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ADVANTAGES AND CHALLENGES IN PROMOTING MODERN 400-V DC DISTRIBUTION NETWORKS WITH INTEGRATED RENEWABLE ENERGY RESOURCES

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Advantages and Challenges in Promoting Modern 400-V DC Distribution Networks with Integrated Renewable Energy Resources

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***Abstract*—Motivated by recent developments of renewable energy resources and the smart grid, a 400-V dc distribution network has a potential to replace the traditional ac distribution network, and to provide high energy efficiency and advanced controllability, protection, sustainability and reliability in the power system. Therefore, in this paper, the advantages of efficiency gain and energy saving are discussed and demonstrated by a case study of a 400-V dc distribution network. Related theoretical analysis in efficiency gain is proven by simulation tests and experiments. The challenges are identified for promoting 400-V dc distribution, in the aspects of stability, protection, and security. Possible solutions for these three challenges are discussed, which may lead to future research focuses.**

***Index Terms*—DC Distribution, Energy Efficiency, Renewable Energy, Stability, Security, Protection.**

I. Introduction – "From Current AC Systems to Next-Generation DC Distribution"

FIG. 1 illustrates the history and framework development of electric power systems over time. Back in the 1880s, the first installation of the Edison electric incandescent lighting system on land took place in New York City. This service installation was known as an "isolated plant" electric dynamo installation. In that era, due to the lack of long-distance power transmission technology, the loads were close to the isolated generators and no sizable electric power system formed in this early stage, when direct current (dc) power systems dominated.

With the development of practical "step-up" and "step-down" electrical transformer systems in the late 1880s, alternating current (ac) power systems were promoted and gradually formed the framework of modern electric power systems later in 1920s–1930s. In modern power systems, electric generators are sized from hundreds of kWs to tens of MWs and their output voltages are boosted to hundreds of kVs to realize long-distance power transmission from state to state and nationwide. In this way, power users don't have to be close to power plants and can avoid the disturbances of noise and dust. A limited number of large power generators (i.e., large red dots in Fig. 1) supply most loads via transmission and distribution networks.

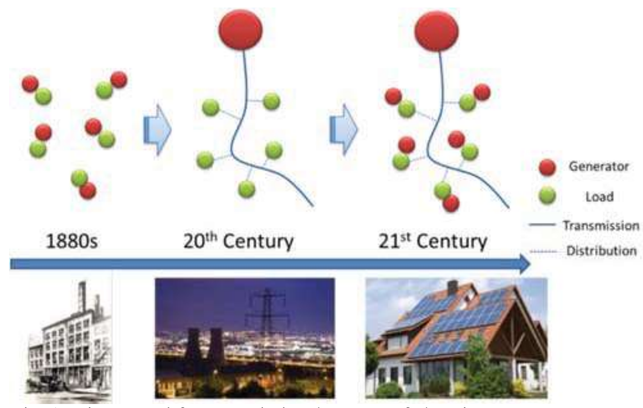

Fig. 1. History and framework development of electric power systems.

With the development and commercialization of renewable energy technologies—e.g., solar, wind, fuel cell—many clean, controllable, small-capacity distributed generators (DGs, demonstrated as the small-size red dots in Fig. 1) can be installed next to the loads without pollution or major investment. Worldwide, small-scale, roof-top solar power installation was 23 GW at the end of 2013, and it is estimated to continue growing at above 20 additional GW per year until 2018 [1]. In the March of 2016, the updated analysis at the National Renewable Energy Laboratory (NREL), U.S. Department of Energy, revealed a technical potential of 1,118 GW of capacity and 1,432 TWh of annual energy generation, close to 40 percent of the nation's electricity needs [2]. The traditional modern power network implements only unidirectional control information delivery. The smart grid has emerged as an enhancement of our 20th-century modern electric power systems that supports bi-directional communications and hence is able to monitor and control hundreds and thousands of DGs. In this way, the smart grid realizes an automated and distributed advanced energy delivery network consisting of wideband information

