Investigation of a micro DC power grid in Glava Hillringsberg – a smart grid

Report

Rev: F
Date: 21 January 2012
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This report ways commissioned by Glava Energy Centre, Arvika. The project is part of the Interreg project FEM. See the project homepage at www.femweb.nu.

Table of contents

Summary

Direct current no longer has the disadvantages that previously motivated use of alternating current. In local networks and building installations, direct current nowadays has a number of advantages compared with alternating current. The main reason behind this change is that almost all electrical appliances have changed their electrical character to being electronic. Almost all appliances have and will have electronic interfaces to the electrical grid. Current breaking, which was previously a large problem, is no longer crucial. It has disappeared with electronic loads. See ref. video 1, Breaking DC current to electronic loads.

At the same time, the basic design of all new appliances is clearly that of DC appliances. In addition, in today's design, they are multi-current and multi-voltage appliances, which can run on both direct and alternating current. In upcoming designs, as only DC appliances, they can be more efficient than today's appliances. This change has been driven by the development of electronics and the desire to achieve the highest possible efficiency in the use of electricity. More recently, the desire for increased efficiency in the use of new local energy sources, in particular solar cells, has pushed ideas in the direction of returning to the use of direct current.

By direct use of DC in generators, local networks, installations and electrical appliances, the number of conversion steps and the concomitant energy losses are reduced at the same time as appliances and systems can be simplified. Taken together, this leads to lower costs, higher dependability (freedom from disturbance) and reliability.

The electrification of the world began with direct current. The first electrical network was a DC power grid designed by the American, Edison. He invented the incandescent light bulb and built what were known as Edison networks with a voltage of +/- 110V and later 220V and a zero-volt earth wire. One of the early networks in Värmland was built in Granbergsdal north of Karlskoga (See ref.) This type of local network became and remained the most common and the standard in the world up until roughly World War II. From the mid- 20th century up until today, they have been rebuilt as AC power grids.

However, the desire to increase the use of solar energy has meant that DC power grids of the Edison type are once again topical. The investigation proposes that a DC power grid with a voltage of +/- 350V is built in Hillringsberg. The grid is laid parallel to the present AC power grid and can thus form an industrial and village network as a hybrid AC and DC power grid. The DC power grid is installed in all properties and together with existing AC power grids, they form hybrid networks. The DC power grid can be very effectively backed up by batteries anywhere, which makes it uninterruptible. If the batteries are made big enough, they can also store solar electricity for use in the evenings and at night. This is, however, expensive, but will be possible if batteries become cheaper. Most of today's appliances and lamps can be connected to both networks. For example, in a data server, which has two standard power supply units, the one can be supplied with alternating current and the other with direct current. It works perfectly.

The project has investigated whether industrial robots can be supplied with direct current. According to one of the manufacturers, it is not possible without modifications to both hard- and software in what they call their drive units and control equipment. It is our opinion, however, that the necessary modifications are limited. This manufacturer has been extremely correct and obliging and has answered our questions promptly. Nevertheless, a project in collaboration with the manufacturer is necessary. The other manufacture has not been willing to answer our inquiries and requests for a meeting, despite repeated reminders.

