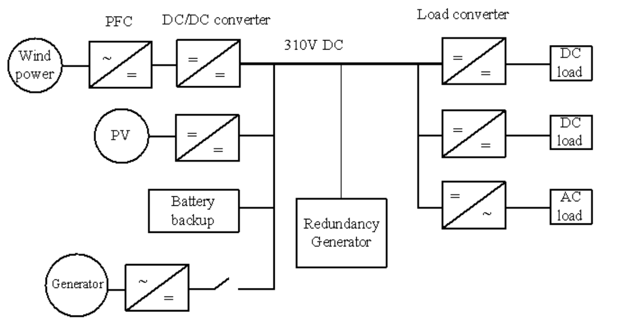


Fig. 2: DC distribution system with renewable sources generation.

The double-layer DC distributed power system employed in this paper is shown in Fig.3. The high voltage DC level is 300V~310V DC and the low voltage DC level is 20V~24V. All the DC buses also have an earth bus for the implementation.

B.DC bus voltage levels

The appropriate DC bus voltage level selection is the key step in the DC distribution system design which has great impact on the performance and characteristic of the entire power system. The DC bus voltage ranges from 12V to 400V in a low voltage distribution system. For most desktop computer system, 12V DC bus is a better choice than the traditional AC bus, which reduces power conversion stage from AC mains to 12V DC voltage while military and aerospace power units have a long history of standardizing on 28V DC. For telecommunication company, the 48V DC has been used for years on the telecommunicate applications powered by 48V DC voltage partly because of the widely available 12V DC batteries. Now, DC has been considered as an alternative system for power distribution or at least a hybrid system which incorporating in parallel existence with AC distribution system since AC power system is still the commonly accepted distribution and still be used for a long time partly due to mature AC standard and regulations. 300V~310 V DC are considered to be economic and effective enough to apply to the existing system and be compatible to the most products in use today. With an agreement on 36 V as the maximum safety voltage that will not create a hazard in China, a nominal voltage of 20V~24V DC has been accepted as the best compromise between DC/DC conversion efficiency and safety. Therefore, 20V~24V DC bus voltage has been considered as the choice of the voltage level in low voltage distributed power system.

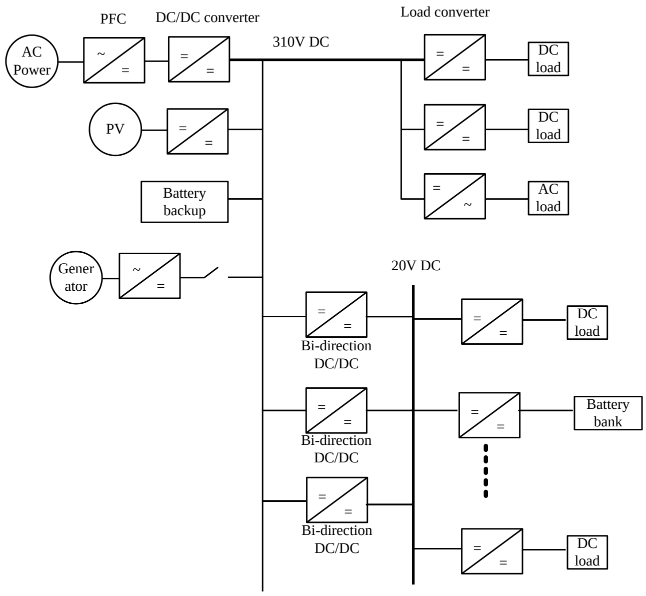


Fig. 3: DC distribution system with double-layer structure.

C. Proposed DC System

The schematic of proposed DC system is shown in Fig. 4. The system includes the power source, AC/DC converters, renewable energy, DC/DC converters, batteries pack and electronics load used in home.

III. Units in DC System

A. Renewable energy system

The recent rapid growth of renewable energy technologies, such as solar photovoltaic and wind turbines, are dramatically changing the nature of transmission, distribution and utilization of electrical energy. Most of storage equipments include batteries and ultra-capacitors that operate on DC voltage. Most renewable energy include solar and wind which have been widely utilized in household, industry and commerce. The electrical energy produced by renewable energy systems like photovoltaic panels is in the form of the DC electrical energy. In effect, despite of the fact that the electrical energy produced by the wind turbines is in the form of AC in certain proportion to the wind speed, this AC energy is converted into the DC energy by its converters. Thus, the DC energy produced by photovoltaic panels and wind turbines have to be converted into AC energy due to the fact that the consumers are all AC. Such a DC/AC conversion brings disadvantages such as the need of a DC/AC converter, the involvement of some harmonics, and the loss of energy in converter stages, special DC link design, the increase in dimension and cost, and degradation of the dynamic response.

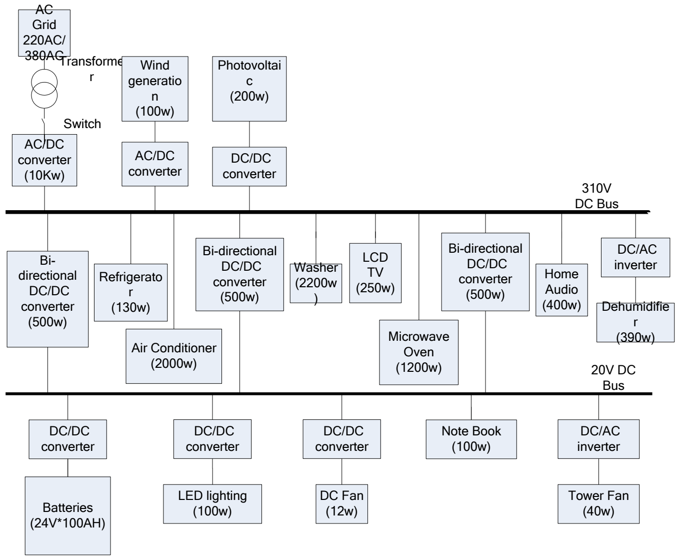


Fig. 4: The schematic of the DC System.

