Abstract - Electric utilities today face increased pressure compared to that faced just ten years ago. De-regulation of the utility industry has brought profitability and performance pressures from shareholders, public service commissions and customers. Recent advancements in padmounted electrical equipment now allow construction alternatives that did not exist when utilities originally created their standard substation designs. It is now possible to construct smaller, padmounted substations with underground sources and feeders. Benefits of this approach include reduced cost, easier construction approval, greater reliability, simplicity and flexibility of design, and improved safety and aesthetics. These benefits will be discussed in detail, with examples of completed installations.

Index Terms - Substation design, substation construction, padmounted equipment, padmounted transformers, padmounted switchgear, padmounted capacitor, voltage regulation.

I. INTRODUCTION

The business environment for utilities has changed substantially in the last ten years. De-regulation has forced utilities into a more competitive marketplace. Expenses are no longer automatically calculated into the customer rate base, and in some cases, customers have the opportunity to choose from whom they purchase power. As a result, utilities are re-examining their practices, from billing to construction. The recovery period for expenditures must be much shorter than it was previously.

Customer demands have also increased. User’s precision electronics have raised reliability requirements. EMF and aesthetic considerations have made projects such as substation and transmission line construction much more difficult than it once was.

A. Traditional Substation

A traditional substation is shown in Fig. 1. It contains overhead incoming and outgoing lines, with open-air connections of switches, the transformer, regulators, capacitors, and breakers. The entire installation is fenced or walled in, and may also have a control house on the property. The capacity of such a product ranges from 5 to 100 MVA, with a primary voltage between 35 and 230 kV, and a secondary voltage 35 kV or lower. Although vital to the electrical system, there is a negative public perception regarding the overhead lines, exposed connections, and potential EMF radiation. This perception can make permitting difficult or impossible.

B. Distributed Padmounted Substation

This paper’s intent is to focus on “distributed padmounted substations”. Just as the mix of generation on a utility system now includes an array of “distributed generation”, a utility’s substation base can apply a similar concept. Although there is no strict definition, these substations are usually defined as using an underground source to a small (10-20 MVA) substation. The underground source is either a higher (25 or 35 KV) distribution voltage or a transmission level voltage. The equipment is padmounted and deadfront. It is typically sited right at a new load growth or development area that cannot be served by the existing distribution system. It can be as simple as a collection of padmount equipment boxes, perhaps without a fence (see Example #1). If a higher distribution voltage is used for the source it can be an “express feeder” from an existing large substation, and need not be a voltage already on the utility’s system. Since express...
feeders serve no customers along the way, it is possible to use this unique voltage without truly introducing another service voltage to the utility.

Substations are not distributed today due to the high fixed cost of a traditional substation. The costs of fencing, real estate, excavation, and open buswork are not directly proportional to the MVA requirements of the station. Distributed substations become economically justifiable when they become padmounted. The individual stations can be sized for the load being added, and installed more easily and less expensively.

II. BENEFITS

1) Cost: It is difficult to compare costs of these two approaches to substations because of the differences between them. A traditional substation may have twice the capacity of a padmount installation, an elaborate relaying scheme, and a control building. Although a distributed padmounted substation may not even have a fence, it may have electronic, vacuum interruption high side protection versus simple power fuses in an overhead design (as shown in Fig.1).

Several projects for which costs were developed both ways to serve the same load indicate that a padmounted substation approach is often 35% less expensive than a traditional substation. Reduced material costs include no “take-off structure”, possibly no fence or control building and less expensive power equipment. Total costs for a complete padmounted substation can be as little as $350,000. Construction and design costs are reduced because both are greatly simplified. Property costs are reduced due to a more compact design and much smaller right-of-ways. In some situations, the just value of deferring a large capital project to install a traditional substation can justify the construction of a distributed padmounted substation.

2) Approval Process: Overhead transmission right-of-ways may be difficult or impossible to obtain in some places. If an underground source is used, the right-of-ways required are much narrower or may already exist. Public, government and regulatory review processes are simplified due to the less obtrusive, clean underground design. Permitting may even be avoided altogether for some projects if only distribution voltages are involved. In addition, there are fewer EMF concerns with an entirely padmounted installation.

3) Reliability: Service reliability is improved since there is no exposure to weather. Underground construction avoids ice and wind problems, and the entire installation is shielded from lightning. Wildlife problems are greatly reduced with no exposed energized parts. Outage restoration is quicker because spare equipment is easily transportable and relatively lightweight. Utilizing single-phase regulators (which can be bypassed) instead of transformer LTCs contributes to a design that can be operated with fewer outages. Additionally, regulators monitor and correct each phase voltage individually. This leads to improved regulation of feeders with substantial single-phase load.

