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Electrical Measurement and Verification of Energy in DC Buildings

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***Abstract*—Today's selection of DC buildings feature a diverse set of electrical topologies and turnkey solutions, and each has specific design trade-offs and optimization. Designers desperately need standardized metrics and procedures for measurement and verification (M&V) to analyze and compare the advantages of each DC solution to the traditional AC building networks. This work develops the Measurement-Informed Modeling (MIM) method, which can be used to determine the full-building efficiency and energy savings. The MIM M&V procedure develops a building model, and refines the model with metered data. This work demonstrates the MIM method by measuring the full-building efficiency of two DC buildings operated by the Institute of Building Research in Shenzhen, China. The MIM procedure can ultimately be used to compare and improve the efficiency of various DC topologies.**

Keywords*—*DC microgrids, buildings, measurement and verification, energy

I. Background and Motivation

A. Motivation for DC Distribution in Buildings

Direct current (DC) microgrids have established academic interest and support due to their potential advantages over traditional alternating current (AC) topologies. Microgrid buildings today feature on-site direct-DC distributed energy resources such as solar generation and battery storage. In addition, most modern loads are natively-DC, including electronics, LEDs, and variable speed motors in HVAC and refrigeration. DC distribution can reduce power conversion losses from DC to alternating current (AC) and back, leading to electricity savings within the building power distribution system.

The potential electricity savings from DC distribution systems in buildings has been estimated or simulated in numerous studies [1]–[4]. However, very few studies have attempted experimental validation. Several studies examine or modify DC end-use loads to determine the savings potential at scale [5], [6]. Other studies conduct a full-system experiment, though for a small system with a limited set of end-use loads [7].

Other potential advantages of DC include cost, resiliency, power quality, safety, combined data and power, and the potential for managed power distribution. Although most of the academic studies have focused on energy savings, these other advantages may well provide a stronger value proposition, and will be important to study in future work.

B. Measurement and Verification in DC Buildings

DC buildings have emerged in many countries, often as an experiment, demonstration, or statement piece. Today, DC building designs vary widely with the selected manufacturer and country-specific building codes. Since the DC industry lacks the standard design practices present for AC buildings, many DC companies have developed all-in-one turnkey solutions. While these solutions often follow guidelines for network voltage levels (e.g., 380 V or 48 V), they are diverse in topology and protocol, and generally only interface with hardware from partner companies. These companies tend to optimize their systems around one or more desirable qualities, while trading-off others. For example, many solutions trade efficiency for controls and managed power distribution, particularly, smart buildings.

It is vitally important to develop metrics to compare commercially-available DC systems among themselves and to a baseline equivalent AC building. Such an analysis will encourage best design practices, develop standards, and advance the overall value proposition for DC power distribution. This work develops a metric for the full-building electrical efficiency and loss. It also develops an M&V procedure for field-testing buildings. Future work is encouraged to measure and quantify the other benefits of DC distribution in buildings.

II. Full-Building Efficiency Metric

Past works have defined many types of building energy metrics that can be useful in conducting a detailed energy

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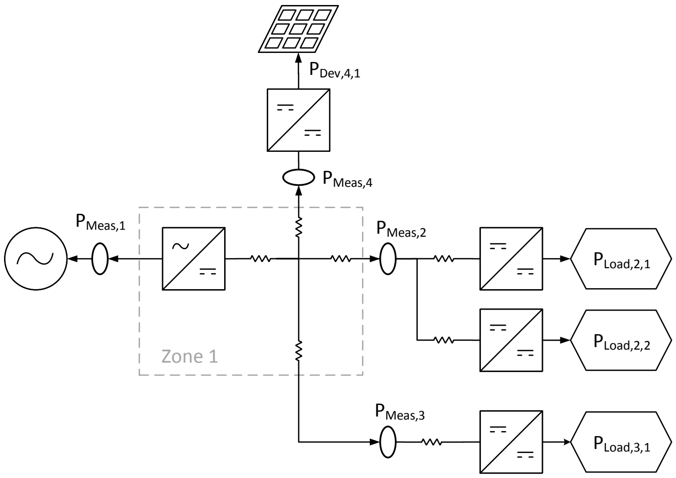

Fig. 1: Example diagram for the MIM method.

analysis and diagnosing problems [4]. This work instead focuses on a single energy metric: the full-building efficiency [2]. This simple metric allows non-technical audiences to easily understand and compare the degree of electrical loss in a building.