B. DC energy systems

The transmission of the electrical energy from the place of production to the place of consumption comes with the problem of the loss of energy. The transmission of the energy produced by renewable energy systems with the least possible loss is extremely important since these systems are expensive and the power generator may be is discontinuous. In the AC energy system, the power factor gets involved and hence this adversely affects the active power transmitted. Such a problem in power factor and the associated energy loss due to power factor does not exist in DC systems as the power factor is considered to be unity in the DC energy transmission. The energy produced by photovoltaic panels, fuel cells and wind turbines is in the form of DC and thus we can abstain from the above mentioned problems if we use DC loads without the need of DC/AC conversion.

In addition, changing DC to AC is relative expensive and inefficient, while regulating DC or changing AC to DC is both cheap and efficient. DC/AC inverters are quite complex, while DC/DC conversion are relatively simple and mature, and AC/DC rectifiers are extremely simple. Therefore, it is quite easy to import either DC or AC power or even both into a DC energy system but relatively difficult to import DC power into an AC grid.

IV. New Challenge of DC System

The switch or breaker should be revisited as the DC condition is different from AC condition. All switching units are examined and new DC switching units are introduced.

A. New Thyristor DC Circuit Breakers with Novel ZCS Technique

DC current is the key concern in DC system. There is no zero crossing point as in the AC system which usually sinusoidally varies with time. Incorrect switching on and off of a DC current will introduce transient incident such as high voltage breakdown. This produces electromagnetic interference, reduces the component age and increases other transient operational risk. The obvious solution is to use zero-current switching (ZCS) that reduce the switching transient. The following is a new introduced DC switching breaker.

In order to simplify the capacitor self-charging circuit of thyristor DC circuit breakers for low voltage residential and commercial applications, a novel topology is developed as shown in Fig.5. In normal operation state, thyristor T_{main} is turned on to carry current for the load. Meanwhile, the Mosfet S is also turned on to provide the charging path for the capacitor C_r. In the beginning of an interruption process, thyristor T_{aux} is turned on and S is being off. The current of the LC resonant tank increases from zero. The main switch T_{main} will be off when the resonant current increases to the level of the load current. At the end of the process, the auxiliary switch T_{aux} is also turned off when the capacitor C_r is fully charged in opposite polarity and the interruption process is completed.

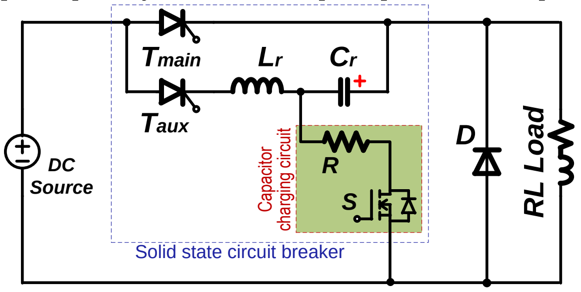


Fig.5: Thyristor DC circuit breaker with simplified self-charging circuit.

Fig 5 gives only a single wire thyristor DC circuit breaker which only has a limited protection as there is still one wire not being off. For complete protection, all electric conductors should be turned off during fault condition. A new four terminal thyristor DC circuit breaker are developed as given in Fig.6. With the proposed unit, faults can be totally isolated from the power source. The positive and negative buses are protected through the two combinations of thyristor switches as seen in the upper rail and lower rail, respectively. However, there is only one capacitor charging circuit required to provide energy for the two capacitors before responding to an interruption command. In order to ensure there are the same amounts of energy pre-charged in the two capacitors, passive balance resistors R_P are employed. It should be noted that the value of R_P is not only far larger than the charging resistor R_S, but also so large that the auxiliary switch T_{aux} could be off automatically at the end of an interruption process. The operation principle of this new circuit breaker is the same as that of one shown in Fig.5, but has extended to the both rails.

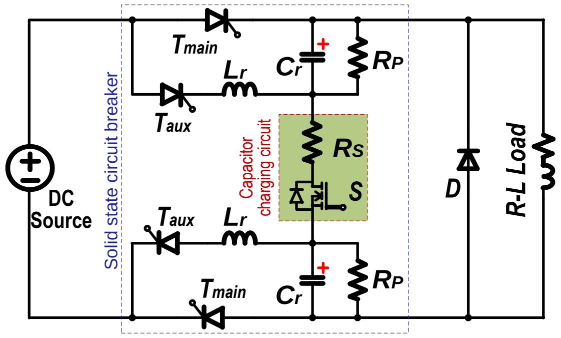


Fig.6: Four-terminal thyristor DC circuit breaker with self-charging circuit.

B. Design of DC RCD

The measurement component of this paper is the single core DC leakage current sensor based on magnetic modulation. The difference with the traditional sensor is that the single core and single coil.

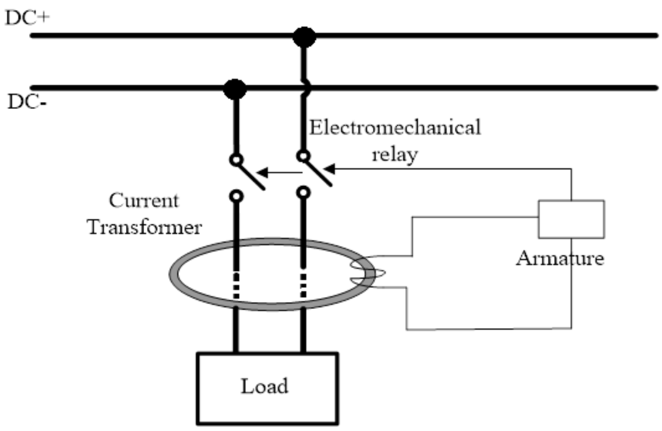


Fig. 7: Connection diagram of RCD in the DC system.

