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The Foundation of Electrical Digital Twins: Maintaining Accurate Single-line Diagrams (SLDs)

White Paper 520

Version 1

by Patrick Donovan

Executive summary

Electrical single-line diagrams (SLDs), also referred to as one-line diagrams (OLDs), provide engineers, operators, and maintenance personnel with critical, foundational information needed to efficiently design and safely operate and maintain electrical distribution networks. However, there is often a failure to modernize or maintain them. Poor management of SLDs can lead to design errors, construction rework, longer mean-time-to-repair, or worse, safety hazards that lead to injury or death. Electrical design software and services exist that can maintain and digitalize SLDs beyond simple 2D CAD drawings by creating, in effect, a “digital twin” of the electrical infrastructure. Accurate, well-maintained SLDs offer safety, efficiency, and cost-saving benefits throughout the lifecycle of the site. This paper explains how this value is achieved and how accurate SLDs are created. Next, intelligent, digitalized SLDs are defined and their value over traditional diagrams described. And finally, considerations for creating and managing SLDs yourself versus outsourcing to a qualified service vendor are discussed.

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Introduction

The electrical distribution network is the "life blood" of an operating factory, industrial site, mission critical facility, hospital, or any commercial building that is dependent on power to serve its business needs. Safe, effective operation and maintenance (O&M) of the power system is an imperative. Along with power monitoring and building management systems, having an accurate, informative map of the electrical system is critically important. These maps are referred to as single-line diagrams (SLDs) or one-line diagrams (OLDs).

In power engineering, a single-line diagram is a drawing representing the electrical devices or assets of a power distribution system. The single-line diagram is represented by standardized symbols[1,2] and nomenclature that describes how these electrical devices are connected and related. These diagrams document the rating and capacity of all electrical equipment including conductors and protection devices. In this way, a single-line diagram provides a fundamental representation, or blueprint, of a three-phase power system. SLDs begin with the incoming power sources along with any on-site generation sources. From there a line for each power path follows the flow of power down through transformers, switchgear, protective devices, etc., on down through to low voltage distribution panels or equipment buses. As the term suggests, a single-line or one-line diagram uses a single solid line to represent all three phases. **Figure 1** shows an example traditional CAD-based SLD for a 500 kW data center.

