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Efficient Utilization of Renewable Energy by Smart DC Micro-grid

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ABSTRACT

A new, smart distributed DC micro-grid suitable for high-penetration and that efficiently utilizes energy available from distributed, renewable generators is described. It is shown that energy saving in excess of 10% is feasible using the proposed DC power system when compared to the current approach where inverters are used. This conclusion is substantiated with used first-order calculations of a 50 kW solar photovoltaics array delivering power to DC-compatible electrical loads typically present in a household and/or commercial building. Further energy saving may be achieved by replacing state-of-the-art silicon-based DC-DC power converters with more-efficient emerging Gallium Nitride FET converters at a reduced cost. The proposed DC micro-grid architecture is hybrid in nature and is easily scalable to other power levels. It is ideally suited for residential and commercial applications as well as for powering sustainable communities.

KEY WORD: DC power distribution, smart micro-grid, renewable energy generators, solar photovoltaics, wind, GaN power FET, DC-DC converter, efficiency, cost

I. INTRODUCTION

The established US electrical utility infrastructure was conceived more than 100 years ago and is vulnerable and relatively inefficient when compared to distributed generation [1]. Distributed generation avoids both the vulnerability of transmission and distribution links and nodes and the 6.5% transmission and distribution losses. The advent of semiconductor electronics and the recent rapid growth of renewable energy technologies, such as photovoltaic sand wind turbines, are dramatically changing the nature of transmission, distribution and utilization of electrical energy. Most of today's electrical loads—lighting, adjustable speed motors, brushless DC motors, and computing and communication equipment—are more compatible with DC power [2]. Most distributed renewable energy generators (DREGs)—including solar PV, wind, fuel cell, rectified high frequency alternator outputs on micro turbines or flywheels and batteries— produce DC voltage. Thus DC power has great potential for increased compatibility with high-penetration, distribution-connected solar PV and other DREGs. Today's solid-state switching DC-DC converters that transform DC from one voltage level to another have a conversion efficiency in the range of 95%. At the point of use converter or rectifier losses are avoided by using DC power, averaging approximately 30% savings across all internal and external power supplies [3]. Thus, the two primary factors that gave AC the advantage over DC more than 100 years ago have been eliminated. As a result, new opportunities and challenges are presented for efficient and low-cost local utilization of renewable energy using a DC system.

Large electrical grids are based on AC for two important reasons. First, changing voltage is simple and cheap; this allows energy to be transported over long distances at high efficiency and relatively low cost. Second, AC motors and generators are more cost-effective than DC counterparts. However, for a localized application such as residential or commercial usage with a large DC power source such as a PV array, it is actually more cost-effective to use a DC power system for DC loads such as lighting and a local AC grid for the remaining AC loads [2]. This is because changing DC to AC is relatively expensive and inefficient, while regulating DC or changing AC to DC is both cheap and efficient. Inverters for converting DC to AC are quite complex; DC regulators for DC-to-DC conversion are relatively simple; and AC-to-DC rectifiers are extremely simple. Therefore, it is quite easy to import both DC and AC power into a DC power system but relatively difficult to import DC power into an AC grid.

Tremendous improvements have been made during the past decade in the efficiency and cost effectiveness of PV technology, but relatively little advancement has occurred in methods for converting PV electricity into a usable form [4]. This is largely due to a lack of imagination on the part of the end users and the limited capital spent on research and development. Instead of taking a fresh look at the best ways to utilize distributed PV energy, most applications simply force it to conform to a system that was designed for centralized generation. For example, inverters are invariably used to convert the DC energy from the PV to AC energy before it is applied to the load. Unfortunately, DC-to-AC inversion is an inherently complex and expensive process, and the efficiency can range as low as 85%. Furthermore, overall system reliability is significantly affected and is often limited by the inverter.

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Voltage inversion is also totally unnecessary if a large DC load is in close proximity to the PV installation. There are several examples where this is the case, three of the most prevalent being lighting, HVAC, and computing/ communication used in residential and commercial buildings. In this paper, we present a new, smart, distributed, low-cost and efficient DC micro-grid ideally suited for local utilization of power generated from renewable energy sources such as the photovoltaics and wind turbines. The proposed DC distribution architecture is easily scalable to residential, commercial and community-level applications. In Section II, a new DC micro-grid is proposed; simple, first order calculations are presented to estimate the energy and cost savings feasible when distributing energy generated from a 50 kW, PV to power typical residential and commercial DC-compatible loads. It is shown that more than 10% energy may be saved by replacing the current inverter based PV utilization approach with the proposed DC power system. Since there is no inverter involved, the new DC power system also results in significant cost savings with improved reliability. Further improvements in energy efficiency and reliability are feasible by embedding sensor-based control. In Section III, efficiency improvements feasible from advanced DC-DC power converters based on emerging GaN power FETs is presented; circuit simulations of a 200V/380V, 10 kW boost converter have yielded an efficiency of 93% using emerging GaN power FETs. Further improvement in efficiency is feasible with more improved GaN power FET designs and power control techniques. The paper concludes with specific recommendations on new challenges that need to be addressed and new technologies that need to be developed in order to render the proposed DC micro-grid commercially successful.

