Using 1kV low voltage distribution for connection of plug-in vehicles

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Abstract—Using 1kV as an intermediate voltage within the electric distribution system can be a cost efficient method for reinforcing the low voltage network when loads increase due to plug-in vehicles. This paper presents cost comparisons between different network reinforcement methods including different system typologies for the 1kV system. An estimation of network reinforcements needed in Sweden for domestic houses have also been conducted. Further on, different types of transformers for the 1kV system are described.

The 1kV system is especially suitable when the voltage on existing cable can be raised from 0.4kV to 1kV. This is possible for most modern low voltage cables.

Examples of applications of 1kV systems are connection of car parks with charging equipment for plug-in vehicles and rural houses with a low short circuit power.

Index Terms—Low voltage distribution, 1kV, electric vehicles, distribution transformers

I. INTRODUCTION

CONNECTING plug-in vehicles to the low voltage network may become a problem if the concentration of plug-in vehicles is large, such as for car parks. Problems may also arise when charging plug-in vehicles in domestic houses with low short circuit impedance and other large loads connected such as electric heating systems. In the latter case, the customer may need to increase the size of the main fuses and move loads between phases. In some cases, the increased load will result in network reinforcements that can be expensive. Raising the voltage in the low voltage network to 1kV and transform the voltage to 0.4kV close to the customer can be a cost-efficient method to reinforce the network. This paper describes different typologies for 1kV-system and suitable transformers.

Network data used in this paper comes from Vattenfall Eldistribution in Sweden. Vattenfall Eldistribution is one of the largest network companies in Scandinavia with networks in Sweden and Finland.

II. THE DISTRIBUTION NETWORK

In Sweden, distribution networks are traditionally built up with a medium voltage network with either 11 or 22kV feeding a low voltage network with 0.4kV. Low voltage customers are connected using three-phase connections.

Since the hurricanes Gudrun and Per, in 2005 and 2007, most network companies are replacing older overhead lines with underground cables on medium and low voltage levels, increasing the capacity of the medium and low voltage networks. Introducing large amounts of new low voltage cables also increases the possibilities to use 1kV on existing cables, while most modern cables are designed with a rated voltage of 1kV.

When larger amounts of electrical vehicles and plug-in hybrid vehicles will be connected to network, some reinforcements may be needed. Using 1kV as an intermediate voltage as illustrated to the right in fig. 1 can be one alternative.

Fig. 1. Traditional distribution system (left) and reinforced low voltage network using 1kV (right)

Using 1kV within the low voltage network is possible according to the Swedish wiring regulations, as long as the installation fulfills the requirements for low voltage installations.

III. POWER NEED FOR CHARGING VEHICLES

The power needed for charging of plug-in vehicles is dependent on the requested energy and maximum allowed time for charging.

In general, charging can either be active or passive. Active charging includes different methods to limit the charging power in order to optimize the charging in respect to other loads connected to the same phase.

Passive charging will use full charging power from start and will only be affected by the charging algorithm of the plug-in vehicle. Passive charging will affect the low voltage network most since full power may be utilized without warning. This is the dimensioning case and therefore the focus for this paper.

A. Charging energy

The needed charging energy will differ in different part of
the network. This due to the different drive patterns for vehicles in different geographical regions. To generalize the need for energy, two main categories have been studied, plug-in hybrid vehicles and plug-in electrical vehicles.

The plug-in hybrid vehicle is assumed to have a battery capacity of 10kWh and the electric vehicle is assumed to have a battery capacity of 24kWh corresponding to vehicles soon to be available on the market. For both types of vehicles, an overnight charging capability has been assumed to 80% of the total battery capacity. These assumptions give a needed charging energy of 8 and 19kWh respectively. Suitable powers for charging is assumed to 2.3 and 3.7kW with charging losses neglected. These assumptions give the charging times in table 1.