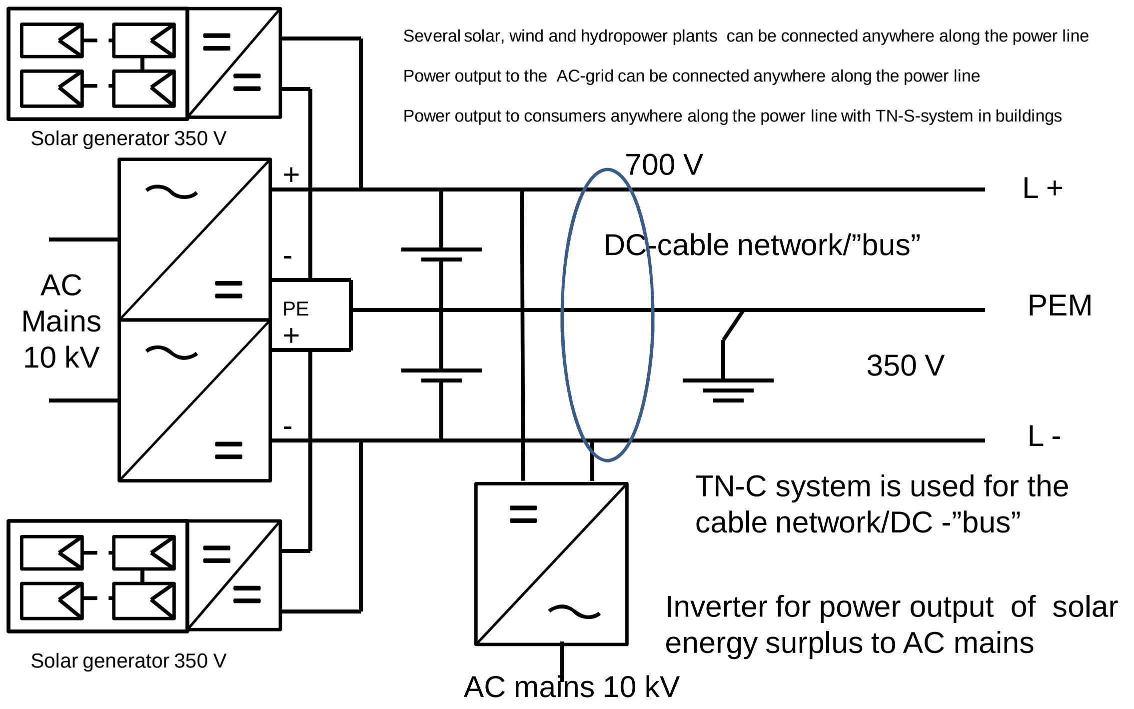
With regard to power supply of asynchronous (induction) motors for fans, pumps and compressors, these are of a different type than in industrial robots and are simpler to run. The project has successfully test-run single-phase-fed fan motors with direct current instead of alternating current. Their frequency inverters have been fed partly on their input so-called DC-intermediate link and partly on their AC input; see video references. Larger frequency inverters for larger motors for 3-phase connection can similarly be fed in their DC-intermediate link. This is most often taken to connection blocks on the frequency inverter and easily accessible for connection of DC voltage. The voltage must, however, be stepped down to 560-600V DC from the 700-volt level in the proposed DC power grid. This is neither a large nor a difficult measure, such regulators are not difficult to make. A modified solar regulator can be used.

The project has been in contact with a researcher at Philips in the Netherlands. This person has shown a great interest in the project. Philips conducts similar studies and has theoretically analysed the introduction of a DC power grid in a large shopping centre in Berlin. It has been shown there that, besides energy savings, about half or more of the cable material, the copper area in the wires for installation, can be saved.

If the proposed network is built in Hillringsberg, it may be a platform for several research and development projects in the field of DC use in electricity distribution, in micro-grids and in alternative energy, both in Sweden and internationally. To our knowledge, there is no corresponding DC-network project elsewhere in the world.

DC–cable network at Glava and power station at new cowshed

DC –network design main voltage 800 V, 2-phase +/- 400 V
Operational main voltage 700 V, operational phase voltage 350 V



Several solar, wind and hydropower plants can be connected anywhere along the power line

Power output to the AC-grid can be connected anywhere along the power line

Power output to consumers anywhere along the power line with TN-S-system in buildings

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Inverter for power output of solar energy surplus to AC mains

See specification IEC 60364-1 chapter 312,313 and 314 and 132.6 etc.