II. PROPOSED DC POWER DISTRIBUTION SYSTEM

The existing AC system is meant for distributing utility-scale AC power generated at a remote site for household, commercial, and industrial applications. However, energy generated from renewable sources such as solar PV and wind is generally DC and can be made available locally at the application site [4]. Figure 1 illustrates today's power system employed for local utilization of DC power generated from a 50 kW PV array to power electrical loads including a computer server and building loads such as ceiling fans, lighting, laptops, desktops, HVAC, and others.

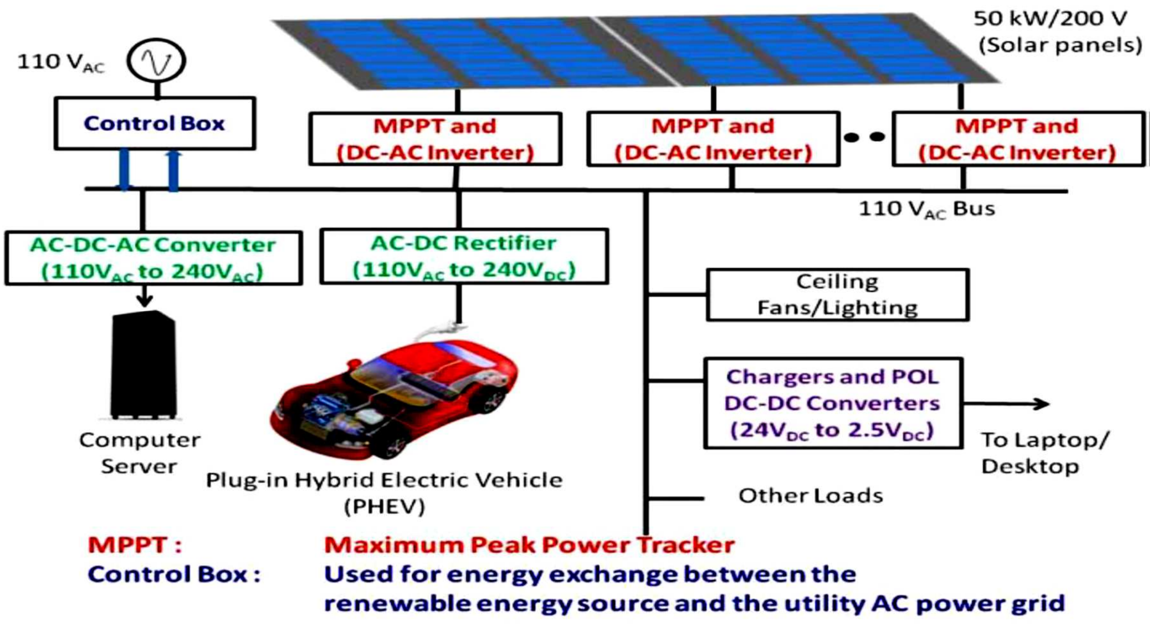


Fig. 1.Schematic representation of current distributed energy integration approach using inverters.

A maximum peak power tracker (MPPT) with an efficiency as high as 97% is used to optimally extract power generated from the PV; it is then inverted and used to power local AC loads. Excess PV energy, if any, is fed back to the utility AC grid. As shown in Fig. 1, the computing server uses 240VAC, and hence requires AC-DC-AC conversion. Likewise, a high-voltage AC-DC rectifier is used to deliver 240VDC to charge plug-in hybrid electric vehicles (PHEVs). Within the building, AC-DC battery chargers are used to deliver point-of-load (POL) DC to low-voltage loads such as laptops, desktops, and cell phones [5-7]. The battery chargers used in mobile OEM devices, the so-called "vampires," are power-hungry [8] and, typically have an efficiency in the range of 65% to 80%. A simple calculation suggests that the power system shown in Fig. 1 results in about 70% to 75% efficient usage of electricity generated from the 50 kW PV array for local utilization; the rest of the electrical energy is lost in various power conversion stages. The efficiency calculations are shown in Table I using the best commercially available silicon-based rectifiers, inverters, and DC-DC converters [9- 13].