As shown in Fig. 7, the transformer coil is used to detect the leakage current signal through the differential current of the load. The signal received is sent to a signal conditioning circuit, and then processed by the signal conditioning circuitry. A microcontroller is used to provide the decision and identification of the leakage current level for human protection. The RCD DC unit executes the turn-off action, and visual display is implemented to assist the operation. An LED light indicates the working status of the system to achieve a real-time display and DC leakage current self-diagnostic result, and of course provides action and alarm.

C. Effect of DC current on human being

As shown in Fig. 8, the impedance of human being can be divided into internal impedance and impedance of the skin. The internal impedance of the human body is considered as resistive. Its value depends primarily on the current path and the contact area. The impedance of the skin is viewed as a combination of resistances and capacitances. The skin impedance falls as the increased current. The total impedance of the human body is higher for DC.

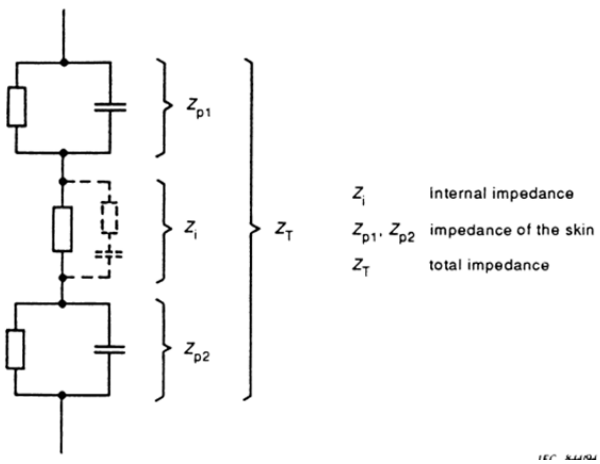
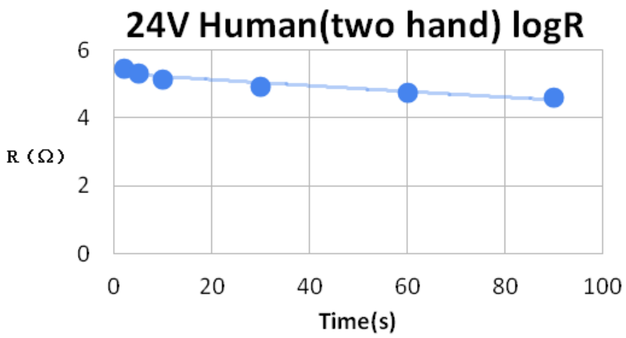
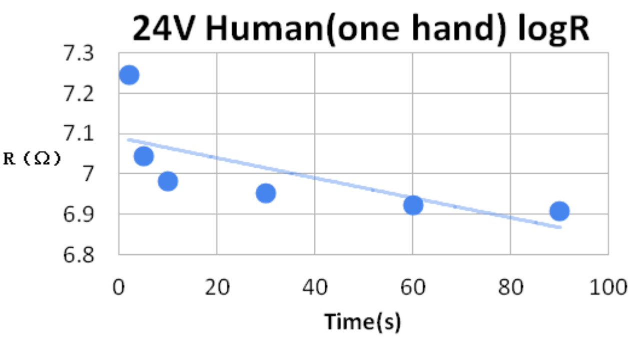


Fig. 8: Impedance of the human body [42].

At the moment of touching voltage, skin impedances are negligible. The initial resistance is approximately equal to the internal impedance of the human body. Therefore, the initial resistance is determined by the current path. The capacitances in the human body are charged as soon as electrical excitation, and the impedance of the human body is close to the addition of internal impedance and skin impedance. The experiments are conducted to measure the DC impedance of human, and the corresponding results are demonstrated in Fig. 9.



(a)



(b)

Fig. 9: DC impedance of human at the given conditions.

The impedances of two hands are shown in Fig. 9a with 24V DC voltage; while the impedances of one hand are shown in Fig. 9b with 24V DC voltage. It can be found that the impedance is decreased along with the time applied duration of DC electric shock.

According to the impedance characteristics of DC current, the raw data processing can be accomplished by wavelet analysis, and the obtained signals are viewed as the input of Neural Network. The compositional structure can avoid the input disturbance to BP Neural Network, and signals preprocessing of wavelet analysis ensures the accuracy and stability. Meanwhile, this structure can fully exert their advantages as the wavelet analysis has high resolution and BP Neural network has nonlinear approximation. The leakage current protection is made intelligent with adaptive identification and high fault tolerance. Since the impedance model is stable and high accurate, the personal electric shock current can be effectively detected with fast response time.

V. THE ANALYSIS AND SIMULATION PLATFORM OF DC SYSTEMS SET UP

A. Simulation System

As shown in Fig. 10, using an ideal voltage source V_S (310V) with a series-connected resistor R_s (1mΩ) as the power source of the whole DC distribution system. In this case, the level of 310V is directly obtained from the power source V_S whereas the level of 20V is converted by a high step-down DC/DC converter.

Considering the load characteristics in the DC distribution system, all different types of loads are replaced by the pure-resistance load with different values. It means just active power is considered here. There are four loads with total power 256W for the lower-voltage bus (20V) while seven loads with the total power 6.78kW on the higher-voltage bus (310V).