1 The difference between AC and DC in distribution networks and building networks with integrated energy storage

1.1 Advantages of DC

1.1.1 Direct current is a better product than alternating current

- Almost all loading to the electricity network is already or will increasingly be electronic, which is due to the general technical development in the electronics field and the need for high energy efficiency in use of electricity.
- The electricity network is not designed for electronic loading, since it did not exist at the time the electricity network was built.
- Breaking off power to electronic loads is not associated with arcs and nowadays is equivalent to cutting off alternating current; see ref [video 1] Breaking off direct current to electronic load. This is because all electronic loads contain an energy store in internal capacitors in the appliance, which means that no voltage surge that can cause an electric arc occurs across the break.
- The interface between the electricity network and the load, i.e., in today's low-voltage distribution with substations or electrical installations in buildings, is not adapted to modern electronic loads, and are not as efficient as they might be. This leads unnecessary energy losses and costs, disturbances, electrical environment problems, harmonics, magnetic fields, higher appliance costs, etc.
- Substations and low-voltage distribution need to be modernised, made more efficient and adapted to modern conditions.
- Almost all modern appliances are universal voltage and current appliances and can be fed from both AC and DC power grid.
- Electrical appliances can be made more efficient and cheaper if they only need to have DC/DC converters instead of AC/DC converters in their power supply units (PSU)

1.1.2 DC in electrical applications offers 20 advantages compared with AC.

DC at 350 V enables the following:

1. **Between 5-30% higher energy efficiency (or saving) compared with AC, depending on the application.** Depending on the comparison, very different results can be obtained. In a comparison between AC and DC for a computer room with cooling system (in today's standard design) it may be 30%. In a house property, however, it is perhaps only 5%. Nevertheless, if we include solar cells in the calculation, the added solar electricity can lead to a much higher saving in a house property. The same applies to the computer room. The reduction of losses and higher efficiency depends mainly on the 1,5 time higher RMS voltage, the proportionally lower current and higher efficiency in power supply circuits in appliances as they can be made more efficient. We never land on the minus side and we have all of the other advantages of DC.
2. **Lower consumption of conducting material such as copper and aluminium in distribution cables.** An evaluation of AC and DC in building networks has been made by Philips in the Netherlands [1]. The evaluation shows that, given the same standard voltage drop of 5% and thermal limits, DC gives 37% of the AC copper area when comparing single-phase 230V AC and 380V DC, and 44% of the

AC copper area in a corresponding comparison between three-phase 380V AC and two-phase 760V DC, i.e., +/- 380V DC. Even if for practical reasons the use of conductive materials cannot be fully reduced, a reduction of the continuous energy losses in the distribution systems is achieved.