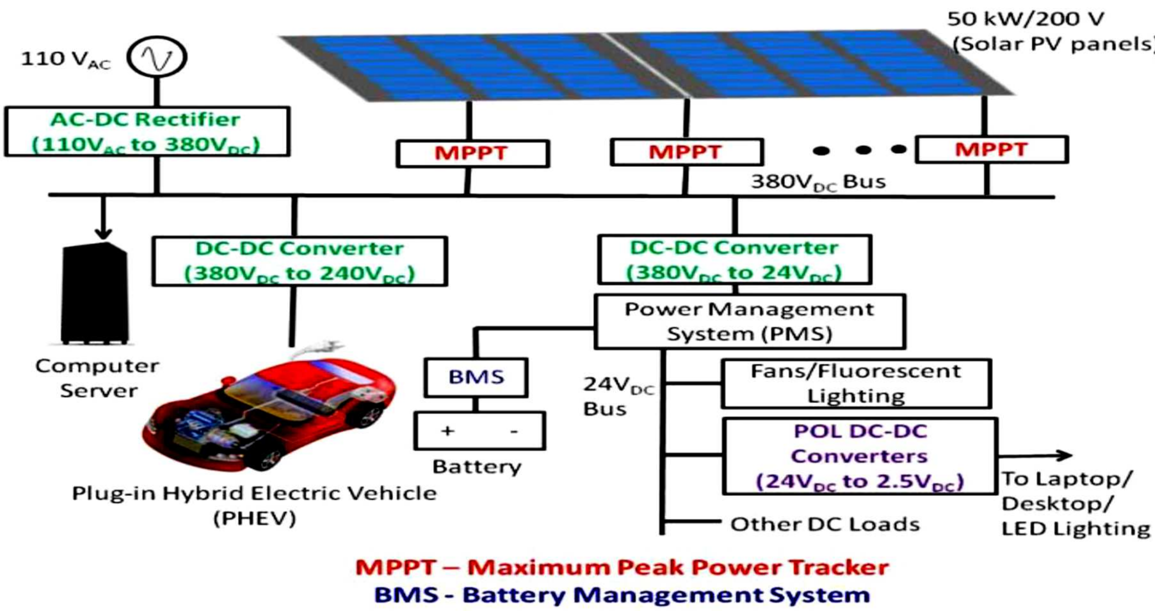


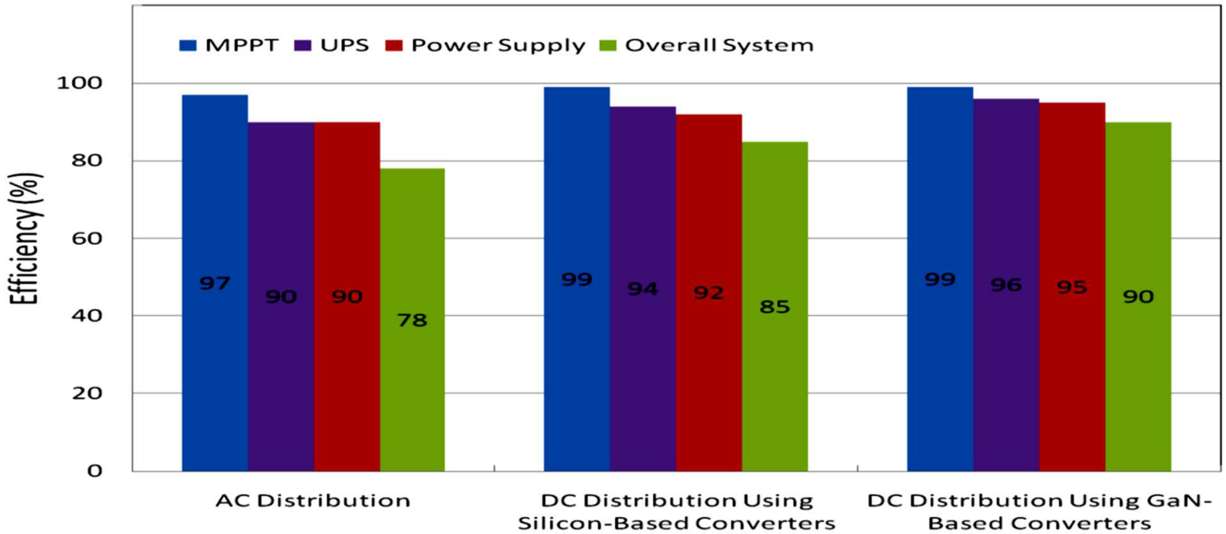
Fig. 2. Schematic representation of the proposed smart DC distribution system for efficient local utilization of the electricity generated from the PV array.