4) Simplicity and Flexibility: The simplicity and flexibility of the distributed padmounted substation is in its “building block” approach. Much of the equipment is available as standard distribution equipment and in many different configurations. These standard blocks can be laid out to create a customized design by simply connecting different blocks. This results in a two-dimensional design that a distribution planning engineer can manage. Substation design engineers are then freed up to focus on more complex work instead. The flexibility of the building blocks yields some very different designs as shown in the attached examples.

Using typical distribution equipment means that distribution crews may construct and maintain a padmounted substation. It is a big advantage for some utilities to have distribution crews (contracted or in-house) able to complete this work (see Fig. 2). The simple design and construction of these substations with common padmounted equipment results in relatively short timelines, allowing utilities to complete projects more quickly and consistently.

There is also the flexibility to incorporate only part of this entire concept on a project. Example #4 utilizes a typical overhead transmission line source, with the rest of the substation built from padmounted components. In this example, existing overhead right-of-way and the proximity of nearby 46 kV overhead lines made this method the most cost effective.

5) Safety: The safety of a padmounted substation is increased because all equipment is deadfront; no exposed energized parts exist. The equipment is also all hot-stick- operable and tamper-resistant. This offers no more risk to the public than the padmounted transformers installed in some customers’ backyards. This degree of safety makes padmounted substations safer for operating personnel, the public and wildlife. The substation shown in Example #1 is near a ski area, which commonly has 10 feet of snow on the
ground. An energized bus at such a location could be a hazard because both people and wildlife frequent the area.

6) Aesthetics: A completed distributed padmounted substation looks like a clean collection of boxes in a field. The low profile and underground design are pleasing to the eye. This makes them a better fit in residential areas or especially at upscale resorts and environmentally sensitive areas.

III. EQUIPMENT

Expansion of the product scope of padmounted equipment over the last twenty years now makes an entirely padmounted substation installation viable. All products listed below can be designed and certified to meet the tamper-resistance criteria set forth in ANSI C57.12.28 – 1999 [1]. It is common practice to install equipment meeting this standard without any additional tamper protection (i.e. fence, enclosure, walls.)

1) Transformers: Padmounted transformers as large as 10 MVA are now available. Primary voltages up to 69 kV are possible, and units with secondary voltages from 4 kV to 25 kV can be designed to accommodate 1200 amps of secondary line current. The paralleling of two or more of these transformers enhances reliability. The total MVA of the station will be determined by load data and load projections. By dividing the required kVA amongst multiple units, the loss of a transformer does not mean a long-term outage. The load can likely be carried by the remaining units, at least until loads have grown into the original projections.

For primary voltages up to 35 kV, integral primary overcurrent protection is available for these large padmounted transformers. A vacuum interrupter can be built into the transformer tank, providing overload and fault protection. This device typically has an interruption rating of 12 kA. This rating can sometimes be increased to 50 kA by the addition of partial-range current-limiting fusing in series with the interrupter, depending on the exact voltage and current ratings required.

2) Connectors: Deadfront primary connectors are common and modestly priced for units with primary voltages up to 35 kV. 600 amp deadfront connectors are commonly used to connect the various pieces of equipment in the substation. These connectors can be certified to 900A operation with the use of all copper components. Deadfront primary connectors are available for 46 kV and 69 kV applications as well. The cost of such connectors is substantial (over $1500 per bushing connection), but if underground 46 kV or 69 kV cable is already a requirement of the installation, this connection method may prove to be the most economical.

3) Switchgear: Padmounted switchgear may be used to accomplish all the switching needs in a substation. The many configurations offered provide a lot of flexibility. They can substitute as a bus and can even provide a bus tie switch (shown in all of the examples). Using vacuum switches, they allow either automatic or manual transfer from a preferred to an alternate source. These switches have fault current ratings of 12-16 kA. Continuous current ratings of 600 amps are common, and units capable of carrying 800 amps are possible.

Padmounted switchgear with overcurrent protection can be used for high side protection and/or outgoing feeder protection. Multiple feeders may be protected by a single piece of vacuum interrupter gear, utilizing an industry-standard configuration. If feeders leaving the substation become overhead lines at some point, padmounted vacuum reclosers can be installed to offer transient fault protection. Micro-processor based controls in these devices provide precision control of TCC curve profile and minimum trip levels.