3. **With lower losses in high-voltage connection (10 kV) of the rectifier station and use of non-insulating rectifiers, one transformer step is saved, which yields better total efficiency**. So far, rectifiers with insulation between the primary and the secondary side have normally been used for low-voltage power feed in DC installations, for example, in the electricity network switchgear 220V DC or the telecom network 48V DC systems. The efficiency in the substation transformer (0.98) in series with that of the rectifier (0.95) will then total 0.98x0.95=0.93%. Here a doubling of the insulation occurs. One of them is unnecessary and can be removed if the rectifiers are made non-insulating (0.97) and are mounted directly on the substation's 10kV connected transformer (0.98). This constitutes gives rise to a 10kV AC 400V DC substation and the secondary side earthing can be done on the DC side. The efficiency will be in total 0.98x0.97=0.95%.
4. **It filters dips and brief power cuts even without battery back-up with the help of the rectifier's capacitors and Power Factor Correction (PFC) technology**. In a normal AC power grid, particularly in rural areas, voltage dips with a duration of 100-200 ms and varying voltage reduction ("under voltage") occur on average 20 times a year. See ref [2]. These are caused by high voltage switchgear operations, often in connection with thunderstorms, but may be due to other events in the electricity network. The dips spread over very large distances in the whole electricity network. The energy storage built into the rectifier switch capacitors allows sufficient bridging to remove the disturbance on the DC side from most frequently occurring dips. If batteries are used in the system, as recommended, the dips or "under voltage" from the AC feed will be eliminated completely and never cause problems in an industrial robot or industrial process, for example.
5. **It protects against transient "overvoltage" from sources such as lightning**. In the same way as in connection with dips, rectifiers and batteries protect against transient "over voltages". The transformer in the system should be equipped with transient protection.
6. **No harmonics into the electricity network.** The rectifier takes the sine wave current from the electricity grid. The rectifier station (10 kV AC/400V DC) is equipped with technology that removes most of the harmonics by means of PFC technology.
7. **It delivers steady voltage when the AC mains supply is connected**. The rectifier can regulate both the over- and "under voltage" of the supplying AC mains. This is done using PFC technology. The DC power grid voltage in normal operation is then very steady and not dependent on AC-voltage variation. Voltage variations in loading points after rectifiers and batteries are only a result of voltage drops in the cables in the event of load changes. If batteries are to be used for diurnal peak-shaving to save energy and use solar electricity during evenings and nights, the voltage will fall due to the permitted degree of discharge in the batteries. However, most electrical appliances can cope with the large variations in voltage that normally occur during battery discharges.
8. **It delivers flicker-free voltage**. The DC voltage will be steadier than AC voltage for the reasons listed above. Flicker arises from rapidly varying voltage to incandescent light bulbs. Flicker will no longer be a large problem, since incandescent light bulbs are about to be forbidden.
9. **It delivers noise-free electricity.** The DC voltage has zero frequency and cannot set off vibrations in lighting fixtures or other appliances. The AC voltage has a frequency of 50 Hz and in many installations and appliances, low-energy lamps or light tubes the 50 Hz causes vibrations, which in varying degrees give rise to a humming sound or more or less intense noise. Even if the noise is not

loud, it is always present, is more or less audible and creates hidden stress, which affects different people to different degrees.

10. **It reduces leakage currents and stray currents outside the earth wire in building systems for heat, water and drainage, and building framework.** These currents to building frameworks, pipe installations and district heating pipes cause circuit breakers and fuses to be triggered inexplicably. The reduction is due to the fact that no harmonics occur and high-frequency currents can be reduced through filter capacitors more easily with DC.
11. **It reduces the risk of undesirable magnetic fields.** Magnetic fields in buildings arise because currents travel above all in different pipe systems as described in 10.If these currents disappear, this reduces the risk of magnetic fields in the buildings.
12. **It delivers EMF-free electricity—**Electromagnetic fields may be fields with both low and high frequency. To reduce these, capacitors are used in appliances. When using direct current, it is much easier to filter and attenuate these fields at source.
13. **It reduces the requirement for transmission of reactive power**. Today, the power grid must transmit what is called reactive power. This power is of no use but requires “space” in the electricity network. Major electricity customers are forced to pay for the reactive power they produce. Residential customers are exempted from paying for reactive power. However, the network provider sometimes has to install equipment to compensate for reactive power in the electricity network and this cost is still borne by the customer in the form of a network charge. To achieve the most efficient and problem-free operation of the AC power grid, it should be loaded with a load that is as close to resistive (cosphi=1) as possible. This is done with PFC technology in the electronic load (there are also other methods). PFC technology should be used in the small and large rectifier stations. This reduces phase shifts and harmonic currents that give rise to reactive power in the electricity network. It allows the supplying AC power grid to cope with the small amounts of reactive power that still occur without special measures.
14. **Uninterruptible operation with battery backup and customised battery standby time**. In a DC power grid with what is called a “DC bus”, batteries can be connected in parallel anywhere, but with certain safety precautions. Then what is known as a UPS function arises for critical loads in the event of power cuts. This UPS function is considerably simpler and cheaper than the present-day AC UPS.
15. **Delivery of peak power from local batteries, which means that the electricity network can be dimensioned for the average power and not for short-lived and infrequent peak levels.** The closer a battery is placed to a large peak power load, the better it is in that respect. An example for a house or flat with a 20A fuse or breaker:
    a. Cooker/oven 5 kW
    b. Microwave oven 1 kW
    c. Dishwasher 2 kW
    d. Vacuum cleaner 2 kW
    e. Washing machine 2 kW
    f. TV, computer, lighting 1 kW
    Total: ~ <u>13 kW peak power need</u>
    g. It should be possible for everything to be on at the same time, or the fuse will be triggered. If there was a battery in the basement, the peak power could be taken from the battery for the cooker, for example.
    h. A large normal household consumes, let’s say, approx. 6 000 kWh for household electricity a year. This is 500 kWh a month (6000/12=500) and the average power is 500 (kWh)/30x24(h)=0.7 kW, i.e., 3 A average current at 230V AC (3x230=690W).
    i. Cable networks for distribution to electricity customers with battery storage can be dimensioned for considerably lower peak power than is practised at present.