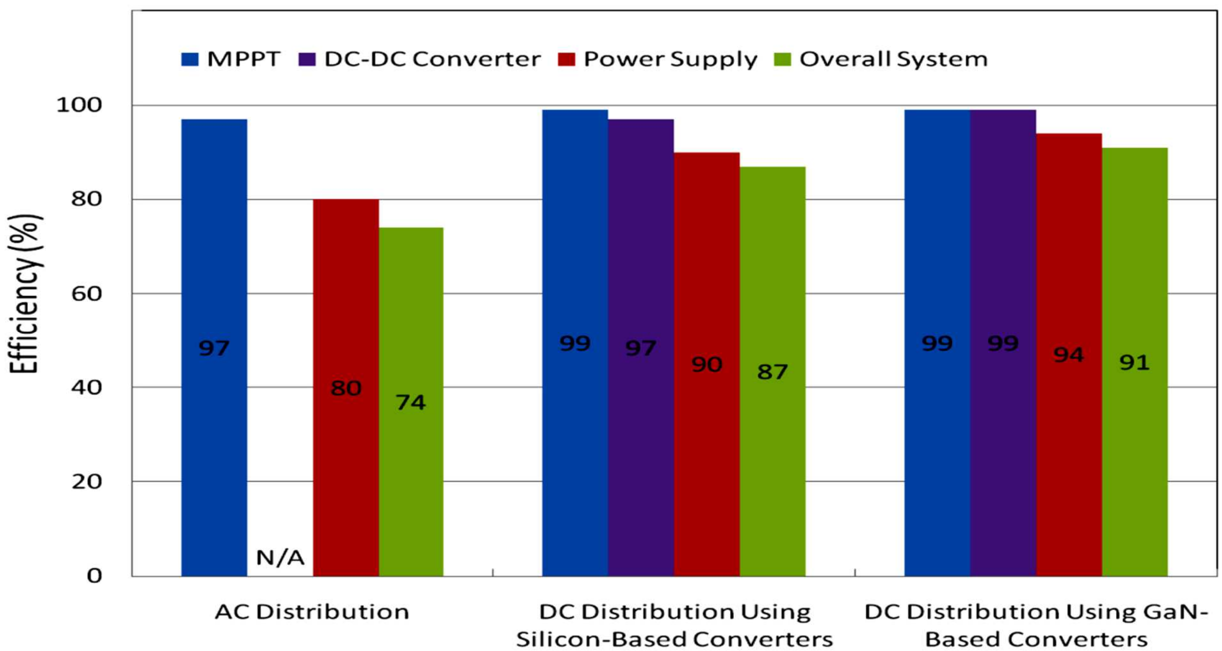
Several new approaches are being developed for direct DC utilization of electricity generated from renewable energy sources [14-18]. In one approach, AC power from the utility grid is rectified and integrated with the DC electricity produced from renewable energy sources [14]. In another approach [15, 16], 380VDC electricity is first developed from the renewable energy source and is used to power internet data center servers [15] and PHEVs [16]. Figure 2 illustrates our proposed smart DC power distribution system for direct DC utilization of the electricity generated from the same 50 kW solar PV array shown in Fig. 1. In the proposed DC system, a 300VDC power bus is first developed and is used to provide continuous DC to the computer server; a 380V/240V DC-DC converter charges the PHEV when needed. A 24VDC power distribution line is developed DC to loads such as fans, lighting, computers, DC-DC converters for the new proposed DC micro-grid compared to the conventional AC power system using inverters. The loads include: (a) high-end computer server (b) laptop/desktop computers, and (c) PHEVs and other loads typically present in a residential and/or commercial building and other DC-compatible loads. To minimize the distribution power loss, loads will have to be located within 10 meters from the point of generation of 24VDC. As a result, multiple 380V/24V DC-DC converters are needed in order to generate a number of 24VDC buses. As shown in Fig. 3, the proposed DC power distribution system results in about 85% to 92 efficient usage of electricity generated from the 50 kW PV array for local utilization when the PV energy is directly utilized to power local DC-compatible loads. Table 2 lists the net energy and cost savings using the proposed DC system.