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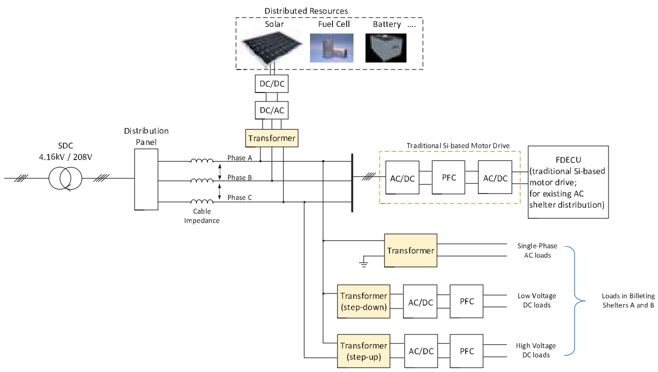
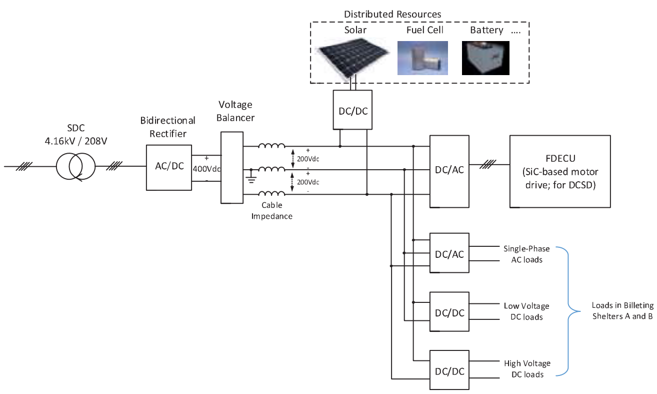
capacity and high security features [3] [4].

Different from relying on power transformers in ac system, high-efficiency power and energy conversion can be realized by adopting emerging silicon carbide (SiC) power semiconductor devices. Also, unwanted dc–ac and ac–dc conversion stages can be removed from dc distribution networks. These two features lead to more-efficient energy utilization than ac distribution affords, by comparing layouts of ac and dc distribution networks as shown in Fig. 2.



(a) traditional 208-Vac distribution network



(b) proposed 400-Vdc distribution network

Fig. 2. Comparison of traditional 208-Vac and proposed 400-Vdc distribution networks.

The remainder of the paper is organized as follows. The advantages of 400-V dc distribution networks in efficiency gain, energy saving and other aspects are demonstrated in section II. Three major challenges: a) stability; b) protection; and c) security, are identified in section III and their solutions are discussed to promote use of 400-V dc distribution networks with integrated renewable energy resources in modern electric power systems.

II. Efficiency Gain and Energy Saving

Here, we compare the layouts of 208-Vac and 400-Vdc distribution networks and the power losses of power components in these networks, and then analyze the efficiency gain and energy saving of 400-Vdc distribution networks in an example distribution system. The example distribution system is originally a 208-Vac distribution network, which consists of a field-deployable environmental control unit (FDECU) of 15.5 kW, 0.95 power factor (inductive) for cooling mode and 1.0 power factor for heating mode, a group of loads of 10 kW, and a roof solar system of 6 kW, as shown in Fig. 2. This example system can also represent a microgrid / nanogrid, such as a sustainable building, a large-size or medium-size smart home, and a small-size telecommunication power system.

A. Layout of 400-Vdc Distribution Networks

In the U.S., 24-Vdc, 48-Vdc, 240-Vdc, 380-Vdc, and 550-Vdc levels have been standard-ready for dc distribution networks for many years [5]. Electronics appliances such as TVs, desktops and laptops operate internally on direct current power supply. The energy efficiency of these power users can be improved by getting rid of unnecessary ac–dc conversion provided by 50/60-Hz transformers [6]. In addition, the variable frequency control for air conditioners and FDECUs is more easily obtained from a dc source [7]. Work of [7] from the PNNL, DOE reveals that "*it was shown that fuel cells or other local dc generation that feed directly into a premise dc bus could have favorable conversion losses …*" In summary, dc distribution networks demonstrate:

a) Better reliability and uninterruptible power supply;
b) Better voltage stability and power quality, which benefit renewable power integration;
c) No synchronization problem;
d) Records of the system states and parameters, which can be used by power system operators and planners at the end for demand-response operation;
e) Fast fault detection and protection (from high-power, fast-acting static power semiconductor devices), thereby significantly reducing the need for mechanical breakers [8]–[10]; and
f) No health concerns from human exposure to 60-Hz distribution [11].

Among these available dc level candidates, the low-voltage dc systems of 24 Vdc and 48 Vdc cannot be selected for the dc distribution network, an alternative to the original 208-Vac distribution network, because: 1) high power losses due to the high current flow; 2) reduced distance of power distribution due to high voltage drop in distribution cable; and 3) consideration of continuing to use currently available electric components and devices from ac systems.

The voltage level of 400 Vdc is an emerging dc distribution level and was recommended as the nominal voltage by some telecommunication power companies and national labs [12]. The 400-Vdc power distribution simplifies power management and brings preferable advantages over 380-Vdc and 550-Vdc systems for a list of reasons, in Table I.