4) Regulators: Voltage control for a padmounted substation is available by using padmounted single-phase step-voltage regulators (see Fig. 3). These devices contain the same components used in structure-mounted substation regulators, except that the source, load, and source-load bushings are deadfront style, capable of carrying up to 600 amps. Single-phase regulators offer independent phase voltage control, and bypass/replacement without service interruption to customers, unlike LTC voltage control on a power transformer.

5) Capacitors: Feeder power-factor correction may also be handled within the padmounted substation since several vendors supply padmounted capacitor banks.

6) Reactors: If a reduction in the available fault current is required, it is possible to install padmounted reactors as part of the substation.

7) Automation: Microprocessor-based controls for regulators, reclosers and switchgear offer many modern
features. These automation capabilities and intelligence are “distributed” out to the individual control boxes, potentially eliminating the need for a control house or dispatch operator involvement.

Some of the available features include:

- Individual feeder metering capability
- Graphical logic programming and oscillography
- Digital or Analog SCADA communication and control

IV. LIMITATIONS

1) KVA Size: This application lends itself to the 5 - 20 MVA range. If MVA requirements are larger than that, equipment and load flow problems exist. Padmount transformers are available up to 10MVA (paralleled to obtain 20MVA). The regulators are available up to 600 amps. Carrying loads larger than 20 MVA for any considerable distance is difficult using a distribution voltage.

2) Primary Voltage Level: 35 kV may be considered a maximum for several reasons. High side protection equipment is difficult to find in a deadfront, padmounted package above 35 kV. The switching equipment and deadfront terminations are also much more affordable at 35 kV and below. Deadfront arresters are available up to 35 kV. These issues may create an incentive to use a higher-distribution voltage express feeder (35 kV or less) so that distribution-class equipment and terminations can be used.

If a radial, express feeder is used, then the overcurrent protection at the origin of that line can act as both line protection and high side protection to the distributed substation. This would eliminate the need of a high side protection device in the padmounted substation, and would promote the use of 46 or 69 kV as the express feeder voltage.

3) Fault Current: Although some padmounted equipment is available with an interrupting rating of 16 kA, the majority of padmount switching equipment is limited to a 12 kA interrupt rating. If required, padmount reactors may be installed, or higher fault-current withstand switches may be available. If the transformer is the first piece of gear in the installation (as shown in Example 4), fault current to the switches is limited by the transformer impedance.

V. APPLICATIONS

The distributed padmounted substation is not a concept that replaces the traditional substation as a standard. It should be considered as an option for specific projects, where a traditional substation may not be the best fit. As a niche application, it has proven to be attractive to even large utilities. Some common applications of this concept include:

- **Exclusive Resorts** – Aesthetics are very important at upscale resorts where property prices are high. Many of these customers demand underground construction anyway. Resorts are quite often large loads in isolated locations, making a good fit for the express feeder concept (see Example #1).

- **Stepdown Applications** – The distributed padmounted design can conveniently be used to create a stepdown substation. These are used to interconnect different distribution systems versus installing a new high voltage transmission substation (see Example #3).

- **Extreme Climates** – Applications at ski areas, coastal areas, and high contamination areas (salt or highway de-icing agent) are all good applications.

- **Environmentally Sensitive Areas** – Places such as State or National Parks and other highly scenic areas are good candidates. Even some residential neighborhoods have aesthetic requirements that justify this type of construction.
EXAMPLES

Example 1
Example 2
Example 3
Example 4
VI. CONCLUSION

Distributed padmounted substations have benefitted those utilities who have installed them. Placing only the required MVA of substation in close proximity to the load requiring it postpones or eliminates the need to install a larger, traditional substation.

There are numerous benefits as compared to a traditional substation. The benefits include:

- Decreased costs (often 35%).
- Construction approval is easier, due to narrower right-of-ways and improved aesthetics.
- Greater reliability, due to reduced exposure to extreme weather.
- Simplicity and flexibility of design, due to two-dimensional “building block” approach.
- Improved safety, due to deadfront construction and underground cable connections.
- Improved aesthetics, due to the lower profile and unobtrusive appearance of padmounted equipment.

The application of this concept is limited by the voltage and ampacity limits of padmounted equipment. A 20 MVA installation is the practical maximum size, with a maximum primary voltage of 69 kV. The available fault current on the secondary side (and perhaps the primary side, depending on the design) of the installation must be kept below 12 kA.

Some particularly good applications for this concept are near resorts, in extreme climates, in environmentally sensitive areas, or as a connection point between distribution systems.

REFERENCES