<table>
<thead>
<tr>
<th>LOADING ENERGY</th>
<th>LOADING POWER (LOADING CURRENT)</th>
<th>LOADING TIME</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 kWh</td>
<td>1kW (4.4 AMP)</td>
<td>8</td>
</tr>
<tr>
<td>8 kWh</td>
<td>2.3kW (10 AMP)</td>
<td>3.5</td>
</tr>
<tr>
<td>8 kWh</td>
<td>3.7kW (16 AMP)</td>
<td>2.2</td>
</tr>
<tr>
<td>19kWh</td>
<td>2.3kW (10 AMP)</td>
<td>8.3</td>
</tr>
<tr>
<td>19kWh</td>
<td>3.7kW (16 AMP)</td>
<td>5.1</td>
</tr>
</tbody>
</table>

The charging times show that the plug-in hybrid vehicle is possible to charge using a charging current of 4.4 and 10 Ampere, corresponding to 1 and 2.3kW charging power, for the overnight charging.

For smaller electrical vehicles such as the Nissan Leaf, 10 Ampere charging current will be sufficient for overnight charging. For larger vehicles, 16 Ampere charging current will be needed, corresponding to 3.7kW charging power.

B. Main fuses in domestic houses

Most Swedish households are today connected via a 16 Ampere main fuse. The main fuse works as a load limiting device and network fees are generally based on the size of the main fuse. Table 2 shows sizes of main fuses for a sample of customers in networks chosen to form a representative sample of Swedish one- and two family houses and holiday houses. The sample contains both urban and rural customers and includes over 200,000 customers.

<table>
<thead>
<tr>
<th>MAIN FUSE</th>
<th>ONE AND TWO FAMILY HOUSES</th>
<th>HOLIDAY HOUSES</th>
</tr>
</thead>
<tbody>
<tr>
<td>16 AMPERE</td>
<td>57%</td>
<td>87%</td>
</tr>
<tr>
<td>20 AMPERE</td>
<td>30%</td>
<td>6%</td>
</tr>
<tr>
<td>25 AMPERE</td>
<td>12%</td>
<td>5%</td>
</tr>
<tr>
<td>35 AMPERE</td>
<td>1%</td>
<td>0%</td>
</tr>
<tr>
<td>OTHER</td>
<td>1%</td>
<td>2%</td>
</tr>
</tbody>
</table>

Within the category “one and two family houses”, it is mainly those with 16 Ampere fuses that are assumed to get problem when charging vehicles. For holiday houses, it is believable to think that the problem is of less importance. For this category, the customer will more likely be able to decrease other loads while charging.

1) Possibility to increase size of main fuse

The local electrician can in most cases increase the fuse size from 16 up to 20 or 25 Ampere as long as the short circuit current is high enough to ensure that the fuses can disconnect within 5 seconds according to Swedish regulations [6]. If the disconnection time cannot be fulfilled, reinforcements must be done before the increase of fuse size is done. The number of reinforcements caused by this reason will be lower than reinforcements caused by power quality problems.

2) Estimated need for network reinforcements when connecting plug-in vehicles to one and two household houses

The reinforcement need due to power quality problems, such as low voltage level, flicker and harmonics will trigger network reinforcements if the customer is aware of the problem and report the problem to the network company. If the charger in the plug-in vehicle is equipped with alarm for low network voltage, it is assumable that many customers will complain and demand network reinforcements. According to European standard [3], the voltage should be in the range of 230 Volts +/- 10% which corresponds to 207-253 Volts.

Voltages lower than the stated limit is mainly a problem in rural areas where few customers are connected to long low voltage cables. Calculations have been performed to determine the voltage at 190,000 one- and two family customers with 16 Ampere main fuses.

The calculations have been performed in Netbas, the network information- and calculation system used by Vattenfall Eldistribution. Fig. 2 shows the distribution of calculated values for lowest voltages during maximum estimated load.