16. **It integrates solar cells simply and efficiently on both a large and a small scale.** Regulators for solar cells need not be inverters and therefore achieve a higher efficiency, since DC/DC converters are simpler designs. Solar cell arrays can be scaled up simply through simple parallel connection to a battery and the mains supply. Solar-cell-fed DC power grids can be automatically operated in what is known as islanding mode, and can easily continue to deliver current in the event of a power failure, something that solar-cell-fed AC power grids with so-called network-commutated inverters are unable to do.
17. **Easier management of rapid voltage variations in the event of rapid changes in solar power.** Batteries in the system can quickly equalise rapid power surges and give a more stable voltage in the event of surplus solar energy.
18. **Backup of IP telephony and Internet communication in the event of power failure.** This plus factor is not directly associated with the difference in properties between AC power grids and DC power grids, but is instead a plus factor bound up with changes in the telephone network and its technical development. It *is,* however, associated with the possibility of simply connecting standby batteries. The old analogue telephony in the telecom network is being phased out and will be replaced by what is known as IP telephony or Internet Telephony, where PCs and smart mobile phones take over the old role of the telephone. The old telephone has an integrated emergency telephone function which consists of what is known as the central battery of the analogue telephone system. It enables the telephone to function even in the event of very long power failures (maybe 12 hours). The new telephone system is made up of a series of mains-fed switches and routers and radio transmitters in the buildings, and there is no central battery in the system. In the event of power failure, therefore, the new system stops working. This is not good from society's point of view, since it is important for security in the community that telephony functions precisely in the context of electrical power cuts. In this respect, increased use of DC contributes to enhanced security in the community.
19. **Lower requirements on the public AC electricity grid in most respects.** This is particularly the case for voltage regulation and other power quality factors
20. **It reduces the vulnerability of society.** Lighting, telephone and computer communication and Internet traffic can more easily be maintained in the event of power failure in the AC power grid. What is known as island operating mode with local energy production can more easily be arranged. This reduces the vulnerability of society generally in the face of different crises, and can make it more sustainable.

1.2 Two disadvantages of DC:

- Direct current (DC) has no zero crossing and automatic electric arc extinguisher such as alternating current (AC) has. This may cause a higher fire risk. However, AC also has a problem with electric arcs. In the US, electric arc detection and disconnection of electricity is a requirement for installations in bedrooms in a similar way to the earth fault monitoring and disconnection (Residual Current Disconnect) of electricity we have in Europe in wet areas, kitchens and bathrooms. Earth fault monitoring and disconnection (RCD) is nowadays a requirement in new buildings and rebuilding projects for all electrical installations on premises for what is termed public use. In aircraft with extensive DC power grids, electric arc detection has long been in operation. In building installations, loose connections in junction boxes and distribution boxes can occur both in AC and DC systems. In both cases, electric arcs can be a problem and cause fire or disturbance. There are already products for dealing with the problem of arcs, and new ones are under development in many places, mainly for the installation of solar cell systems. Standards for electric arc protection in solar cell equipment are being drawn up in the IEC after a number of major fires in solar cell systems. Products for installation in test equipment such as that in Glava are available.