Also shown is the additional energy saving using advanced converters designed using GaN HEMT power switches. As before, in estimating this efficiency improvement, we have used data based on the best commercially available silicon-based MPPTs and DC-DC converters [17]. Note that the 24-volt DC standard is actively promoted by the EMerge Alliance [18].

Table I. Overall Power Savings In The Proposed 50 Kilo-Watt Dc Shown In Fig. 2 Using Commercial Silicon Power Converters And Proposed Advanced Gallium Nitride Fet-Based Power Converter

Electrical Load	Power Usage (kW)	Energy Saving Using Commercial Silicon Power Converters	Cost Saving using DC Distribution and by Using Commercial Silicon Power Converters ($)	Energy Saving Using Proposed GaN-based Power Converters (kW)
Building Electrical	33	5.25	5000	6.65
PHEVs and other	10	0.45	1000	0.85
Computer Server	5	00.35	800	0.60


MPPT
UPS
Power Supply
Overall System
Efficiency (%)
0
20
40
60
80
100
97
90
90
78
99
94
92
85
99
96
95
90
AC Distribution
DC Distribution Using Silicon-Based Converters
DC Distribution Using GaN-Based Converters


MPPT
DC-DC Converter
Power Supply
Overall System
Efficiency (%)
0
20
40
60
80
100
97
N/A
80
74
99
97
90
87
99
99
94
91
AC Distribution
DC Distribution Using Silicon-Based Converters
DC Distribution Using GaN-Based Converters

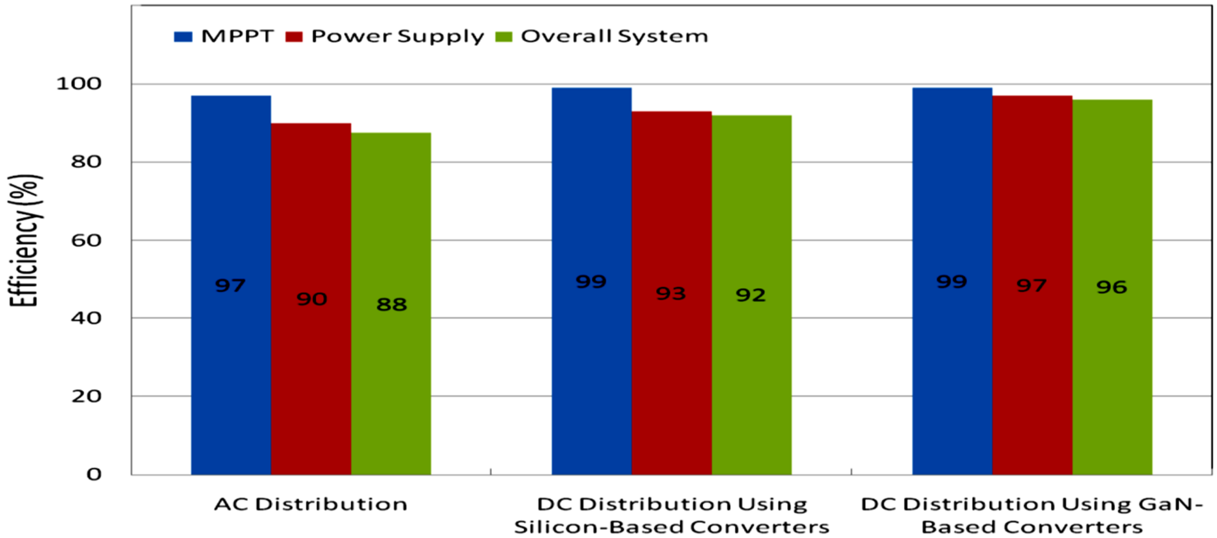


Fig. 3. Efficiency improvements from commercially available silicon-based DC-DC converters and proposed GaN HEMT based

III. ADVANCED GALLIUM NITRIDE HEMT-BASED DC-DC POWER CONVERTERS

It has been well-known for more than two decades that power devices made from wide band gap semiconductors such as Silicon Carbide and GaN offer much lower on-state resistance (RDS(on)) than silicon power devices because of their superior electrical conductivity and breakdown field compared to silicon [5, 19]. However, only recently, GaN power high electron mobility transistors (HEMTs) are being made available in samples by select commercial vendors [20, 21]. The electricity produced from the PV is time varying and fluctuating in nature. Also, MPPT is used to extract optimum electricity from the PV energy conversion process. The PV output is 200VDC; it needs to be boosted to 380VDC in the proposed DC system as shown in Fig. 2. The same boost converter [22, 23] can also be used to perform the MPPT function. We have chosen the boost converter circuit shown in Fig. 4 to evaluate the efficiency gains possible from emerging GaN power HEMTs; the results are compared to the best commercially available silicon Cool MOS devices [24].