The full-building efficiency, η, is defined over a period of performance as:

$$\eta = 1 - \frac{E_{Loss}}{E_{Loss} + E_{Load}}, \tag{1}$$

where E_{Loss} is the total electrical loss and E_{Load} is the total load energy consumed over the period of performance.

III. Measurement-Informed Modeling Method

To precisely determine E_{Loss} and E_{Load}, one must meter every single electrical node, which is impractical in a typical building with thousands of devices. Instead, this work suggests a Measurement-Informed Modeling (MIM) method for M&V. With this procedure, the efficiency calculations are based on a model of the building's electrical network. The model can be refined and calibrated based on field measurements with power meters located in the building. A greater number of meters allows for a better model.

The losses in a system are calculated based on the location of the meters. As shown in Figure 1, the electrical network can be partitioned into zones and branches. Zones are electrical regions that are completely enclosed by metered nodes. Branches are electrical regions that have a single upstream meter. It is often convenient to meter the subcircuits of a breaker panel.

A. Zone Loss

Since zones are completely enclosed by meters, zone loss can be precisely calculated via a power balance equation. The total loss in Zone z, $P_{LossZ,z}$ is calculated from the metered power $P_{Meas,m}$, as:

$$P_{LossZ,z} = \left| \sum_{m \subseteq M} P_{Meas,m} \right|, \tag{2}$$

where m is the subset of meters that borders zone z. In Figure 1, there is only one zone, and $m = 1$ to 4. Note that Equation (2) only works if there are no sinks or sources within the zone. Zones should only contain wiring and converters, and any generation, loads, or storage should be on a metered branch. Also, note the direction of the meters and be consistent with the signs for power into or out of the zone.

B. Branch Loss

Each meter measures the power, $P_{Meas,b}$, at branch b of a total B branches. For each branch b, the branch loss, $P_{Loss,b}$, is calculated as

$$P_{LossB,b} = \left| P_{Meas,b} - \sum_{d} P_{Dev,b,d} \right| \tag{3}$$

where $P_{Dev,b,d}$ is the power into generic device d that is connected to branch b. If the device is a load, $P_{Dev,b,d} = P_{Load,b,d}$, and is always positive. If the generic device is a PV panel, battery, or grid connection, $P_{Dev,b,d}$ is positive when the device acts as a sink and negative when the device is a source.

While some devices can report their own $P_{Dev,b,d}$ consumption, $P_{Dev,b,d}$ usually must be calculated from $P_{Meas,b}$. This calculation is accomplished by modeling the wiring and converter loss in a branch and back-solving for $P_{Dev,b,d}$. For example, if $P_{Meas,3}$ in Figure 1 measures 100 W and the DC/DC converter in branch 3 is known to be 95% efficient, then $P_{Load,3,1}$ = 95 W (assuming no wire loss). Ideally, the wire resistance and converter efficiency curves are known or can be measured. In the absence of such data, modeling assumptions can be made based on typical design practices for wiring and aggregated manufacturer data for efficiency. Branches with multiple types of loads (e.g., branch 2 in Figure 1) require additional modeling assumptions about the distribution of power between the loads, which can be approximated based on each load's typical consumption [8], [9].