TABLE I
Preferable Advantages of 400 Vdc over Other DC Levels [12] [13]

• No phase balancing is required, which reduces the complexity of power strips and wiring;
• No synchronization is required to parallel multiple sources;
• There are no harmonic currents to worry about, eliminating the need for power factor correction (PFC) circuits;
• It can use fewer breakers because it uses fewer power conversion stages;
• It simplifies wiring because only two conductors are required;

• A link voltage of approximately 400 Vdc already exists in today's ac power supplies, as well as the bus in light ballasts and adjustable speed drives (ASDs), which are often used to power fans and pumps in the data center;
• Uninterruptable power supply (UPS) systems typically use a higher voltage dc bus of 540-Vdc which can easily be re-designed to support 400 Vdc;
• The spacing requirements per the IEC 60905-1 standard for power supplies are the same for universal input (90–264 Vac) power supplies and for dc power supplies with a working voltage below 420 Vdc;
• It is well within an existing 600-V safety limit and can operate over standard 600-V rated wiring and busing systems;
• Commercial solutions are already emerging;
• It is simpler and more efficient to connect to renewable energy sources such as photovoltaics, fuel cells, and wind turbines with variable frequency generators, because they also already have a higher voltage dc bus at a voltage in this range.

According to the specifications of power users in the example distribution system, a 400-Vdc three-wire bi-polar dc distribution network with neutral grounding was selected in [14] and [15] as an alternative to the original 208-Vac system. The considerations of this selection are listed below:

a) Allow loads to be energized from +400 Vdc, +200 Vdc, and -200 Vdc, analogous to the split 240-Vac/120-Vac level in ac distribution networks;
b) Flexibility in load supply. When a temporary overload occurs at a single-phase load, electric power can be shared between load-side converters;
c) Continue to use the original 4/0 power cables;
d) Continue to use the original fuses/circuit breakers;
e) High-efficiency variable frequency drive (VFD) for the FDECU of 208 Vac;
f) High-efficiency bi-directional rectifier for 400 Vdc distribution;
g) Reported highly efficient 400-Vdc LED lighting. For example, 2490-lm light output with an outstanding efficacy of 90 lm/W [16].

B. Power Losses in Components

The losses associated with power MOSFETs, diodes, and inductors are taken into account in the power loss analysis of power electronics converters. The losses in low-voltage dry-type transformers under reference temperature (20°C), critical temperature (50°C) and extremely critical temperature (75°C) are considered in the efficiency gain analysis.

- Losses in Power MOSFETs

Losses of power MOSFETs mainly consist of the conduction loss defined in (1) and switching loss defined in (2). The turn-on and turn-off delay times of MOSFETs are counted into switching loss calculations.

$$P_{cond.} = {I_{out}}^2 \cdot R_{DS(ON)} \cdot D \tag{1}$$

$$P_{swit.} = \frac{I_{out} \cdot V_{in}}{2} \cdot \left(t_{rise} + t_{fall}\right) \cdot f_{Sw} \tag{2}$$

where I_{out} is through-current in amps; V_{in} is across-voltage of MOSFET in volts; $R_{DS(ON)}$ is on-resistance of MOSFET in ohms; D is duty cycle of conduction; t_{rise} and t_{fall} are rise time and fall time of MOSFET in seconds, respectively; f_{Sw} is switching frequency in Hz.

- Losses in Power Inductors

Power inductors operate as choking inductors to limit current harmonics. Two types of losses are presented in power inductors: core loss and low-frequency copper loss. For power inductors and transformers, high operating flux density leads to reduced size, weight and cost. Silicon steel and similar materials exhibit saturation flux densities of 1.5 T to 2 T, but also exhibit high core losses. In case of low-resistance materials, eddy losses will be high. The core loss can be approximately calculated from (3) [17].

$$P_{fe} = k_{fe} \cdot (\Delta B)^{\beta} \cdot A_c \cdot l_m \tag{3}$$

where A_c is the area across the core in cm^2; k_{fe} , β and l_m are decided by selecting magnetic cores, and here $\beta = 2.7$, which usually lies in the range of [2.6–2.8].

For the dc–dc solar converter in boost mode, $\Delta B = \frac{T \cdot D \cdot V_g}{N \cdot A_c}$;
For the dc-dc solar converter in buck mode, $\Delta B = \frac{T \cdot D \cdot (V_g - V_{in})}{N \cdot A_c}$;
For the bidirectional rectifier of dc–dc distribution, $\Delta B = \frac{T \cdot V_g}{N \cdot A_c}$.
For the intended ΔB, T is the period of ac signal in seconds. T equals $1/f_{Sw}$ for the solar converters operating at specified switching frequency and equals $1/60$ Hz= 16.7 ms for the bidirectional rectifier, respectively; N is the number of turns in the winding and is specified by magnetic core selection and power inductor design according to the switching frequency of power components.

- Losses in Power Transformers

Losses of power transformers include iron loss (hysteresis loss "+" eddy current loss) and copper loss. The efficiency and distribution of power losses with various load conditions of a 24.6-kVA power transformer is described in [18]. The iron loss remains almost constant, and the copper increases with loading level and thus strongly effect the energy efficiency of power transformers.