Each load is connected to the DC buses through an ideal switch. This switch is just used to start and stop the load operation and there is no power regulation function.

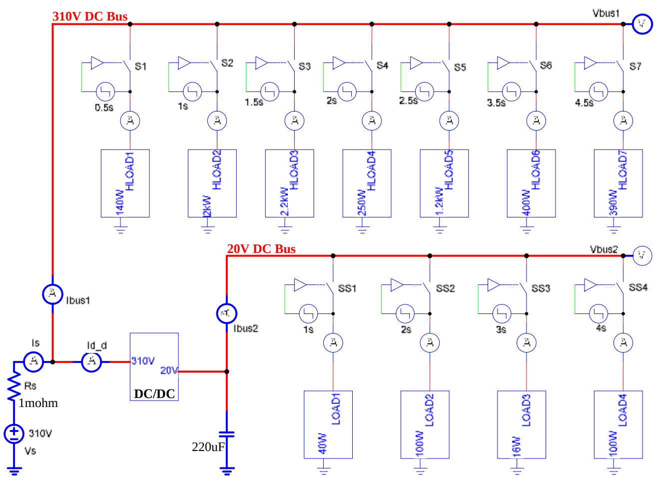


Fig. 10: Simulation System for DC Distribution.

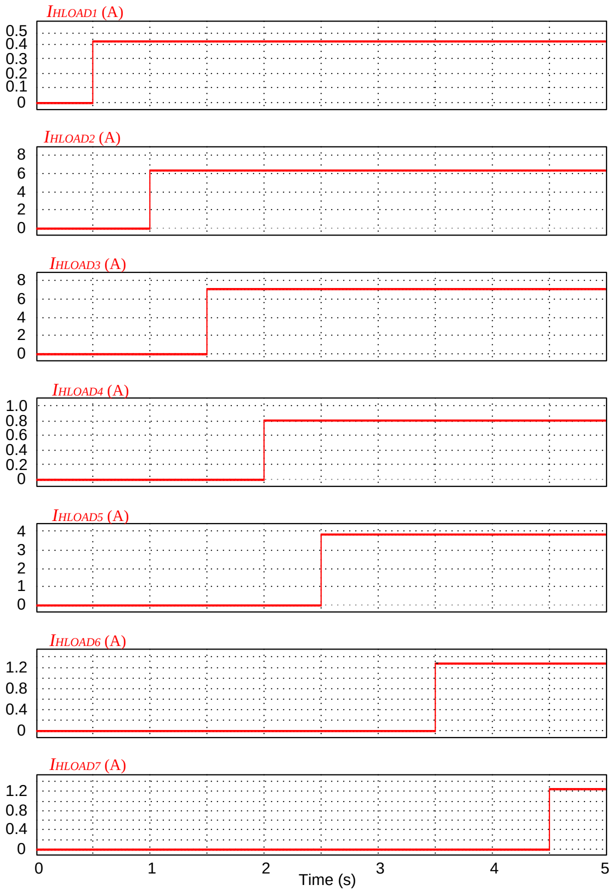
B. Step Loads Response

Step Load means the loads are gradually added to the DC bus and the power source will endure maximum power operation test at the end when all loads run simultaneously. Fig. 11 (a) and 11 (b) provide the start-up sequence of all loads for the higher- and lower-voltage buses, respectively.

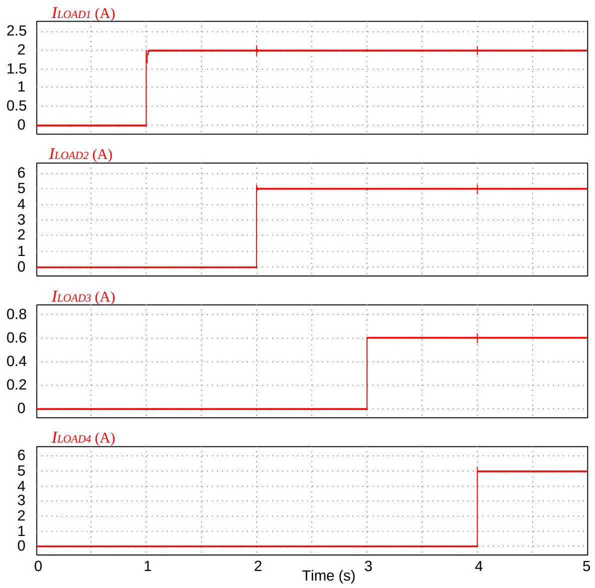
When the four loads are connected to the lower-voltage bus step by step, the bus responses including voltage V_{bus2} and current I_{bus2} are obtained as shown in the upper of Fig. 11(c). It shows the bus current increases gradually from zero to maximum value 12.8A whereas the bus voltage remains constant 20V. However, there are small spikes found in the bus voltage when the load is changed suddenly. These voltage spikes could be eliminated or reduced by using the more advanced DC/DC power converter to obtain the lower bus voltage from higher-voltage bus. It also could be optimized by employing an energy storage device with high power density, like super-capacitor.

Similarly, with the seven loads are gradually added to the higher-voltage bus, the bus current I_{bus1} also increases from zero to the maximum 21.9A. As shown in the lower of Fig. 11(c), it could be found there is a slight bus voltage drop with the increase in load. It is actually caused by the internal resistance of the power source, i.e. R_S. In practical, the resistance of wires also will contribute for the voltage drop. It means the high internal resistance of both source and wires should be avoided in practical DC distribution system.