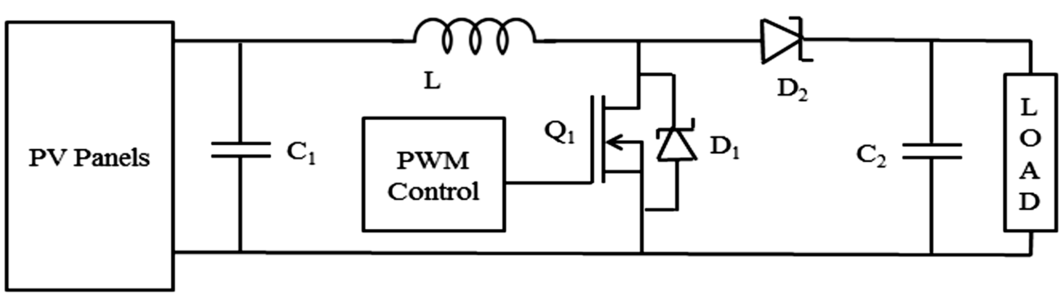


Fig. 4. Circuit schematic of the DC-DC boost converter studied in this work.

In the boost converter circuit shown in Fig 4, when switch Q1 is turned, inductor is charged by PV. During this time, diode D2 is reverse-biased. In order to avoid a voltage spike at the drain of Q1, the reverse recovery of diode D2 must be negligible. When switch Q1 is turned off, and when the solar power is available, the output capacitor C2is charged from the energy stored in the inductor as well as by the electricity produced from the PV source. When solar power is not available, appropriate provision is made for the circuit to operate in the boost mode.

The minimum inductor value needed to maintain continuous current conduction as a function of switching frequency, and a corresponding capacitor value for the desired output ripple are calculated using standard closed form expression:

$$L_{\min} = \frac{\mathrm{D}.(1-\mathrm{D})^2(\mathrm{v_o})}{2.\mathrm{I_o f_s}}, \qquad c = \frac{D}{f_s.R(\Delta v_o/v_o)} \tag{1}$$

where$D$ is the duty ratio (and is equal to {(Vo-Vin)/Vo}), Io is the output current, fs is the gate-switching frequency, R is load resistance and $\Delta Vo$is the output ripple. In this study, the semiconductor switch, CMOS control IC and the inductor areassumed to be the only lossy elements in the circuit. The circuit and packaging parasitics and the stored charge in semiconductors are neglected. The duty cycle is slightly adjusted to obtain the desired converter performance. The total power loss in the circuit is then given by

$$p_{cond} = I_o^2 . R_{DS(on)} . D \quad ; \quad p_{sw} = V_{GS}^2 . C_{iss} . f_s$$
$$p_D = V_D . I_o . (1 - D); \quad p_l = I_o^2 . R_{DC} (2)$$

where $Pcond$and $Psw$are the conduction and switching power losses in the FET, respectively; $RDS(on)$ is the FET on-state resistance; VGS is the gate-to-source voltage needed to switch the FET; $Ciss$is the FET input capacitance; PD is the on-state power loss in the diode D; VD is the voltage across the diode in the on state; PL is the power loss in the inductor; and, RDC is the DC ohmic resistance of the inductor coil. The semiconductor die size is optimized to obtain the lowest switch power loss for a given switching frequency [5]