The National Electrical Manufacturing Association (NEMA) in the U.S. specified the NEMA premium efficiency transformer to help utilities, commercial buildings, and industrial plants incorporate super high-efficiency electrical transformers into their operations [18]. NEMA also defined the "Guide for Determining Energy Efficiency for Distribution Transformers" or "NEMA Standards Publication TP-1-1996" to promote the manufacture and use of energy-efficient transformers by establishing minimum efficiency standards, albeit with certain assumptions built in. At 100% loading and room temperature, the efficiency of 75-kVA dry-Type transformers is within [95.9%–98.45%], according to the winding material and the standards applied in manufacturing, as listed in Table II.

TABLE II
Efficiency of 75-kVA Dry-Type Transformers at 100% Loading

Type:	Efficiency at 23 °C:	Efficiency at 75 °C:
Standard (Aluminum)	95.90%	95.05%
TP-1 (Aluminum)	97.12%	96.52%

TP-1 (Copper)	97.74%	97.29%
Premium (Copper)	98.45%	98.14%

In rural and expeditionary power systems, power density of components is an essential factor in the consideration of application, and aluminum-winding transformers are frequently applied to reduce lifting weight and pressure on soil land and desert. Based on the temperature constants of aluminum material ($= 228.1$ ℃) and copper material ($= 241.5$ ℃), the copper loss increases from 23 ℃ to 75 ℃ as listed in Table II. In this paper, the efficiencies of TP-1 (aluminum) and TP-1 (copper) dry-type transformers at 75 ℃ are used in the efficiency gain analysis for the worst-case study.

C. Analysis of Efficiency Gain and Energy Saving

According to the power loss discussions in section II-B, the efficiencies of power components are calculated and listed in Table III. Both silicon (Si) and SiC MOSFETs are considered. The switching frequencies of power converters are 20 kHz, 50 kHz, and 100 kHz, and the power inductors are separately designed for each switching frequency.

TABLE III
Efficiencies of Power Components for Energy Saving Analysis

Type	Si MOSFETs		
	20 kHz	50 kHz	100 kHz
Rectifiers	96.95%	96.49%	95.64%
VFDs	96.49%	94.95%	92.39%
Dc–dc solar converters (buck mode)	97.35%	96.68%	95.59%
Dc–dc solar converters (boost mode)	96.92%	96.52%	95.87%
Load converters	96.25%	95.75%	94.45%
Transformer	95.05% (Standard Aluminum at 75°C) ~ 98.45% (Premium Copper at 23°C)		
Dc–ac solar inverters	96.3%		

Type	SiC MOSFETs		
	20 kHz	50 kHz	100 kHz
Rectifiers	97.72%	97.06%	95.90%
VFDs	99.32%	98.81%	97.95%
Dc–dc solar converters (buck mode)	99.45%	99.4%	99.33%
Dc–dc solar converters (boost mode)	99.35%	99.31%	98.25%
Load converters	97.5%	97.15%	96.2%
Transformer	95.05% (Standard Aluminum at 75°C) ~ 98.45% (Premium Copper at 23°C)		
Dc–ac solar inverters	96.3%		

The following discussion focuses on the power loss analysis of each fundamental power components for the proposed 400-Vdc distribution network in Fig. 2-b. The three-phase inductors in a VFD are neglected due to the current harmonics filtering from the inductive windings of induction motors.

A 30-kVA 208-Vac/400-Vdc bidirectional rectifier was simulated as shown in Fig. 3. The ac-side inductor is 5 mH; the dc-side inductor is 100 μH; the dc-link capacitor is 4500 μF; for the specified Si MOSFET module, $R_{DS(ON)}$ is 480 mΩ and t_{rise} and t_{fall} are 31 ns and 48 ns, respectively; for the specified SiC MOSFET module, $R_{DS(ON)}$ is 80 mΩ and t_{rise} and t_{fall} are 14 ns and 53 ns, respectively. The dc output voltage was regulated to 400 V stably as shown in Fig. 3.