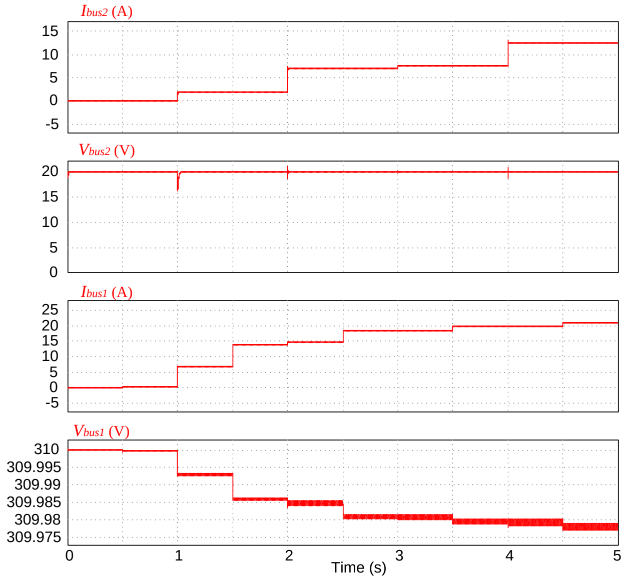
Additionally, the injection current I_{d_d} from the higher-voltage bus to the lower bus and the total current I_S flowing out of the power source are also obtained as shown in Fig. 11(d).



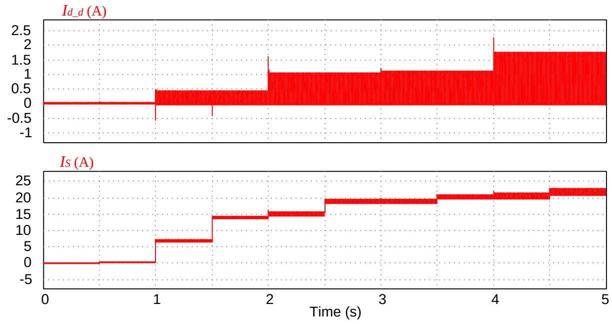
(a) Loads start-up sequence of the higher-voltage bus



(b) Loads start-up sequence of the lower-voltage bus



(c) Bus currents and voltages



(d) Exchanging current *Id_d* between buses and total input current.

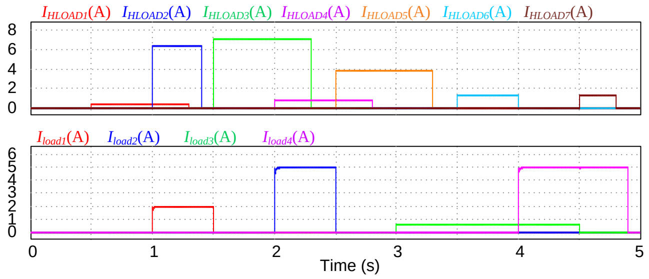
Fig. 11: Simulation results for the dual-level DC distribution system with step loads.

C. Pulse Load Response

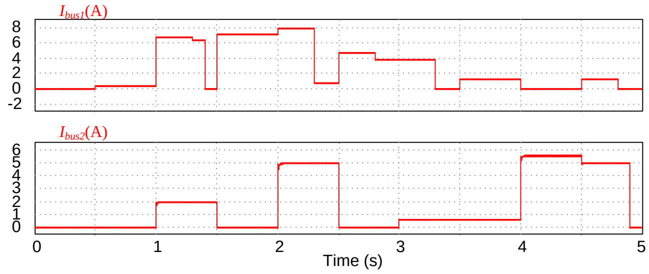
Pulse loads sequence is given in Fig. 11(a) of which the upper is for the higher-voltage bus and the lower is for the lower-voltage bus. Each load is connected to the buses just for a short period. It means the DC buses will withstand the impact of frequent load change.

The corresponding bus currents under pulse loads operation are obtained as shown in Fig. 11(b). It depicts that the bus currents fluctuate frequently with loads connected or disconnected from the buses.

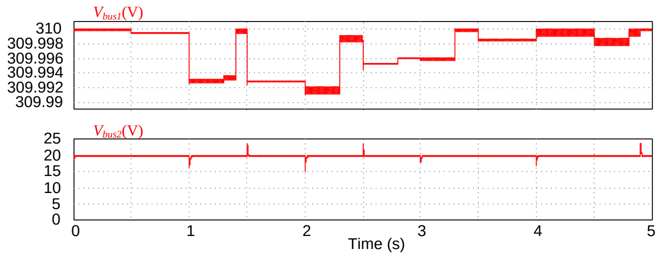
The bus voltage response for the pulse load is depicted in Fig. 11(c). For the higher bus voltage V_{bus1}, it also fluctuates with the change of bus current I_{bus1}. This could be still explained as the effect of the internal resistance R_S. In contrast, the lower bus voltage V_{bus2} still remain constant 20V but with small voltage spike when the load is connected or disconnected from the bus. This performance could be also optimized by using the same methods present in the last section. Additionally, the soft-start and soft-stop of loads also benefit the bus voltage spike reduction.



(a) Loads start-up sequence



(b) Bus currents



(c) Bus voltages

Fig. 12: Simulation results for the dual-level DC distribution system with pulse loads.

D. Efficiency

The preferred voltage for DC high voltage is examined. The study is using common apparatus for home and office. As shown in Table 4, in the simulation study of higher DC voltage, these selected appliances are typical ones and of course other combination can also be used.