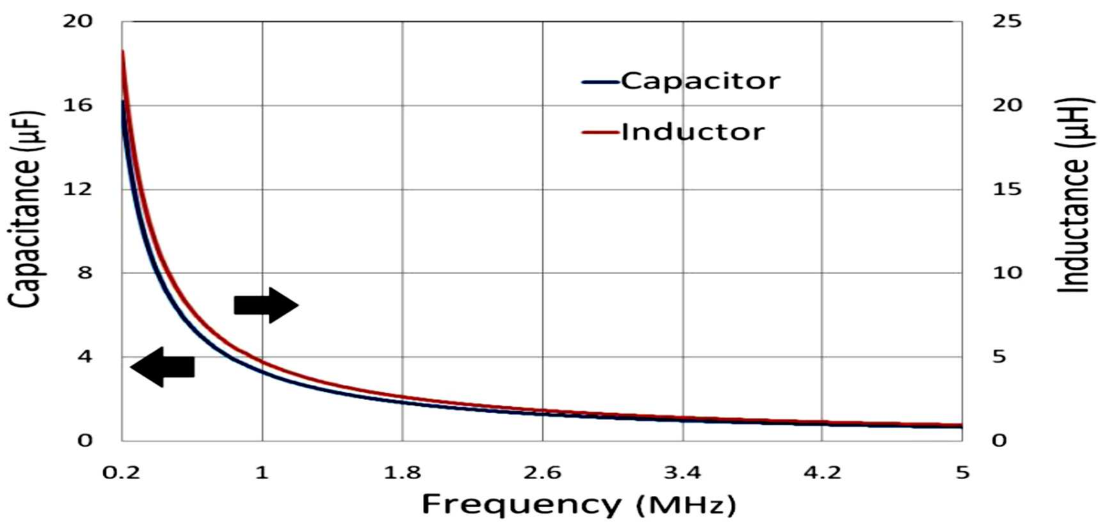


Fig. 5. A plot of calculated inductor and capacitor values vs. frequency in the 200V/380V, 10kW DC-DC boost converter.

The sizes of magnetic components and capacitors in the circuit vary inversely with frequency; hence, higher switching frequency is desired for reducing the converter size and cost.

The main advantage of using the GaN HEMT for power switching is that switching frequency can be kept high (>1 MHz) while still maintaining lower conduction power loss (compared to a silicon power MOSFET with identical rating); higher switching frequency can reduce capacitor and inductor values exponentially as shown in Fig 5. Thus, by using wide bandgap materials, DC-DC converters can be made more compact, thereby facilitating dense integration in the proposed DC power system. A simple FET circuit model, first proposed by Shenai [25], is used in this study; this model is applicable to both GaN power HEMT as well as to a silicon CoolMOS device. The best available 600V/30A commercial silicon CoolMOS data was used [24]; the 600V/30A GaN HEMT circuit model parameters were estimated by scaling the results reported for 200V/12A normally-off GaN power HEMTs [26].

In both converters, 600V/30A Silicon Carbide power diode [27] was used for diode D2 as it offers the Lowes forward voltage drop with negligible reverse recovery amongst commercially available diodes in this rating. A simple diode circuit model, first proposed by Pendharkar *et al.*[28], was used in circuit simulations to accurately represent the diode characteristics; diode parameters were extracted from the product data sheet.

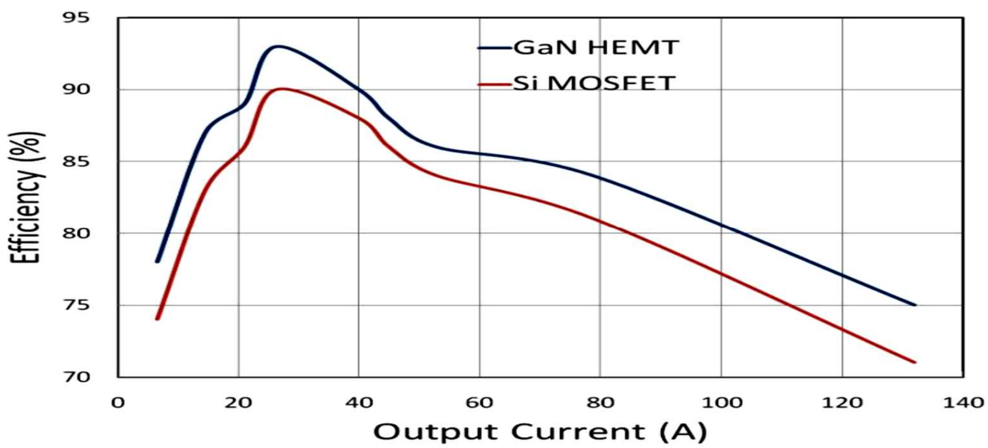


Fig. 6. A plot of calculated efficiency vs. frequency for 200V/380V DC-DCboost converter at a switching frequency of 1MHz and an ambient temperature of T = 298K.