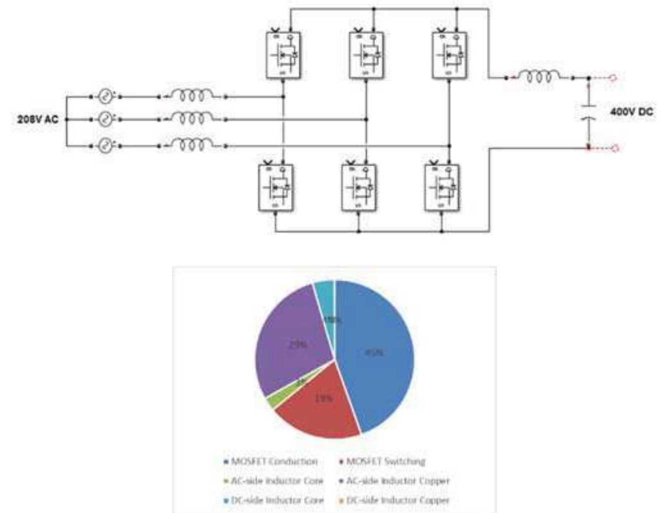


Fig. 3. Simulation in Matlab/Simulink and power loss distribution of bidirectional rectifier, which consists of SiC MOSFETS at switching frequency of 20 kHz.

An 18-kVA 400-Vdc/208-Vac VFD for FDECU was simulated as shown in Fig. 4. There are three capacitors internally line–line connected to induction motors of FDECUs to correct the power factor to 0.95. Therefore, no extra capacitors are needed in the VFD for the FDECUs. The voltage of the VFD was regulated to drive the FDECUs at 100% loading, as shown in Fig. 4. The specification of MOSFET modules is identical to the ones of bidirectional rectifiers due to their similarity in power rating.

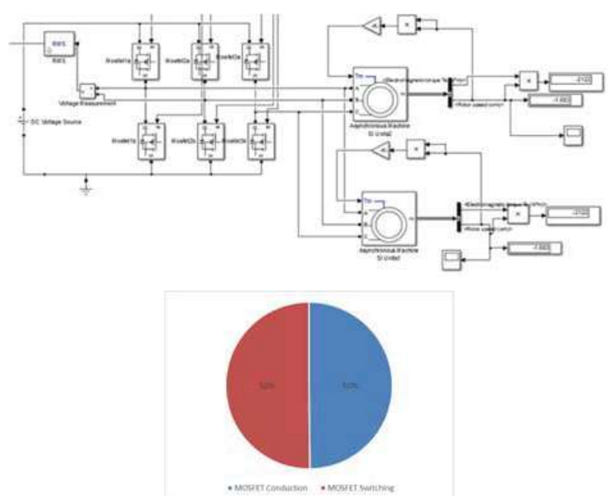
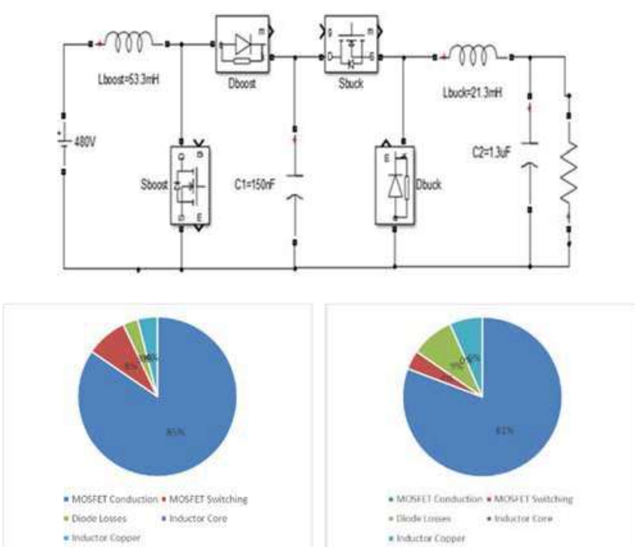


Fig. 4. Simulation in Matlab/Simulink and power loss distribution of VFD for FDECUs, which consists of SiC MOSFETS at switching frequency of

20 kHz.

As candidates for renewable energy harvesting in a dc distribution network, several two-switch buck-boost-type dc–dc converters have been proposed for solar power integration, including: 1) Buck-Cascaded Buck–Boost (BuCBB); 2) Boost-Cascaded Buck–Boost (BoCBB); 3) Buck-Interleaved Buck–Boost (BuIBB); and 4) Boost-Interleaved Buck–Boost (BoIBB) dc–dc converters [19] [20]. It is noted that a traditional buck–boost converter cannot be used for this case because of the poor switch utilization, achieving a maximum of 25% at a duty ratio of 50%, when $V_g = V_{in}$ (for continuous conduction mode operation) [21]. Therefore, the BoCBB converter is applied in this study. The BoCBB converter acts as a boost converter at low input voltage and a buck converter at high input voltage. The input solar power is controlled by an embedded MPPT function and the *V/I* curve depends on the ambient temperature and irradiance.

From the design of a 6-kW BoCBB solar converter and its simulation verification, the inductor at the boost side is 53.3 mH and the inductor at buck side is 21.3 mH. For the specified Si single MOSFET, $R_{DS(ON)}$ is 1.2 Ω and t_{rise} and t_{fall} are 95 ns and 80 ns, respectively; for the specified SiC single MOSFET, $R_{DS(ON)}$ is 160 mΩ and t_{rise} and t_{fall} are 11 ns and 10 ns, respectively. For Schottky diodes, only conduction losses are considered and switching losses are negligible.