C. Total Loss

When all the system losses have been calculated, the total loss, P_{Loss}, and total load, P_{Load}, are aggregated as:

$$P_{Loss} = \sum_{b}^{B} P_{LossB,b} + \sum_{z}^{Z} P_{LossZ,z} \tag{4}$$

$$P_{Load} = \sum_{b}^{B} \sum_{d}^{D} P_{Load,b,d}. \tag{5}$$

The full-building efficiency over the K samples during the period of performance is determined via Equation (1), with the understanding that:

$$E_{Loss} = \sum_{k}^{K} P_{Loss}[k] \tag{6}$$

$$E_{Load} = \sum_{k}^{K} P_{Load}[k]. \tag{7}$$

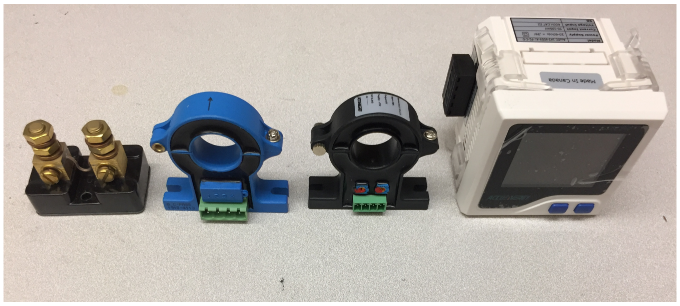

Fig. 2: Some measurement equipment, including (left to right) a current shunt, two hall-effect current transducers, and a DC power meter.

D. Equivalent Building Models

The MIM method solves for the power profile of each device $P_{Dev,b,d}$ in the system, including all sources and loads. This information allows for developing an equivalent building, with identical $P_{Dev,b,d}$ profiles. This can be particularly useful in comparing a metered DC building to an equivalent modeled AC building.

IV. DC Measurement Equipment

Metering the power through a node requires the measurement and instantaneous multiplication of the node's voltage and current. The most accurate DC metering solution is a specialized DC meter, such as the AccuEnergy's AcuDC meter, shown in Figure 2. These units may often include logging functionality and some means of uploading data to the cloud. While they may include internal current sensing, they often require the use of external DC current transducers or shunts. DC meters generally vary in quality and cost, with the more expensive meters typically being more accurate. Since the MIM procedure requires metering many nodes at once, this work investigates metering alternatives that are affordable but still accurate.

For most DC systems, the voltage and current at a node can be sampled, averaged, and logged from separate devices, and then multiplied in post-processing. In contrast, AC metering generally requires the simultaneous combined measurement and multiplication of voltage and current due to the AC-specific artifacts of displacement and distortion power factor. The separate measurement of voltage and current can greatly reduce the cost of DC metering, but requires that:

- The measured voltage must be stable and constant on the time scale of the sampling/averaging period.
- The measured current must not have harmonics or transients that cross zero during most of the sampling/averaging periods.

In general, these conditions are easily met in most DC systems.

Independent voltage and current measurements require a logger and two or more sensors. It is often convenient to install a logger in a breaker panel with a single bus voltage sensor and multiple current sensors, one for each subcircuit. Examples of loggers include the Campbell CR1000 and Labjack, both of which have many analog channels and the ability to log and upload data.

The easiest method of sensing voltage is with a precision resistor divider. However, this method is not galvanically isolated and couples the logger directly to the power bus. Such a non-isolated approach is generally acceptable for low voltage systems (i.e. $\leq$ 48 V), though may be problematic if the system ground and logger ground are at different potentials. An isolated voltage transducer is recommended for high-voltage systems, and could also be useful in low-voltage systems with complicated grounding.

There are two methods of sensing DC current: shunts and hall-effect sensors, shown in Figure 2. Current shunts involve measuring the voltage drop across an extremely precise shunt resistor. They are the most accurate method, and are recommended for low-power applications ($\leq$ 10 A). However, as a non-isolated measurement solution, users must take caution to avoid grounding issues. Resistive loss also becomes a problem at high current. Finally, shunts are installed in-line with the measured circuitry and might incur in higher installation time and cost.

Hall-effect sensors extrapolate the current in a wire by sensing the resulting magnetic field. The most accurate hall-effect sensors include on-chip or board-mount solutions. However, the magnetic hall-effect current transducers shown in Figure 2 are more useful for field testing. These sensors often have a clamp-on magnetic core, making them convenient for rapid installation. However, they generally require calibration, as the readings may vary greatly depending on the ambient temperature and the tightness of the clamp. These devices also have accuracy issues when measuring below 20% rated current, and thus are most useful in high-current applications.