![Fig. 2. One and two family households: Calculated voltages at maximum estimated load (worst case) in existing network without plug-in vehicles for customers with 16 Ampere main fuse](image)

The voltages are calculated for a load condition representing the dimensioning load during winter, which can be seen as a worst-case scenario. Table 3 shows calculated number of customers that will obtain a voltage below 207 Volts under these conditions.
TABLE III
PERCENTAGE OF CUSTOMERS WITH LOW VOLTAGE AT FULL LOAD

<table>
<thead>
<tr>
<th>CATEGORY:</th>
<th>CUSTOMERS WITH U&lt;207 VOLTS:</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXISTING CUSTOMER LOADS (FULL LOAD):</td>
<td>2.4%</td>
</tr>
<tr>
<td>WITH 10 AMPERE CHARGING CURRENT</td>
<td>EXISTING % + 0.4%</td>
</tr>
<tr>
<td>WITH 16 AMPERE CHARGING CURRENT</td>
<td>EXISTING % + 1.6%</td>
</tr>
<tr>
<td>WITH 16 AMPERE CHARGING + 3 AMPERE OTHER LOAD</td>
<td>EXISTING % + 2.4%</td>
</tr>
</tbody>
</table>

As seen in table 3, approximately 4.8% of the customers will obtain a voltage less than 207 Volts when charging 16 Ampere and having 3 Ampere other loads connected to the same phase. However, the real number of customer that will be affected of low voltage during charging of plug-in vehicles will be lower than presented in table 3 because the majority of customers within this group are rural customers and assumed not to be early adopters of plug-in vehicles.

Another factor that will decrease the reinforcement need is that low voltages will mainly occur during a short time period during the coldest winter months. The real need for network reinforcements is therefore assumed to be 1% or less for all one- and two family houses connecting plug-in vehicles.

For other types of customers, the reinforcement need will depend on the existing low voltage network and the concentration of vehicles being charged at the same time.

IV. NETWORK REINFORCEMENTS

The traditional method for reinforcing the low voltage network is to extend the medium voltage network and build a new secondary substation close to the customer or using low voltage cables with a larger conductor area. This is expensive and will cause an environmental impact caused by the installation of new overhead lines or new underground cables.

If the existing 0.4kV cables are rated at 1kV and of good condition, the voltage can be raised to 1kV and transformed to 0.4kV close to the customer. Most new low voltage cables in Sweden are rated and type tested for 1kV rms voltage according to Swedish standard [4].

A. Comparison of costs for different reinforcement methods

The cost of reinforcing the network connection for a low voltage customer is dependent on many factors, such as closeness to medium voltage network, type of environment (rural, town or city) and the condition of the existing low voltage network.

Two networks have been chosen for cost comparison. The first one is a house in a rural area connected to a secondary substation using a long and weak cable. The reinforcement need for this category is often triggered by power quality problems.

The second network is car park in an urban environment. In this case, the reinforcement need is caused by the maximum allowed current in the low voltage cable. The two studied networks are described in fig. 3.

The used price data comes mainly from the annual cost catalog [7] assembled by Swedenergy, a non-profit industry organization representing companies involved in the production, distribution and trading of electricity in Sweden. Prices of transformers come from a previous work [2] conducted at Vattenfall Eldistribution.

Four different network configurations have been studied as reinforcement alternatives for network 1 and 2 in fig. 3 above. The five alternatives are described in fig. 4 below.

The costs for network reinforcements according to alternative A-D are listed in table 4 below.

<table>
<thead>
<tr>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>ALTERNATIVE A (REINFORCED 0.4kV CABLES)</td>
<td>39 700</td>
<td>34 300</td>
</tr>
<tr>
<td>ALTERNATIVE B (EXTENDED MEDIUM VOLTAGE NETWORK)</td>
<td>21 400*</td>
<td>48 200</td>
</tr>
<tr>
<td>ALTERNATIVE C (1kV SYSTEM)</td>
<td>17 400**</td>
<td>19 400</td>
</tr>
<tr>
<td>ALTERNATIVE D (1kV SYSTEM WITH THREE WINDING TRANSFORMER)</td>
<td>36 100*</td>
<td>11 700</td>
</tr>
</tbody>
</table>

*The cost decreases by 3000 EUR if pole mounted transformers (1/0.4kV) are used.
**The cost decreases by 6000 EUR if pole mounted transformers (0.4/1kV and 1/0.4kV) are used.