- The rupture or breaking capacity in standard fuses and standard circuit breakers is lower than for AC. (This is in fact a consequence of DC not having a zero crossing). A lower short-circuit power must therefore be chosen in DC systems than in AC. For example, battery banks should not be too large. Large batteries give large short-circuit currents, and these must not be larger than the fuses are able to disconnect. It is also good for safety reasons in the case of accidents not to have too large energy storage concentrated in one single point. Since it is easy to connect in parallel and plug in batteries to direct-current systems, these should instead be spread out in the system. This is also entirely in line with the advantage of peak power equalisation as close as possible to the load according to point 15 in the section on advantages. Here, it is a case of considering this difference between DC and AC when doing systems engineering, and calculations for dimensioning and design. This is not a problem in practice, since the short-circuit power in normal equipment is not limited for dimensioning and design of DC power grids. Cost advantages for large batteries are limited if all costs for handling heavy units, etc., are factored in. The purchase price of large batteries is not always lower per Ah than smaller batteries.

2 Possible realisations of the micro-DC power grid in Glava

2.1 General

With regard to solar and wind power, these types of energy are already naturally distributed. Production and consumption can and should, therefore, be as close to each other as possible. These generators should thus be placed near the largest points of consumption, where this is practical and efficient. There is no reason to transmit electricity from these generators over long distances as is the case with hydropower, for instance, since waterfalls cannot be moved. Distribution of solar and wind power via the electric power grid only involves unnecessary network installation costs, energy losses and operating costs. In the same way, energy storage should not be centralised but distributed and placed as close to the largest peak power loads as possible, in order to deliver peak power locally. The batteries should be dedicated to their respective building or critical load which requires uninterruptible operation, such as data centres, industrial processes and communication equipment, important computers, or appliances with high short-term peak power such as cookers in households. The dedication can be achieved using back diodes so that the battery can only deliver current to its respective critical load. This means then that the electrical grid, which combines and distributes electricity in a community, for example, need not be dimensioned for extreme peak power loads but rather for distribution of average power to achieve equalising in different loading situations. In the case of a DC power grid in Glava, there are good conditions for applying this approach in practice.

The planned new cow shed with its large solar generator on the roof is situated at one end of the planned network and may consume a large part of the solar energy produced there. Close by is a 10 kV electrical mains connection and the possibility of supplying surplus solar energy over a short distance to the 10 kV AC power grid. A storage battery should be placed at this location.

Along the intended network, near the middle, there is already a solar generator, which is to be expanded to one-third of the power planned for the new cow shed. This solar generator is close to the solar cell factory. Here, a wind power plant is also planned. The electricity produced by these solar and wind generators can be consumed in the solar cell factory. The solar cell factory might need additional power and this can be taken from the larger solar cell plant at the cow shed via the DC power grid. A battery storage unit should be located in the solar cell factory to shave the peak power during operation in the factory and provide uninterruptible supply to critical parts of the process.

In the far end of the network are the manor house and its conference building along with the old cow shed with the farmhouse. Furthermore, there are a number of residential buildings and various other types of building near the pond. The plan is to bring a small hydropower plant there into service again. The hydro/pump/power plant could also be used for supplying to the DC power grid. The power plant could then be used to deliver electricity at night-time when the solar generators are not delivering electricity, if it were possible to use the pond as a diurnal peak-shaving energy store. A smaller battery storage unit should be placed in the manor house and in the residential buildings. It should be possible to mount solar cells on roofs of some of the buildings in that part of the community, e.g., on the roof of the old cow shed, and in this way achieve a balance so that solar energy could be produced in this part of the network as well.

By spreading the feed-in to the DC power grid along its full length, the network need not be dimensioned

In the same way as a radial network, where infrequently occurring peak power could be transmitted the whole way. The feed-in to the DC power grid with rectifiers from the AC power grid should be possible at several places, preferably at the solar cell plants or in the factory or where it is suitable considering where the AC cables are laid. For this reason, the DC power grid should be regarded as a DC power grid/”bus” and not as a radial network for feed-out of electricity from a single feed-in point to different points of consumption.