Perhaps the most convenient method of voltage and current sensing is when the sensors are integrated into the power distribution electronics. Managed DC power distribution servers often monitor and report the voltage and current on each channel. They generally employ fairly accurate PCB-based measurement techniques such as resistor dividers, shunts, or on-chip hall-effect sensors. The authors generally recommend that all power distribution electronics should employ self monitoring and energy reporting.

V. Field Testing Results

This section details the field testing and M&V within the Low Carbon City campus of the Institute of Building Research (IBR) in the outskirts of Shenzhen, China. The MIM procedure was employed to analyze the power flow and loss at these two sites.

A. IBR DC Demonstration Lab

The IBR DC Demonstration Lab, pictured in Figure 3, showcases a small-scale DC microgrid. As shown in Figure 4, the DC Lab microgrid uses a 540 V DC bus to connect the solar panels (not shown), storage, and grid-tie inverters. The microgrid powers its direct-DC loads with several voltage levels. These loads include HVAC, lighting, displays, and a number of small-scale experiments that demonstrate DC applications to visitors.

Fig. 3: The DC Demonstration Lab is on the first floor, and is powered entirely from a DC microgrid.

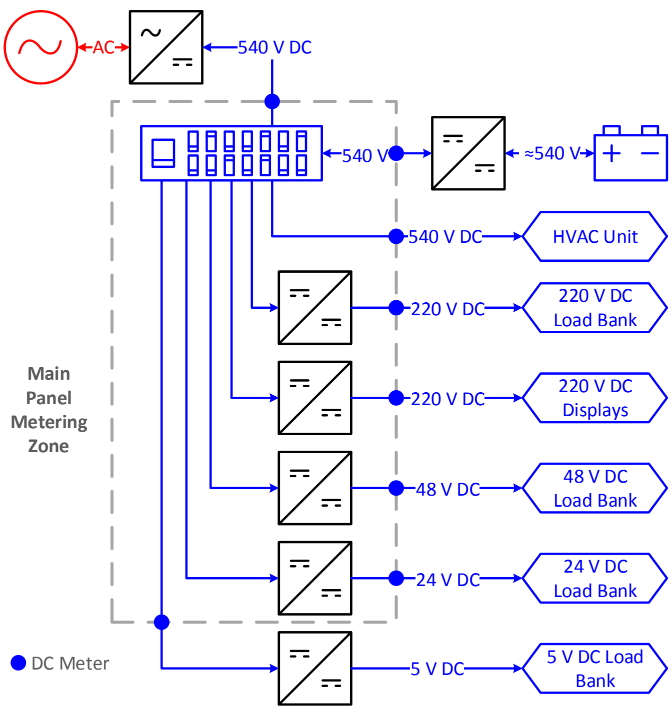

Fig. 4: Block Diagram for the IBR DC Lab, with metering points shown.

As shown in Figure 5, the authors metered the system using a Labjack T7 Pro data logger and clamp-on YHDC 50 A hall-effect sensors. The centralized data logger could easily meter the measurement points in Figure 4, which were all within the same electrical cabinet. Unfortunately, clamp-on hall-effect sensors were required due to constraints in budget and allowable system modification. They were considerably over-sized compared to the typical measured currents and had to be manually calibrated. The voltage level at each bus (540 V, 220 V, 24 V, 5 V) was measured via a resistive divider, which was very accurate but required careful testing to verify that each bus shared a common ground.

Fig. 5: A prototyped metering setup within the electrical cabinet of the DC Lab.

TABLE I: IBR DC Lab Efficiency and Loss

Source of Loss	**Islanded Experiment**	**Grid-tied Experiment**
Electrical Cabinet Zone (Wh)	70.4	75.6
Grid-tied Inverter Branch (Wh)	1.1	26.9
All Load Branches (Wh)	8.1	8.4
Total Loss (Wh)	79.6	111.0
Total Load (Wh)	706.5	747.7
System Efficiency	89.9%	87.1%

The field testing included two experiments: islanded and grid-tied operation. In each ten-minute experiment, the air conditioner ran during the middle eight minutes. The total network efficiency, shown in Table I, was 89.9% for islanded operation and 87.1% for grid-tied operation. A detailed loss breakdown revealed the electrical cabinet accounted for most of the total system loss. Most likely, the electronics and fans within the electrical cabinet had been sized for a much larger power capacity than what the DC Lab actually required.