Table 4: Load for higher DC voltage

Load	Rated Power(W)
Refrigerator	140
Air Conditioner	2000
Washer	2200
LCD TV	250
Microwave Oven	1200
Home Audio	400
Dehumidifier	390

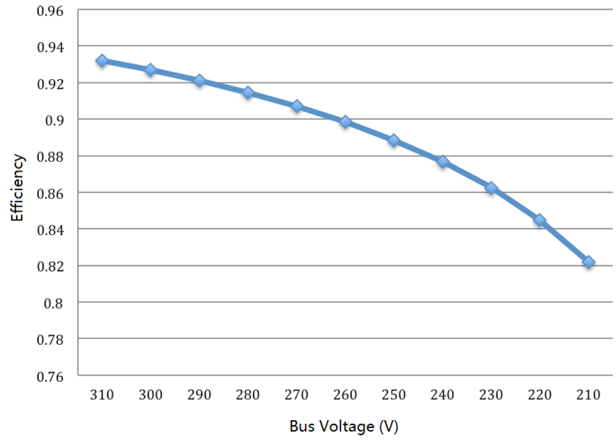


Fig.13: Simulated Efficiency curve for higher DC voltage.

The simulated efficiency curve of higher DC voltage is shown in Fig.13, the efficiency approaches maximum when the voltage reaches over 300V, for the existing electronics appliances, the DC bus voltage is usually smaller than 310V. Also, for single-phase full bridge rectifier, the output voltage is around 310V. If taking into account the input energy from a power source to the DC distribution system, the higher DC voltage needs to be less than 310V. 300V can be used as the preferred voltage in the DC distribution system.

As shown in Table 5, in the simulation study of lower dc voltage, these appliances are used as the load.

Table 5: Load for lower DC voltage

Load	Rated Power(W)
LED lighting	100
Note book	100
DC fan	16
Battery Charger	40

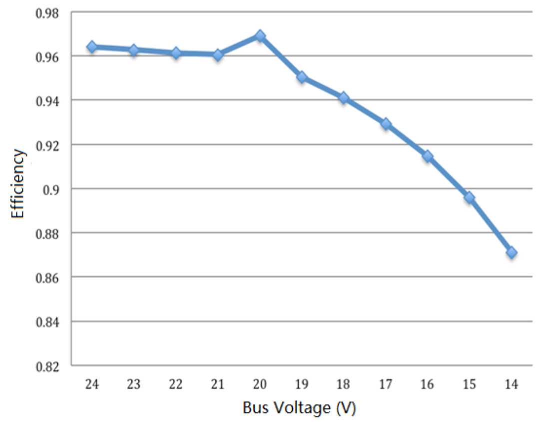


Fig.14: Simulated Efficiency curve for Lower DC voltage.

The simulated efficiency curve of lower DC voltage is shown in Fig.14. The dc bus voltage can be connected to the 20V voltage, so the efficiency of power conversion from 20V dc bus to notebook is 100%. In the simulated curve, the total efficiency is approaching maximum at the voltage of 20V. 20V can be used as the preferred lower dc voltage in the DC distribution system.

E. Simulation Results

Both the quality of power sources and interfaces limit the performance of DC distribution system. The bus voltage drop is mainly caused by the internal resistance of power sources and wires while the voltage spike is mainly related to the ability interfaces.

High quality power source (AC/DC converter) and power interface (DC/DC converter) should be selected to build the well performance DC distribution system. Employing energy storage device with high power/energy density can also contribute to improve the ability of anti-load-disturbance. Meanwhile, the soft-start and soft-stop techniques also should be developed to reduce the pulse impact on the DC buses.

VI. Development of DC Distribution Standards

A. Protection and Electrical Safety Standard

System protection and electrical safety facilities, which are well-established in AC power systems, but little practice exists for DC systems. The existing DC standards for protection and electrical safety standard is re-configured to set up the DC distribution standard. This standard is formulated with a view to ensuring personal and property safety, energy conservation, advanced technology, full function, economic rationality, reliable electrical installation as well as convenient installation and operation in the design of low-voltage DC distribution electrical installations. This standard is applicable to the design of low-voltage DC distribution electrical installations at 1000VDC in construction, extension and renovation engineering. The DC Distribution Standards for Protection and Electrical Safety developed mainly includes 1) Rules for Selection of DC Distribution Conductors; 2) Safety measures in arrangement of DC distribution equipment; 3) Protection of DC distribution line, etc.

B. The DC Distribution Standard for switch gear

The DC Distribution Standard for switch gear covers DC Distribution power circuit-breaker switch gear assemblies. In this standard, the ratings of a DC switchgear assembly are designations of operating limits under specified conditions of ambient temperature and temperature rise. DC Switchgear shall have the following ratings: (1) Rated maximum voltage; (2) Rated insulation level; (3) Rated continuous current; (4) Rated short-time current; (5) Rated short-circuit current Physical and electrical conditions for tests and methods of determining temperatures and test values have been established. The voltage shall be 1000 V or below.

C. Standard for retrofitting

In the past, AC is used for most of the transmission and distribution system because a simple transformer can provide the AC voltage conversion whereas DC cannot be used in transformer for voltage step-up and down. With the development of renewable energy technology, the AC energy production is replaced by DC. The conventional two-stage conversion that is the AC-DC and DC-AC for AC-AC conversion to AC appliances is not usable for DC distribution network. It is possible to skip one stage conversion and to use DC-DC conversion only by using DC for distribution systems. The developed standard for retrofitting includes retrofitting of power supplies, Inverter Air conditioner, Motor Drive & Inverter, LED Driver, Charger, Solar Power Conditioning, Wind Power Generation and Fuel Cell Power Generation. In these applications, the AC-DC stage is skipped and the main power is directly connected to the DC bus.