Alternative A and B include costs for cables and installation works. The installation cost per km for cable in city areas, as for network 2, is approximately three times higher than for rural areas, as for network 1.

Alternative C includes costs for two transformers 1/0.4kV placed in small secondary substations.

Alternative D includes costs for three winding transformer plus installation cost, minus residual value of existing transformer. The cost for network 1 includes a new secondary.
substation. The first reason for this is that many rural transformers are pole-mounted and newer transformers are placed in secondary substations. The second reason is that three winding transformers are larger than ordinary two winding transformers and will need larger secondary substations.

V. 1KV LOW VOLTAGE DISTRIBUTION

The main difference between an ordinary low voltage network and networks using 1kV is the introduction of new transformers and fuses. For fuses, less possibilities is available to the network designer, therefore the focus will be on the transformers.

In general, transformers for 1kV systems can be arranged in three different ways, as described in fig. 5. The different configurations are described below.

![Transformer configurations for 1kV-systems](image)

Configuration A can be used to increase the power capacity of a single cable supplying one major load. In most cases, the secondary substation will serve both customers connected to 0.4kV and 1kV and therefore, it will be more advantageous to use a three winding transformer in most cases.

Configuration B can be used if only a part of a 0.4kV cable should be used with 1kV. A typical application is in rural areas where customers nearby the secondary substation are connected to 0.4kV and there are more remotely customers with long cable in between. The long cable can in this case be used for 1kV.

Configuration C uses a three winding transformer for supplying nearby customer directly with 0.4kV and remotely, or high power customers, via the 1kV system. One application for this system can be to supply car parks for electric vehicles from an existing secondary substation.

VI. TRANSFORMERS FOR 1KV SYSTEMS

The use of 1kV in the low voltage network is mainly used in weak networks or together with cables that limit the maximum current. Utilizing the three-phase cables as good as possible in these networks are of big importance and therefore should transformers in 1kV systems have a good equalizing effect on load currents in different phases. Of this reason, zigzag (z) or delta (d) connected transformers should be used close to the customer.

The choice of transformers for the 1kV system is also dependent on national regulations. In Sweden, the 1kV system is categorized as a low voltage system and should fulfill the requirements for effectively grounding within the low voltage network [6].

A. Distribution transformers connected to medium voltage networks

Dependent on system grounding in the medium voltage network, overvoltages can arise on unfaulted phases during a single line to ground fault. This is especially common in reactance grounded systems. Therefore, it is preferable to use transformers that provide separation in zero sequence between the medium voltage network and low voltage network. According to standard [5], transformers with vector groups Dy or Yz should be used. Both these transformers give separation in zero sequence.

B. 11/0.4kV transformer

The choice of transformer for 11/0.4kV can preferably follow standard [5] and be chosen either Dy or Yz. Other vector groups such as Y(d)z or Zz will also provide separation in zero sequence but will become more expensive because of the additional windings.

C. 1/0.4kV transformer

The 1/0.4kV transformer should give good load equalization between phases. Load equalization is especially important for the transformer closest to the customer and therefore is transformers with windings connected in delta (d) or zigzag (z) favourable to use for this type of transformers.

From a store-keeping perspective, it is preferable to use transformers that can be used both as a step-up transformer and step-down transformer. This will reduce the number of transformers necessary to keep in safety stock.

Characteristics of five different vector groups are described for this type of transformer.

1) Yy
The Yy connected transformer will not give any load equalizing effect and is therefore not suitable for 1kV systems.

2) Dy
The Dy connected transformer gives a load equalizing effect but cannot be used for transformation 0.4/1kV because it would give insulated grounding on the 1kV level.

3) Yz
The Yz connected transformer gives good load equalization and low zero sequence impedance on the z-side. The zero sequence impedance on the Y-side will be very high because the zero sequence current on the z-side will sum to zero on each leg of the transformer. This will cause the magnetomotoric force to decrease for the zero sequence currents. The resulting zero sequence impedance seen from the Y-side will therefore be in the same size as the magnetizing impedance.