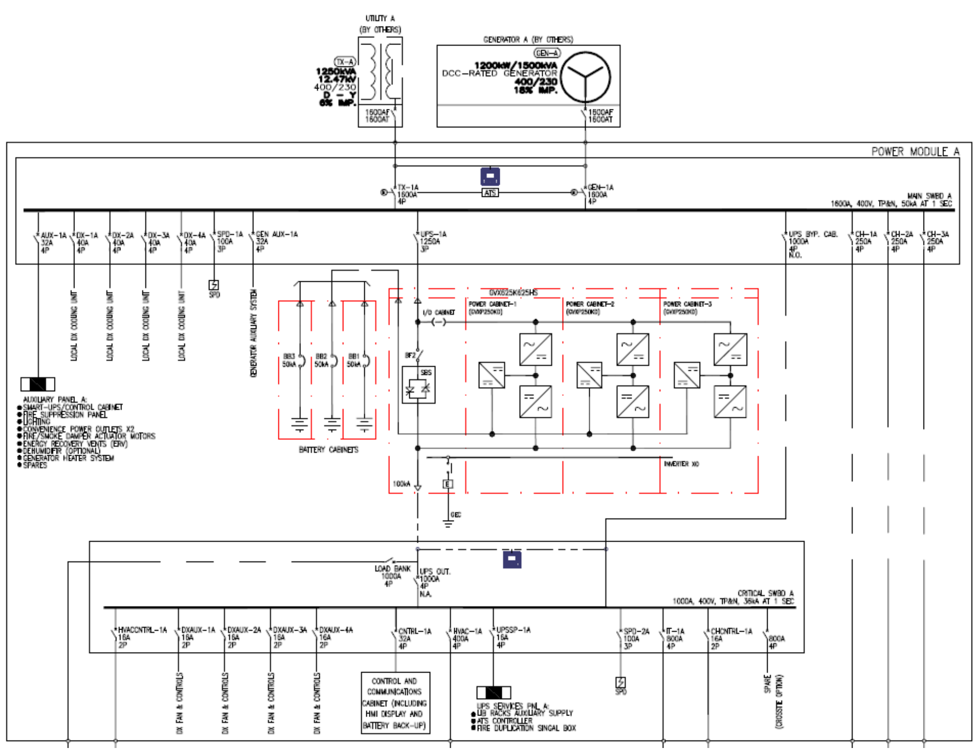

Figure 1

To illustrate an example one-line diagram of an electrical system, this figure shows an SLD for a 500 kW data center, taken from one of Schneider Electric's Data Center Reference Designs

In Schneider Electric's experience, roughly 60% of facilities operate today with simple paper-based SLDs. Most of these SLDs are not synchronized with the actual electrical system today because they haven't been regularly reviewed or maintained over time. We've also found that about 10-20% of sites have no SLDs at all. Sites with no or poorly managed electrical blueprints run a higher risk of experiencing critical safety incidents, service interruptions, longer mean time to diagnose and repair, as well as being in a state of non-compliance with local codes and standards.

[1] North America: IEEE, *Graphic Symbols for Electrical and Electronics Diagrams*

[2] Global reference guide: Allen-Bradley, *A Global Reference Guide for Reading Schematic Diagrams*

Electrical design software and services exist to simplify the creation and maintenance of single-line diagrams. When there is a lack of expertise or time, there are vendors who can employ these tools to digitally create and maintain the SLDs as a service. These software tools enable the creation of digitalized intelligent SLDs (iSLDs) which include more information (e.g., operation modes[3]) than would be included with a typical paper or simple 2D CAD-based diagram. These iSLDs become the basis for conducting technical studies (e.g. fault current analysis), experimenting with what-if scenarios, as well as performing training and maintenance activities. This assumes power system engineering software is used as support. iSLDs also put owners on a path towards advanced BIM modeling, AI-based operations using a digital twin of the site, and further automation. This leads to increased electrical efficiency and lower greenhouse gas emissions. Note that this paper does not cover the topic of electrical efficiency improvements.

In this paper, we explain the value of updated SLDs throughout the lifecycle of the site. We discuss the steps to create and maintain SLDs to set expectations for doing this yourself. We then define intelligent, digitalized SLDs and explain how they are more effective than traditional CAD or Visio-based drawings. And finally, we provide considerations on whether to create and maintain SLDs yourself or contract with a qualified vendor to do it as a service.

Creating accurate SLDs for existing sites

To be effective, an electrical single-line diagram must be an accurate and complete representation of the physical reality at the site. Otherwise, the value of having a map of the distribution network is lost. Being accurate and complete means that the diagram not only includes all the actual electrical devices and conductors installed, but also the information needed to understand how these devices and conductors are connected and related to each other.

Imagine, for example, replacing an upstream transformer with one that has a lower impedance rating and not reflecting that rating change in the SLD. Operators may not know that the incident energy now exceeds safety limits at the low voltage switchboard they are working on. This creates a serious risk of injury or death. **So, creating and continuously maintaining accurate SLDs is imperative for operations teams. And, it is a regulatory requirement in many locations** (as explained later in the paper).

Data collection

Creating or validating SLDs for an existing installation requires collecting some key site information. The following bullets[4] provide a high level summary of this information.

- Incoming service voltage & utilization voltages
- Electrical distribution equipment ampacity and short-circuit ratings
- Overcurrent & short-circuit protection
- Conductor types (i.e., cable or busway) & sizes
- Cable lengths
- Transformer kVA ratings, impedance, & voltages
- Generator kW ratings & voltages

[3] E.g., how transfers are made from utility power to generator power via closed or open transitions.