VII. Conclusion

DC distribution is a future technology. Today, all the necessary materials and electronics are ready to realize this new method to a city, building and office or home. It represents the high efficient, high dynamic performance and an environmentally friendly method of processing electric power. The new method will change the electricity concept and usage in all electrical parts and units. It will change the world electricity market. It is obvious to enhance the control and safety and reduce the energy loss and materials. The detailed electric and performance standard includes choice of voltage level, selection of one or two layer DC distribution structure. The analysis and simulation platform of DC systems have set up to examine the new DC distribution system. That includes steady-state and transient simulations under different operating conditions, load type, storage device and renewable energy source. Power distribution technology, switching method, protection and electrical safety, retrofitting to the electrical appliances, interfacing with the renewable energy and energy storage have been developed. A new set of standard has been developed that will be used to support the new method of DC distribution.

References

[1] S. Luo, and I. Batarseh, “A review of Distributed power systems Part 1: DC distributed power system”, *IEEE Aerosp. Electron. Syst. Mag.*, vol. 21, no. 6, Jun. 2006, pp. 5-14.

[2] S. G. Luo, I. Batarseh, “A review of distributed power systems part2: high frequency ac distributed power systems”, *IEEE A&E Mag.*, vol. 21, no. 6, June. 2006, pp. 5-13.

[3] D. Boroyevich, I. Cvetkovic, D. Dong, R. Burgos, F. Wang, F. C. Lee, “Future electronic power distribution system- a contemplative view”, OPTIM’ 2010, pp. 1369 – 1380.

[4] M. N. Marwali, A. Keyhani, “Control of distributed generation systems-part 1: voltages and current controls”, *IEEE Trans. on Power Electron.,* vol. 19, no. 6, Nov. 2004, pp. 1541-1550.

[5] M. N. Marwali, J. W. Jung, A. Keyhani, “Control of distributed generation systems-part 2: load sharing controls”, *IEEE Trans. on Power Electron.*, vol. 19 , no. 6, 2004, pp. 1551-1561.

[6] K. W. E. Cheng, “Overview of the dc power conversion and distribution”, *Asian Power Electron. J.*, Oct. 2008, vol. 2, no. 2, pp. 75-82.

[7] L. X. Tang; B. T. Ooi, “Locating and isolating dc faults in multi-terminal dc systems”, *IEEE Trans. on Power Del.*, vol. 22, no. 3, 2007, pp. 1877-1884.

[8] M. E. Baran; N. R. Mahajan, “Overcurrent protection on voltage-source-converter based multiterminal dc distribution systems”, *IEEE Trans. on Power Del.*, vol. 22, no. 1, 2007, pp. 406 – 412.

[9] E. Cinieri, A. Fumi, V. Salvatori, C. Spalvieri, “A new high-speed digital relay for the 3-kV dc electrical railway

lines", *IEEE Trans. on Power Del.*,vol. 22, no. 4, 2007, pp. 2262-2270.

[10] F. Luo; J. Chen; X. H. Lin; Y. Kang; S. X. Duan, "A novel solid state fault current limiter for dc power distribution network", APEC Conference, 2008, pp. 1284-1289.

[11] D. Salomonsson, L. Soder, A.Sannino, "Protection of low voltage dc microgrids", *IEEE Trans. on Power Del.*,vol. 24, no. 3, 2009, pp. 1045-1053.

[12] B. Morton, I. M. Y. Mareels, "The prospects for dc power distribution in buildings", AUPEC'99.

[13] H. Pang; E. Lo, B. Pong, "Dc electrical distribution systems in buildings", ICPESA '06, pp. 115-119.

[14] K. Engelen, J, Dridsen, et al., "Small-scale residential dc distribution systems", 3rd IEEE Benelux Young Reasearchers Symposium in Electrical Power Engineering, Ghent (2006-4), pp. 1-7.

[15] P. Pertti, K. Tero, P. Jarmo, "Dc supply of low voltage electricity appliances in residential buildings", CIRED' 2009, pp. 1-4.

[16] V. Sithmolada, P. W. Sauer, "Facility-level dc vs. typical ac distribution for data centers", TENCON 2010, Nov. 2010, pp. 2102-2107.

[17] Tabari, M.; Yazdani, A., "Stability of a dc Distribution System for Power System Integration of Plug-In Hybrid Electric Vehicles," *IEEE Trans. on Smart Grid* , vol.5, no.5, pp.2564,2573, Sept. 2014

[18] Wu, T.-F.; Chang, C.-H.; Lin, L.-C.; Yu, G.-R.; Chang, Y.-R., "DC-Bus Voltage Control With a Three-Phase Bidirectional Inverter for DC Distribution Systems," *IEEE Trans. on Power Electron.*, vol.28, no.4, pp.1890,1899, April 2013

[19] Mohsenian-Rad, H.; Davoudi, A., "Towards Building an Optimal Demand Response Framework for DC Distribution Networks", *IEEE Trans. on Smart Grid*, vol.5, no.5, pp.2626,2634, Sept. 2014

[20] Byeon, G.; Yoon, T.; Oh, S.; Jang, G., "Energy Management Strategy of the DC Distribution System in Buildings Using the EV Service Model", *IEEE Trans. on Power Electron*., vol.28, no.4, pp.1544,1554, April 2013

[21] Guerrero, J.M.; Davoudi, A.; Aminifar, F.; Jatskevich, J.; Kakigano, H., "Guest Editorial: Special Section on Smart DC Distribution Systems," *IEEE Trans. on Smart Grid*, vol.5, no.5, pp.2473,2475, Sept. 2014

[22] Sato, Y.; Tanaka, Y.; Fukui, A.; Yamasaki, M.; Ohashi, H., "SiC-SIT Circuit Breakers With Controllable Interruption Voltage for 400-V DC Distribution Systems," *IEEE Trans. on Power Electron.* , vol.29, no.5, pp.2597,2605, May 2014

[23] Kazemlou, S.; Mehraeen, S., "Decentralized Discrete-Time Adaptive Neural Network Control of Interconnected DC Distribution System," *IEEE Trans. on Smart Grid* , vol.5, no.5, pp.2496,2507, Sept. 2014.