Buck mode Boost mode

Fig. 5. Simulation in Matlab/Simulink and power loss distribution of BoCBB solar power converter, which consists of SiC MOSFETS at a switching frequency of 20 kHz.

Comparing to the conversion efficiency of BoCBB solar converters, the conversion efficiency of a transformerless three-phase neutral-point-clamped (NPC) solar inverter was calculated as about 96.3% at 100% loading, from a power loss analysis and simulation study as shown in Fig. 6. As a reference, an example COTS dc–ac solar inverter product has a CEC-weighted efficiency in the range of [95%–96.5%].

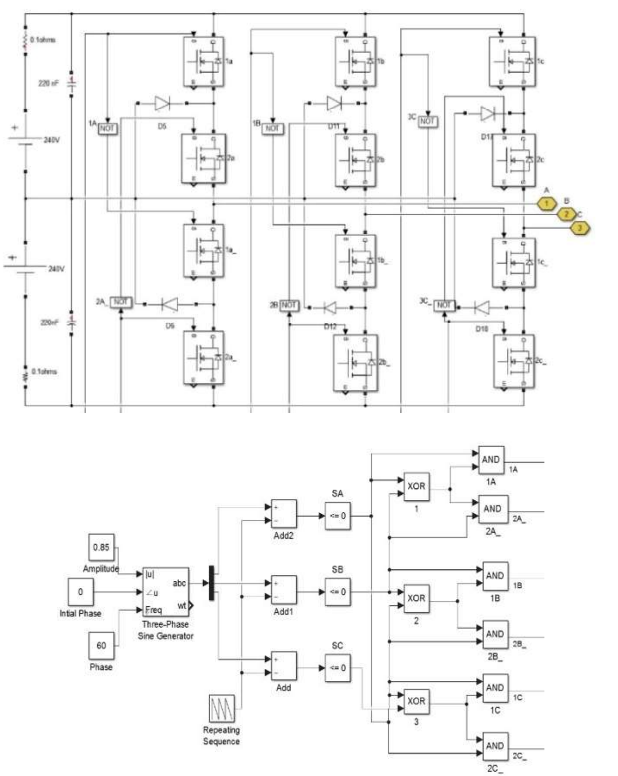


Fig. 6. Simulation and modulation of an NPC solar inverter in Matlab/Simulink, which consists of Si MOSFETS at a switching frequency of 20 kHz.

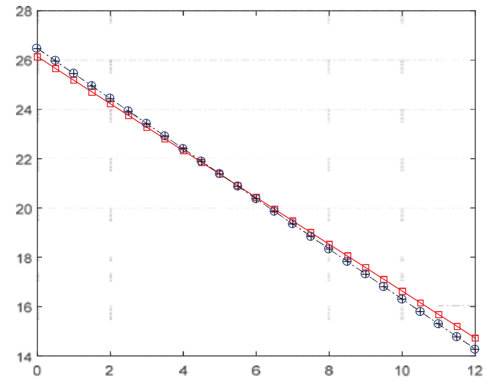
D. Conclusion

Based on the efficiency analysis in section II-C, the efficiency gain in the example system of 25.5 kW was calculated as shown in Fig. 7. The numerical analysis was designed based on the distribution layouts in Fig. 2. High-efficiency transformers were considered in the original ac distribution network and thus we can specify the lowest energy/fuel efficiency gain from the proposed dc distribution network for the worst-case study. We can see that:

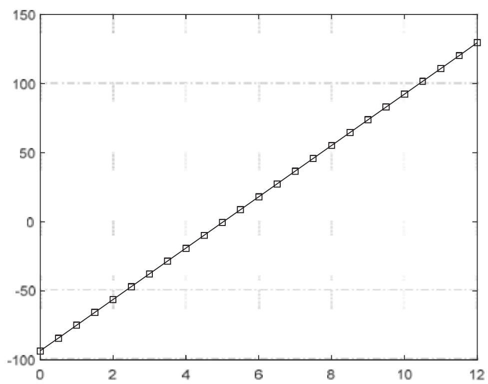
a) the dc distribution network indicated energy/efficiency gain when the installed PV for the medium-size shelter is higher than about 5 kW (19.6% of capacity);

b) when the installed PV is 12 kW (47% of capacity), there is an efficiency gain of at least 19419.39 gallons of fuel per year. This calculation is based the fuel consumption of 750-kVA gas turbine gen-sets.