[4] EEP, *The essentials of designing MV/LV single line diagrams (symbols & drawings analysis)*

- Motor loads & voltages
- Other power quality equipment (e.g., TVSS, power factor correction capacitors)
- Site network and grid operating parameters

To give a view of the more detailed device data that ultimately needs to be collected, **Figure 2** shows an example data collection form used by Schneider Electric's Electrical Digital Twin Service team to collect data on low voltage switchboards.

Figure 2

A sample data collection form used by Schneider Electric's Electrical Digital Twin Service team for gathering information on low voltage switchboards

7 LV Switchboards

- Look in the documents you have collected
- Look in the electricity supplier contract
- Look on the asset
- Ask your customer

▼ EXAMPLE ▼ EXAMPLE ▼ EXAMPLE ▼ EXAMPLE ▼ EXAMPLE ▼ EXAMPLE ▼ EXAMPLE ▼ EXAMPLE ▼ EXAMPLE ▼ EXAMPLE ▼ EXAMPLE ▼ EXAMPLE ▼ EXAMPLE

LV switchboard 1	
Name of the Medium voltage switchboard	
Nominal voltage level of the LV switchboard (Un in kV)	
Switchboard Brand	
Switchboard Model	
Earthing connection (TN-S, TN-C, IT, ...)	
Thermal withstand current-time(s)	
SLD and electrical drawing name / Picture file name	
Type of dedicated arc flash protection (e.g. arc flash detector)	

EXAMPLE

Note: please provide detailed SLD and LV panels electrical detailed drawings

Identification		Protecting Device			Tripping unit	Range / Settings					Cable caracteristics					
Switchgear TAG	Feeder ID Load ID	Type (CB/fuse) Brand and Model	Ultimate Breaking Capacity (Icu)	Short-time Withstand current (Icw)	Brand Model Rating	LTPU (Ir)	LTD (tr)	STPU (Isd)	STD (tsd)	INST. (It)	Length (m)	#cable /phase	Type (#core)	Phase & Neutral Cross Section	#PE/PEN cross section	Isolation (EPR/ XLPE/ PVC)
						Range / Settings	Range / Settings	Range / Settings	Range / Settings	Range / Settings						
SWB_1	301 Incomer	SE NW16H1	65kA	35kA - 3s	SE Micrologic 6.0 1600A	0.4-1.0	0.5-24(6Ir)	1.5-10	0-0.4	2.0-15	95	2	4C Cu	300 mm²	1 x 300 mm²	XLPE
						0.7	0.5	10	0.1	Off						
SWB_1	302 Feeder to M-SS21	SE NSX160H	70kA	-	SE MA25 25A	-	-	-	-	9.0 - 14	55	1	1C Al	240 mm²	1 x 120 mm²	XLPE
						-	-	-	-	10						

It is the site owner's responsibility to ensure that whatever data is provided as input to the creation of an SLD model reflects what is physically installed at the site. Service vendors will generally accept existing SLDs, cable schedules, and equipment ID label data as inputs for model creation, **but the vendor's scope of work generally stipulates that the onus is on the site owner to validate that the data is accurate.** For reasons of simplicity and expedience, there is a temptation to rely on existing paper or original "as built" diagrams for this type of information without having done any field validation. Validation includes things like visually confirming that the cable and equipment data match the cable schedule and visually confirming that the equipment (e.g., switchboards, transformers, loads) is connected as shown in the site owner's SLD documentation, from the utility service entrance down to the LV loads. Unless a site owner validates their documentation, they cannot be absolutely sure they have an accurate understanding of the network. Ultimately it is the responsibility of the site owner to validate the accuracy of their SLDs, whether done by themselves or through a third party vendor service.

Collecting the data necessary to make an accurate SLD takes a commitment of time and effort. The work should be done by a licensed electrical contractor or similar expert. For a small-to-medium sized site (i.e., installed power of 2000 kVA – 2500 kVA), it takes an experienced vendor service team about 4 to 5 business days to collect device data. For organizations lacking this expertise and/or staff availability, this process will likely take much longer.