[1]

Using the Yz connected transformer for transformation 0.4/1kV will need relay protection for protection of the 1kV cable, while the single line to ground current will be too low for fuses to act on.
4) \( Y(d)z \)

Introducing a delta winding to the \( Yz \) connected transformer decreases the zero sequence impedance seen from the \( Y \)-side. The \( Y(d)z \) connected transformer will be possible to use both as \( 1/0.4 \text{kV} \) as well as \( 0.4/1 \text{kV} \) and can be used together with fuses for protection of the \( 1 \text{kV} \) system.

5) \( Zz \)

The \( Zz \) connected transformer has the same good properties as the \( Y(d)z \) connected transformer. However, this type of transformer are generally more expensive then the \( Y(d)z \) connected transformer due to a more complex manufacturing process.

D. \( 11/1/0.4 \text{kV} \) transformer

The three winding transformer is used for supplying both \( 0.4 \text{kV} \) and \( 1 \text{kV} \) system should be chosen such that the low- and high voltages sides are separated in zero sequence. The most simple transformer for this application is the \( Dyz \) connected transformer. If separation in zero sequence between \( 0.4 \text{kV} \) and \( 1 \text{kV} \) is needed, the \( Dyz \) connected transformer will be a good alternative.

E. Recommendations for transformers in \( 1 \text{kV} \) systems

From the discussion above, recommended vector groups for transformers for \( 1 \text{kV} \) systems are given in table 5.

<table>
<thead>
<tr>
<th>TABLE V</th>
<th>RECOMMENDED VECTOR GROUPS FOR TRANSFORMERS IN 1KV SYSTEMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>TYPE:</td>
<td>11/1/0.4kV</td>
</tr>
<tr>
<td>VECTOR GROUP:</td>
<td>Dy or Yz</td>
</tr>
</tbody>
</table>

VII. CONCLUSIONS

This paper has shown how \( 1 \text{kV} \) can be used as an intermediate voltage with in the low voltage network. Raising the voltage to \( 1 \text{kV} \) on existing cables can be used as a method to reinforce the low voltage network. This can be cost saving compared to conventional methods of network reinforcements such as extending the medium voltage network or install new low voltage cables with larger conductor areas. Using \( 1 \text{kV} \) is beneficial when the existing \( 0.4 \text{kV} \) cables are rated at \( 1 \text{kV} \).

A cost comparison has been presented that compare the cost of raising the voltage to \( 1 \text{kV} \) on existing cables and costs of conventional methods of network reinforcement. For rural applications, a \( 1 \text{kV} \) system with transformation from \( 0.4 \text{kV} \) to \( 1 \text{kV} \) will be a good alternative. For urban applications, the use of three winding transformers supplying both \( 1 \text{kV} \) and \( 0.4 \text{kV} \) systems are most advantageous.

The paper has also shown that the need to reinforce the \( 0.4 \text{kV} \) network for domestic customers will be small until electric vehicles with larger batteries are developed. For existing electric vehicles and plug-in hybrid vehicles, charging will be possible for most domestic customers without any network reinforcements. However most of these customers will need to increase the size of the main fuse from 16 Ampere to 20 Ampere. For areas with high concentrations of charging stations, such as car parks, reinforcement of the low voltage network will be needed in many cases.

VIII. REFERENCES

Books:

Dissertations:

Standards:
[4] SS 4241418 Power cables of rated voltage 0.6/1 kV – Specifications for design and testing, SEK Svensk Elstandard, Stockholm, 2007

Regulations:

Others:

IX. BIOGRAPHIES

David Söderberg (M’2007) received his BSc degree in electrical engineering in 2006 and MSc degree in International Project Management in 2007 from Chalmers University of Technology, Sweden and Northumbria University, UK, respectively. He is now working towards a MBA degree at Blekinge Institute of Technology, Sweden.

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