We found that an optimal promotion in energy efficiency can be made by: a) utilizing SiC MOSFETs and diodes; and b) operating at switching frequency at 50 kHz. This conclusion was further verified by experimental tests on a 3-kW test bed of a BoCBB solar converter, as shown in Fig. 8. The duty cycle varies within [0.1–0.5] in the response of input solar potential. The peak conversion efficiency reaches 97% at duty cycles of 0.2 and 0.1 (excessive power loss from handmade power inductors), and can be further improved by optimal design and COTS design.

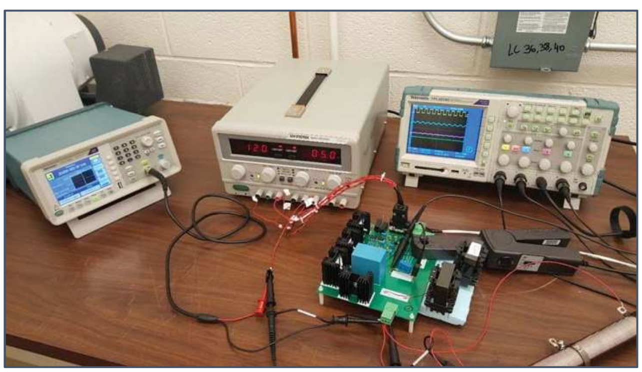


(a) net load demand from grid in kW
(from ac network: red, square; from dc network: blue, circle)

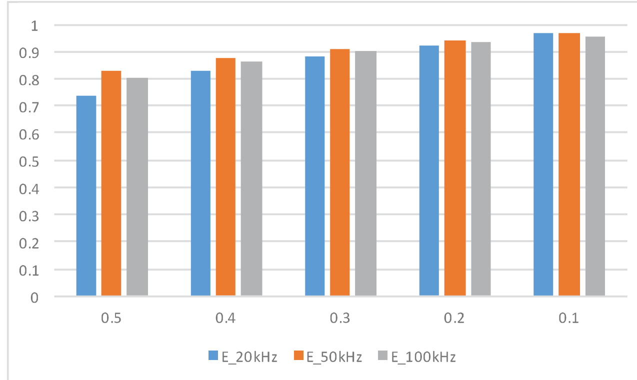


(b) annual fuel saving per shelter in gallons

Fig. 7 Efficiency/fuel gain analysis between ac and dc distribution networks.



(a) setup of experiment test-bed



(b) comparison of conversion efficiencies at switching frequencies of 20 kHz, 50 kHz, and 100 kHz
(x-axis: duty cycle; y-axis: conversion efficiency)

Fig. 8 Experimental verification of a 3-kW SiC-based BoCBB solar converter in lab.

III. Challenges in Promoting 400V DC Distribution

Although dc distribution brings in benefits of energy gain and energy saving, there are three challenges that people are facing and that must be solved to promote 400-Vdc distribution to integrate various renewable energy resources: a) stability; b) protection; and c) security. The stability problem in dc distribution is caused by constant power load (CPL, P_L) which demonstrated negative impedance in (4).

$$\begin{cases} i(t) = \begin{cases} 0, if\ v(t) < V_{lim} \\ \frac{P_L}{v(t)}, if\ v(t) > V_{lim} \end{cases} \\ \delta z = \frac{dv_B}{di_B} = -\frac{P_L}{i_B^2} \end{cases} \tag{4}$$

where v_B and i_B are across voltage and through-current of the CPL.

Non-zero-crossing current during fault causes the problem of protection and many traditional circuit breakers (CBs) for ac application cannot be applied to a dc network directly. Both stability and protection issues in dc distribution might be solved via system supervisory control based on large-area communication networks, e.g., wireless networks, internet of things (IoT)-based networks. Therefore, the problem of security must be considered in a promotion of dc distribution.

Fig. 9 summarizes these three challenges and their possible solutions. These three challenges are addressed in detail below.

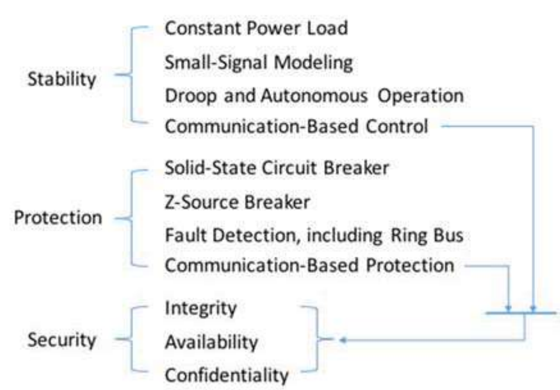


Fig. 9 Three challenges and their possible solutions in promoting dc distribution networks.