SLD model creation

Once all the device data and information about their relationship with each other is collected, the next step is to create the digital model of the single-line diagram, derived from this collected information. The software used to create the SLD depends on whether you want a simple 2D SLD or a digitalized iSLD. 2D SLDs can be created with standard CAD software. However, as we explain later in this paper, we recommend intelligent, digitalized SLDs which requires modern power system engineering software. Although these intelligent, digitalized iSLD software tools gather all power system data in one unique database and user interface, these software tools do require training and practice to become efficient at using them. For the same 2000 kVA – 2500 kVA site described above, it would take an experienced team well-trained with these electrical design software tools only about 2-3 days to construct the model.

Roles and value of SLDs

Continuously maintaining SLDs requires an on-going commitment of time, money, and staffing. So, whether done by the organization itself or outsourced to experts as a service, it is important for management to be aware of the regulatory requirements to maintain SLDs along with knowing the value that accurate SLDs bring throughout the lifecycle of the building. This section provides a summary of the important roles and benefits that SLDs offer in the design, construction, and operation phases of a site's lifecycle.

Design & construction phases

SLDs are typically created initially by engineering firms during the initial design phase of a site. The diagram documents the architecture and layout of the electrical distribution network while serving as a single source of the truth for project teams. SLDs are a tool to analyze the impact and tradeoffs of various design elements in terms of cost, redundancy, and expected physical space requirements and constraints. As the project moves from the initial early planning stage of the design phase into the detailed design stage, the SLD will evolve and grow in terms of information detail that is associated with the diagram.

From the detailed design phase, SLDs next serve as a key input into the creation of the construction documents. SLDs provide the necessary details about the electrical network to enable competing electrical contractors to make accurate pricing proposals or bids. Mistakes and misunderstandings about the design can result in project delays and costly change orders or lost bids.

Finally, they serve as a single source of truth or blueprint for all project documents. Everything in the project related to the electrical network is referenced or evaluated against the SLDs for accuracy. This includes items such as vendor cut sheets, specifications, wiring diagrams, and logic diagrams. This documentation along with the SLD itself is then used as foundational content for following:

- performing commissioning tests
- conducting power system studies
- creating methods of procedure (MOPs)
- documenting emergency preparedness and response procedures
- training O&M teams

In addition to being a critical element in the design and construction phases, SLDs are also crucial for preparing the O&M team for the operation phase.

Operation phase

Preparing a critical response plan begins with maintaining accurate SLDs. One-line diagrams enable electrical personnel to fully understand the design of the facility's electrical distribution system. Whether it's a new or an existing facility, the single-line diagram is a roadmap for all future testing, service, and maintenance activities done during the operation phase of the site.

Well-maintained SLDs will help ensure safety, maintain regulatory compliance, reduce downtime, and make operations more efficient. We explain how this is achieved below.

Help ensure safety

An accurate single-line diagram is critical for ensuring safety any time work is to be performed on energized equipment or during the performance of a lockout/tagout procedure. The information contained in the SLD helps ensure electrical personnel have the information needed to perform the work properly and safely. Safety consultants and inspectors, such as Occupational Safety and Health Administration (OSHA) inspectors in the U.S., will ask for a copy of the latest SLD to base their inspection or consultation on.

Also, throughout the life of the site, various technical studies and safety assessments will need to be performed to ensure on-going safe operation of the electrical distribution network, control of hazardous energy, optimize costs, and ensure existing equipment can withstand short circuit currents. This is required, for example, whenever the building goes through a retrofit or expansion where the electrical network is changed. To perform these studies and assessments properly, an updated, accurate SLD is required.