[24] Seo, G.-S.; Lee, K.-C.; Cho, B.-H., "A New DC Anti-Islanding Technique of Electrolytic Capacitor-Less Photovoltaic Interface in DC Distribution Systems," *IEEE Trans. on Power Electron.* , vol.28, no.4, pp.1632,1641, April 2013.

[25] Zhan Wang; Hui Li, "An Integrated Three-Port Bidirectional DC–DC Converter for PV Application on a DC Distribution System," *IEEE Trans. on Power Electron.*, vol.28, no.10, pp.4612,4624, Oct. 2013

[26] Tsai-Fu Wu; Chia-Ling Kuo; Kun-Han Sun; Yu-Kai Chen; Yung-Ruei Chang; Yih-Der Lee, "Integration and Operation of a Single-Phase Bidirectional Inverter With Two Buck/Boost MPPTs for DC-Distribution Applications," *IEEE Trans. on Power Electron.* , vol.28, no.11, pp.5098,5106, Nov. 2013

[27] Guest editorial - special issue on power electronics in DC distribution systems," *IEEE Trans. on Power Electron.*, vol.28, no.4, pp.1507,1508, April 2013

[28] Dong, D.; Cvetkovic, I.; Boroyevich, D.; Zhang, W.; Wang, R.; Mattavelli, P., "Grid-Interface Bidirectional Converter for Residential DC Distribution Systems—Part One: High-Density Two-Stage Topology," *IEEE Trans. on Power Electron.*, vol.28, no.4, pp.1655,1666, April 2013

[29] Shamsi, P.; Fahimi, B., "Stability Assessment of a DC Distribution Network in a Hybrid Micro-Grid Application," *IEEE Trans. on Smart Grid* , vol.5, no.5, pp.2527,2534, Sept. 2014

[30] Shadmand, M.B.; Balog, R.S.; Abu-Rub, H., "Model Predictive Control of PV Sources in a Smart DC Distribution System: Maximum Power Point Tracking and Droop Control," *IEEE Trans. on Energy Convers.*, vol.29, no.4, pp.913,921, Dec. 2014

[31] Dong, D.; Luo, F.; Zhang, X.; Boroyevich, D.; Mattavelli, P., "Grid-Interface Bidirectional Converter for Residential DC Distribution Systems—Part 2: AC and DC Interface Design With Passive Components Minimization," *IEEE Trans. on Power Electron.* , vol.28, no.4, pp.1667,1679, April 2013

[32] Kim, H.-S.; Ryu, M.-H.; Baek, J.-W.; Jung, J.-H., "High-Efficiency Isolated Bidirectional AC–DC Converter for a DC Distribution System," *IEEE Trans. on Power Electron.*, vol.28, no.4, pp.1642,1654, April 2013

[33] Kakigano, H.; Miura, Y.; Ise, T., "Distribution Voltage Control for DC Microgrids Using Fuzzy Control and Gain-Scheduling Technique," *IEEE Trans. on Power Electron.*, vol.28, no.5, pp.2246,2258, May 2013

[34] Nuutinen, P.; Pinomaa, A.; Ström, J.-P.; Kaipia, T.; Silventoinen, P., "On Common-Mode and RF EMI in a Low-Voltage DC Distribution Network," *IEEE Trans. on Smart Grid* , vol.5, no.5, pp.2583,2592, Sept. 2014

[35] Riccobono, A.; Santi, E., "Comprehensive Review of Stability Criteria for DC Power Distribution Systems," *IEEE Transactions on Ind. Appl.*, vol.50, no.5, pp.3525,3535, Sept.-Oct. 2014

[36] Fletcher, S.D.A.; Norman, P.J.; Fong, K.; Galloway, S.J.; Burt, G.M., "High-Speed Differential Protection for Smart DC Distribution Systems," *IEEE Trans. on Smart Grid* , vol.5, no.5, pp.2610,2617, Sept. 2014

[37] Hamad, A.A.; Farag, H.E.; El-Saadany, E.F., "A Novel Multiagent Control Scheme for Voltage Regulation in DC Distribution Systems," *IEEE Trans. on Sustain. Energy*, vol.6, no.2, pp.534,545, April 2015

[38] Soeiro, T.B.; Vancu, F.; Kolar, J.W., "Hybrid Active Third-Harmonic Current Injection Mains Interface Concept for DC Distribution Systems," *IEEE Trans. on Power Electron.*, vol.28, no.1, pp.7,13, Jan. 2013

[39] Chang, Y.-C.; Kuo, C.-L.; Sun, K.-H.; Li, T.-C., "Development and Operational Control of Two-String Maximum Power Point Trackers in DC Distribution Systems," *IEEE Trans. on Power Electron.* , vol.28, no.4, pp.1852,1861, April 2013

[40] Stupar, A.; Friedli, T.; Minibock, J.; Kolar, J.W., "Towards a 99% Efficient Three-Phase Buck-Type PFC Rectifier for 400-V DC Distribution Systems," *IEEE Trans. on Power Electron.* , vol.27, no.4, pp.1732,1744, April 2012

[41] Gab-Su Seo; Jong-Won Shin; Bo-Hyung Cho; Kyu-Chan Lee, "Digitally Controlled Current Sensorless Photovoltaic Micro-Converter for DC Distribution," *IEEE Trans. on Ind. Inform.*, vol.10, no.1, pp.117,126, Feb. 2014.

[42] IEC 479-1: 1994 Guide to Effects of current on human beings and livestock

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