A behavioral gate switching waveform was used to determine the optimum switching frequency and timing sequence so as to achieve the highest power conversion efficiency. Since load is never constant in practical implementation, simulations at different load currents and at a constant frequency of 1MHz were performed. Fig. 6 shows the efficiency of the 200V/380V DC-DC power converter as a function of current; calculations were performed at a room temperature of 25°C. The results clearly show that efficiency changes with load current and that there is about 4% improvement in peak efficiency for the GaN FET-based converter compared to the converter using silicon CoolMOS. Since the inductor and capacitor values in a circuit are optimized for a particular load current, load current variations change circuit dynamics. At higher load current, conduction loss in the FET increases, which results in a drop in the converter efficiency; and, at lower currents, *dv/dt*loss in the output capacitor lowers the efficiency of the converter.

The converter simulations were also performed at various temperatures and frequency. Fig 7 shows the simulation results for the converter where the efficiency is plotted vs. frequency (at a room temperature of 23°C) and temperature (at 1MHz) for an output ripple of 1%. These results suggest that there is about a 4% drop in efficiency as the temperature is increased from -55°C to 150°C. This variation in efficiency is primarily due to change in the on-state resistance of power FETs with temperature. Results also suggest that a room-temperature efficiency η = 93% can be achieved at a power conversion frequency *fs* = 1 MHz using the GaN power HEMT. The efficiency gain for GaN HEMT-based power converter is about 4% compared to the converter with the best commercially available silicon CoolMOS. The enhance performance of a GaN HEMT-based converter is largely due to reduced device capacitances compared to state-of-the-art commercial silicon power MOSFETs; a smaller input capacitance results in reduced gate charge, and hence, the switching loss is reduced.

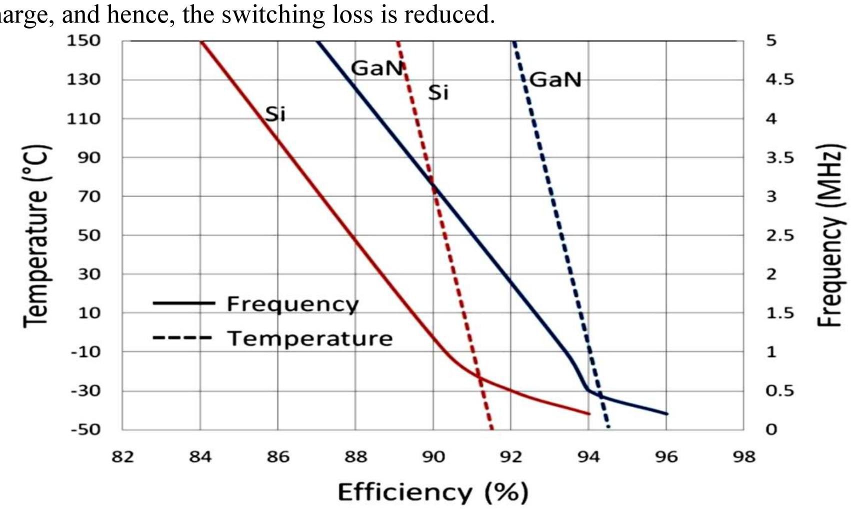


Fig. 7. Simulation results showing efficiency vs. temperature (at 1MHz) and frequency for a 220V/380V, 10kW DC-DC boost converter.

IV. SUMMARY AND DISCUSSIONS

A new, smart, DC power distribution system architecture is proposed in which available energy from renewable generators is optimally utilized to power local DC-compatible electrical loads. The excess energy, if available, is first stored in a battery; it is only fed back to the utility AC grid only when absolutely necessary as it requires an expensive and unreliable inverter. The new proposed DC system allows for low-cost design of distributed renewable energy generators (DREGs); the proposed system is easily scalable to different power levels and is suitable for rapid, high-penetration of DREGs.

First-order efficiency and cost calculations are presented for a 50 kW solar PV system delivering DC power to typical building loads in addition to powering a 380VDC computer server and plug-in hybrid electric vehicles (PHEVs). It is shown that savings of more than 10% in energy generated by the solar PV array and significant cost reduction can be accomplished by the proposed DC power distribution system compared to the conventional approach using inverters. When the current state-of-the-art silicon power converters are replaced with new and emerging GaNFET based DC-DC power converters, further energy savings in excess of 4% can be achieved using the proposed smart DC power distribution system. These results are based on design calculations performed for a 200V/380V, 10kW DC-DC converter. The peak power efficiency and load regulation can be further improved by using larger inductor and capacitor values in the circuit, and improved control and switching circuitry [22].

It must be noted that smart wireless sensors and controls can be incorporated within the proposed DC system in order to further enhance energy efficiency and improve reliability. This approach is also needed to render the proposed DC system suitable for high-penetration scenarios.

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