B. *IBR DC Office Building*

IBR's recently-built eight-floor DC office building, pictured in Figure 6, features a loosely-coupled +/- 375 V DC bipolar distribution system. Its 150 kW solar array and 100 kWh battery bank provide DC power to its loads, of which over 95% are direct-DC. The bipolar distribution network powers several 750 V DC air conditioner units and EV chargers. Each floor has ten programmable power distribution boxes, which convert 375 V to 48 V at 95% efficiency and distribute power to lighting, fans, and plug loads. These boxes each contain a 1 kWh battery to assist with peak shaving and resiliency.

Fig. 6: The IBR DC office building, under construction at the time of the photo.

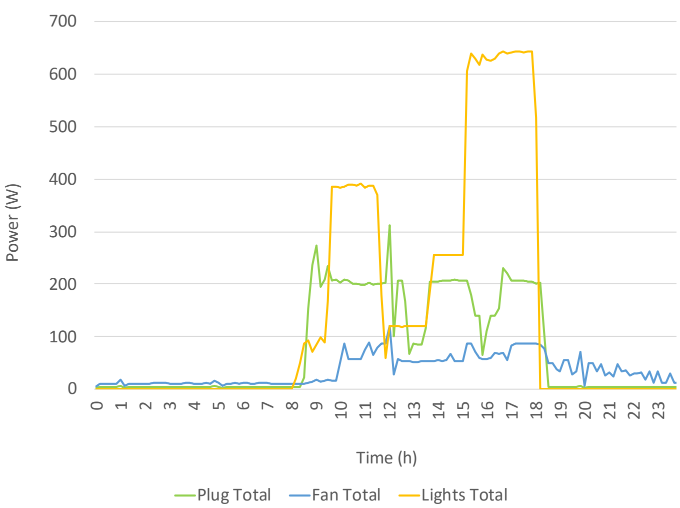

Fig. 7: Aggregate load profile on floor 7 of the IBR DC office building.

Each power distribution box precisely controls, measures, and reports the power flow from each of the 48 V ports. They can easily meter the power flow throughout the entire floor.

The field test analyzed the power flow and loss of the seventh floor for a full day. The aggregate load profile in Figure 7 indicates a relatively low occupancy, likely due to social distancing. As shown in Table II, the network efficiency of the 7th floor is 92.6%, which is slightly higher than the 90.9% efficiency in a modeled equivalent AC system. The 380 V to 48 V conversion in each power distribution box accounts for 64% of the losses in the DC network. While the programmable power distribution boxes offer a number of benefits, there is a slight cost in efficiency. These results have implications for controlled point-to-point DC power distribution in general.

VI. Conclusion and Future Work

The DC industry desperately needs a metric and a basis of comparison for diverse types of DC buildings emerging today. This work establishes a metric and details a procedure

TABLE II: IBR DC Office Efficiency and Loss

Source of Loss	IBR DC Office Building	Equivalent AC Building
All Box Zones (Wh)	316	0
All Load Branches (Wh)	177	612
Total Loss (Wh)	493	612
Total Load (Wh)	6143	6143
System Efficiency	92.6%	90.9%

for evaluating the full-building efficiency. The Measurement-Informed Modeling (MIM) method involves constructing a full-building efficiency model and refining the model via metered data. This work details the field-test of two buildings in Shenzhen. The loss analysis of this field test shows that managed DC power may come at the cost of system efficiency.

In the near future, the authors intend to extend the M&V guidelines to include power quality. At this point, power quality issues in DC buildings are well-understood by engineers, but enigmatic to developers and non-technical personnel. The authors intend to develop a simple unified power quality index that applies to both DC and AC systems. Beyond power quality, future M&V procedures must be established to evaluate and compare the reliability, cost, and safety between AC and DC. In addition, the value propositions of managed power distribution and combined data and power should both be assessed quantitatively.

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