Safety studies and assessments requiring accurate SLDs include[5]:

- Short-circuit and device evaluation study
- Protection coordination
- Arc flash risk assessment
- Lock-out and Tag-out (LOTO) program
- Electrical safety studies and evaluations
- Electrical safety and emergency response procedure development
- Power quality assessments

Maintain regulatory compliance

Some standards require testing of a building's electrical system (e.g. Lock-out and Tag-out). As a prerequisite to the testing, these standards also require accurate SLDs (i.e. SLDs match the current electrical system). These requirements become mandatory when governments adopt these standards as regulations (i.e. law). As an example of such a standard that may be adopted by your local code, National Fire Protection Association (NFPA) 70E (Chapter 2, under "General Maintenance Requirements", Article 205.2) states, "A single line diagram, where provided for the electrical system, shall be maintained in a legible condition and shall be kept current."

Reduce downtime

Fundamentally, accurate SLDs help reduce electrical system downtime in two ways: (1) by reducing the likelihood of human error and (2) by minimizing the time needed

[5] https://www.omazaki.co.id/en/the-importance-of-single-line-diagram-sld/

to troubleshoot, isolate failures, and get the network back up and running. Human error is often cited[6,7] as a top cause of system downtime. Error occurs from lack of knowledge, maintenance procedures not keeping up with changes in the electrical system, poor training, mistakes in judgement, and so on. Addressing these causes begins with having an accurate, up-to-date map of the electrical system along with all the associated data that is included. SLDs should provide the foundational content for MOPS, emergency operating procedures, and O&M staff training programs. They also should be close in hand when operations are performed to help double-check that the right procedures are being applied to the correct equipment. Doing this will reduce the chances for human error in operations. Not doing this well increases chances of mistakes happening, and it tends to lead to longer mean-time to recover (MTTR) when systems go down. More time must be spent trying to figure out where equipment is and what it's connected to, for example.

Facilitates efficient operations and maintenance

In a related way, the knowledge provided by accurate SLDs makes operations and maintenance activities more efficient than they would be otherwise. Their standardized naming conventions help reduce confusion when performing maintenance, in terms of clarifying which specific device is being serviced and where it is in the network. Avoiding errors and being clear about where equipment is located, what its connected to, along with knowledge of other operating parameters, reduces the time and effort required to perform O&M activities and leads to better decision making and less rework. Cost-saving efficiency is also gained through not having to pay for additional model creation or data collection services whenever technical studies or assessments are conducted.

It is worth noting that all these benefits (summarized in Figure 3) are dependent not just on having accurate SLDs, but also on management's on-going commitment to use them.

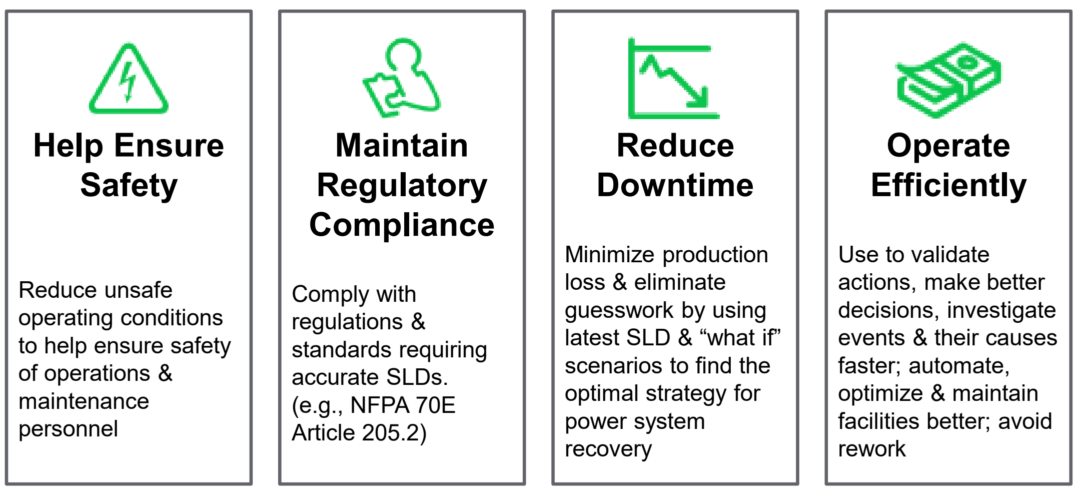

Figure 3

A high level summary of the benefits that accurate SLDs provide in the operation phase of a facility

These benefits are more easily achieved and additional benefits are made possible when intelligent, digitalized SLDs are employed instead of the traditional, simple 2D CAD-based diagrams. In the next section, we define what these more modern diagrams are and explain their advantages over traditional SLDs.