A. Stability

CPL is a major cause of instability in dc distribution networks. In a smart grid, the charging of batteries in electric vehicles and energy storage act as CPL and thus lead to oscillation in the main dc bus voltage beyond certain power levels, making the system unstable [22]. Induction motors and dynamic loads are also considered as CPL. Small-signal stability analysis is conducted to assess the system stability under different operation conditions and design parameters [23] [24]. The eigenvalues of the system matrix can be analyzed to examine stability. [25] introduces a stability analysis and stabilization methods for a dc microgrid with multiple parallel-connected dc–dc connections loaded by CPLs. Their methods transform the eigenvalue problem into a quadratic eigenvalue problem for practical engineering application. A small-signal model for dc distribution was designed from the control point of view [26]. This model can be applied to multiple dc connections and dc clusters to demonstrate their interactions. To ensure stability under dynamic load conditions, an optimal control algorithm is designed to improve the system performance by appropriately selecting the operation modes. [27] Also, [28] introduces an approach to evaluate the degree of influence by system parameters on the stability of a dc microgrid.

From a system point of view, the system stability of dc distribution can be improved by applying appropriate droop control of distributed power converters. Voltage droop control is adopted in the controllers of power converters for distributed generators (*e.g.* solar, wind) and loads, and in the engine governor of distributed generators (*e.g.,* gas turbines, diesel engines) to achieve power sharing and autonomous operation of a dc distribution network [29] [30]. Proper control in an engine governor can improve the stability of a dc microgrid [31]. A grid impedance can be estimated based on a recursive method for large signal stability analysis at the common coupling point of a dc microgrid [32]. By using the grid impedance estimation around an operation point, it is possible to define a space variable/parameter to obtain a qualitative or quantitative measure from the operation to the unstable boundary. Based on wired/wireless networks and/or IoT networks, a master–slave control structure can be realized to improve stability in a dc distribution network [33].

B. Protection Issue

As there is no zero-crossing point in current, a natural characteristic in dc networks, series arcing is a problem in low- and medium-voltage dc applications. Series arcing might be caused by loose connectors or unintentional unplugging of energized loads. Rapid arc detection and elimination is a critical requirement and influenced by network parameters [34]. Solid state circuit breakers (SSCBs) are a good candidate to replace traditional circuit breakers for dc applications. A self-powered SSCB using normally-on wideband gap power semiconductor devices is introduced in [35]. An inductor-coupled SSCB is introduced in [36] and an ultrafast SSCB is demonstrated in [37]. A RCD snubber can be embedded into an SSCB to suppress the voltage across the SSCB and thus improve system protection reliability [38]. The effect of fault current limitation can be achieved by combing the SSCB with passive components [39]. In addition to SSCB, *z*-source breakers also provide fault protection, especially to the zonal-based distribution [40]-[42].

A ring bus provides flexibility and high reliability to a power supply in a dc distribution network. [43] introduces a protection scheme of using the line current derivative in a ring bus dc microgrid. This scheme is based on the concept of dc current profile under transients, which depends on the fault location. The fault location can be identified by segmenting the busses into overlapping nodes in the ring bus network [44]. A protection scheme of current differential protection as the main protection and under voltage protection as the backup one is proposed in [45].

Fault detection is another critical requirement for dc distribution protection. Protection coordination must be achieved in a protection design, including the protection device and protection scheme [46]. A fast fault detection and location scheme for a multiple PV-based dc microgrid is realized by using differential current assistance [47]. And a centralized protection strategy for dc microgrids introduced in [48] is based on a communication-assisted fault detection method.

C. Security

The problems of stability and protection can be improved by system-level monitoring and control based on wired/wireless and/or IoT communication networks [49]. Therefore, Security is a big concern in a smart grid and the security threats are typically divided into three categories [50] [51]: integrity, availability and confidentiality. Integrity assures that the data are not modified without authorization, *e.g.,* source of data and time stamp associated with the data are authenticated. Availability requires the time latency to be met for different operations and data transmissions. For example, a signal of a protective action needs to be generated and transmitted in the order of milliseconds. Confidentiality requires protecting the privacy of customer information, power usage data, etc., as well as general corporate information.

Security of a smart dc distribution network is a multi-disciplinary problem and its potential solutions can be identified in each aspect of a) power system layer (physical layer); b) communication network layer; c) data harvesting layer (in computer science); and d) power control layer (SCADA layer), hierarchically.

IV. Conclusion

To promote 400-Vdc distribution applications, advantages in efficiency gain and energy saving are discussed and demonstrated by a case study of a 400-Vdc distribution network. We found that SiC power semiconductor devices operating at 50 kHz lead to higher efficiency gain and a certain percentage of renewable energy resources should be installed in distribution networks to obtain the energy saving from the dc distribution network. Also, a group of possible solutions related to the stability, protection, and security and their coordination should be investigated to clear obstacles in the road of promoting 400-Vdc distribution networks. Particularly, the security is a multi-disciplinary issue to be dealt with by several disciplines of engineering and science.

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