[6] https://techchannel.com/SMB/10/2018/Human-Error-Top-Cause-of-Downtime

[7] https://www.diva-portal.org/smash/get/diva2:1566773/FULLTEXT01.pdf

Intelligent, digitalized SLDs (iSLDs)

Traditional SLDs take the form of simple CAD or Visio drawings where the drawing of the electrical network and equipment includes simple information labels to convey basic attributes such as voltage levels, short-circuit current ratings, amperage, and so on. Often these are kept only as PDF files. These non-dynamic, standalone files are independent of other systems and tools. Unless diligently managed and controlled, these files can easily be lost, copied and shared without revision history control, and tend to be forgotten when changes and expansions occur to the network. This means costly data collection and circuit tracing must occur each time an assessment or study needs to be performed.

Modern power system engineering (i.e., electrical design) software tools have emerged that make it easier to create and maintain SLDs while improving their overall value to the site. The SLDs created by this software are referred to as intelligent, digitalized SLDs (iSLDs). Intelligent refers to them having additional technical information attached to the drawings and to being more dynamic or flexible. For example, the added information includes detailed descriptions of the network's operating modes. Digitalized refers to them being digital representations of the physical network while benefiting from other embedded digital technologies such as rules-based logic for auto creating one lines and pre-installed asset libraries containing detailed vendor-specific device data. Put more simply, an iSLD is a more advanced single-line diagram stored and managed in specialized software that includes advanced functionality and awareness of the devices' characteristics and operating behavior. It creates, in effect, a digital twin of the physical electrical network. In this way, this one software platform can be used to:

- design the electrical network
- create and maintain the SLD
- perform all technical studies and safety assessments
- report on and provide views of the system based on specific audiences

These (typically) cloud-based platforms provide a single version of the truth for all stakeholders including plant personnel, suppliers, management, auditors seeking asset and network topology information, as well as electrical engineers who use the SLDs to provide power system calculations. Having all the data and functions in one software platform enables site owners to avoid the financial and time expense of modeling and collecting data every time a technical study or audit is needed.

On the other hand, traditional drawings are more likely to be copied across multiple platforms to multiple users and are characterized by a lack of data reusability and for having limited information. This can lead to errors, omissions, and inflated assumptions. This then leads to expensive change orders and project cost overruns during the execution phase of a project to build or expand.

Having a digital twin of the electrical network also enables the possibility to connect the iSLD model with electrical power monitoring system (EPMS) or Power SCADA software to provide operation management functions like root cause analysis, 'what if' scenario simulations, risk analysis to prevent unintended switching, and more realistic operator training. These new applications for SLDs significantly expand their value to site owners beyond what is possible with traditional drawings.

While a modern electrical design software platform improves the creation and management of SLDs, becoming proficient with the software takes a significant investment of time and money. For many organizations, who do not have the time or staff resources to do it themselves, it is preferrable to outsource the use of the

software and management of their SLDs to a qualified vendor, as a service. Ideal vendors have electrical distribution experts who are very experienced at data collection and digital twin model development. This experience should translate to faster delivery of an effective digital twin model that reflects the current reality of the site's electrical infrastructure.

Schneider Electric believes in a future where site operations will become increasingly more digital and automated. Technologies such as advanced BIM modeling, machine learning, cloud computing, and IoT will lead to greater operational efficiency, resiliency, and sustainability. Creating a digital twin of the electrical system (iSLD) is a first step to putting site owners on the path to this future.

In the final section, we provide some considerations regarding managing SLDs yourself or hiring a qualified vendor to fulfill it as a service.

DIY or outsource considerations

As mentioned, benefiting from accurate SLDs requires an on-going commitment from management and owners to provide the resources needed to create and maintain them throughout the lifecycle of the site. This is regardless of whether this is done by the organization who owns the site or is outsourced as a service to a qualified vendor. The decision to do-it-yourself (DIY) or outsource as a service boils down to two factors:

1. Whether there is the time and qualified staffing available to do it effectively
2. The cost of purchasing a power system engineering software package and using staffing resources compared to the cost of a digital twin service

As stated earlier in this paper, it takes well-trained and experienced experts a total of about 6 to 8 days to both collect the data (4-5 days) and build an iSLD model (2-3 days) for a small to medium-sized site. For most, however, there would be the additional time and added expense of procuring and being trained to use the iSLD software. The time to collect data and ultimately build an accurate model could vary widely depending on the number of staff involved and the percent of their time dedicated to performing the tasks. The quality of the output will vary, too, depending on how well versed the team is in taking advantage of the software's functionality. Further, the ultimate long-term success depends on the organization's commitment to keep SLDs updated as things evolve and change over time.

Vendors that offer electrical digital twin services to create iSLDs offer a variety of service options, scopes of work, and fee schedules. However, in general, the owner would initially pay the vendor to:

- collect data
- build and provide the iSLD model
- provide software license to own, edit, and view the model

Note, some service vendors give the owner the option of collecting their own data themselves to save on that expense. This is not recommended, however, given how vital it is to collect and verify all the data.

By having ownership of the model, site operators can quickly grant or share access to the service vendor or any engineering services firms to make model updates or perform technical studies and assessments. This saves time and expense of having to go through the process of collecting data every time this is needed. Note, some of these service vendors also offer maintenance contracts to keep iSLDs up to date and perform additional services such as technical studies and power calculations for modernization and expansion projects.

If the decision is made to pursue a service, consider the following questions to evaluate service vendors:

- What electrical engineering experience and expertise can the vendor demonstrate?
- What are the capabilities of the electrical design software platform?
- What is their cybersecurity strategy for the platform?
- What data is collected and how does that compare to others?
- How flexible is the vendor in tailoring the service to meet your specific requirements?
- Do they offer services to maintain the model over time?
- Do they offer services to conduct technical studies and assessments?

Conclusion

Single-line diagrams (SLDs) are, in effect, a blue-print of the electrical distribution system. These diagrams, along with the information contained within them, are critical tools for operations and maintenance (O&M) teams to operate their sites safely, reliably, and efficiently. Therefore, continuously maintaining SLDs to accurately reflect the built environment is an imperative. An iSLD is a more advanced single-line diagram stored and managed in specialized software that includes advanced functionality and awareness of the devices' characteristics and operating behavior. It creates, in effect, a digital twin of the physical electrical network.

Creating and maintaining SLDs yourself requires an on-going commitment and effort from both management and O&M teams. For those who lack the time and/or expertise, there are qualified vendors who can create intelligent, digitalized SLDs (iSLDs) as a service. Well-qualified vendors will have the electrical and power system engineering software expertise. A good vendor will also have experience in collecting the data and developing the electrical digital twin (iSLD) of the system, likely more quickly and effectively.

Schneider Electric believes in a future where site operations will become increasingly more digital and automated. Technologies such as advanced BIM modeling, machine learning, cloud computing, and IoT will lead to greater operational efficiency, resiliency, and sustainability. Creating a digital twin of the electrical system (iSLD) is a first step to putting site owners on the path to this future.

About the author

Patrick Donovan is a Senior Research Analyst for the Energy Management Research Center at Schneider Electric. He has over 25 years of experience developing and supporting critical power and cooling systems for Schneider Electric's Secure Power Business unit including several award-winning power protection, efficiency, and availability solutions. An author of numerous white papers, industry articles, and technology assessments, Patrick's research on data center physical infrastructure technologies and markets offers guidance and advice on best practices for planning, designing, and operation of data center facilities.

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