The dimensioning calculation of the DC power grid/bus should be possible to do with the focus on average power rather than peak power. Factors to be taken into account are natural variations in supply of solar, wind and hydropower and variations in operational load needs - day and night, - high and low production in the solar cell factory and cases of fault, etc.

In the discussion on use of DC in comparison with AC, we should consider using DC where its advantages outweigh those of AC and vice versa, and be open to using both in so-called hybrid systems. Particularly in existing plants, going over totally to DC may incur high costs, since all the appliances and equipment are built for AC. However, a transition to DC should be made where it is simple and where it means advantages, for example, in the form of better energy efficiency or where disturbances in critical/robot processes can be reduced. For instance, high-power heating units in the laminators in the solar cell factory should be fed with existing AC, since these cannot be disturbed by dips and short power cuts. However, computer systems and control systems for robots, which cannot take short power cuts without data loss should be fed by DC. The power needs for sensitive computer and control systems are usually less than for heating systems. Parallel building networks (know as hybrid networks), one for DC and one for AC, are fully acceptable both technically and in terms of electrical safety. Making conditions safe and manageable is mainly a matter of clear marking and of training of electricians.

By building new electrical networks and using existing networks in this new way, what is known as “premium electricity” for business-critical needs can be created. A DC power grid should be built as an independent micro grid, which, in the event of major power cuts, can automatically switch to island mode and with limited power deliver electricity to high-priority and sensitive loads. Possibly, standby power plants can be included if the need arises. The price for premium electricity must be possible to set higher than for household electricity for non-critical use, for instance, if it were to be provided by an electricity company.

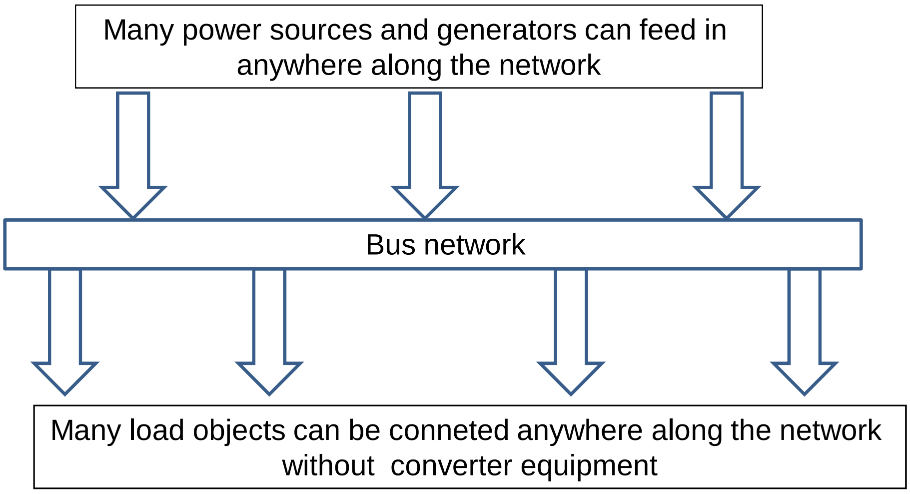
2.2 An Edison network +/. 350 V DC with main voltage 700 V DC

DC systems were the standard systems for electricity distribution in all countries before alternating current was introduced. Edison’s two-phase distribution system with earth wire and a voltage of +/- 220V DC was used. An example of this is seen in the tender from ASEA to Granbergsdal Farm north of Karlskoga in 1905, signed by ASEA’s managing director for many years, Sigfrid Edström. The tender was for an electrical power line of 2x220V for direct current from the power plant in Sågfallet to the farm for running electric motors [13]. See also the government decision in 1906 on permission for such an installation signed in a Cabinet meeting by Crown Prince Gustav, later King Gustav V [14-15]. The last systems of this type were shut down in Stockholm about 1970, and the last DC power grid in New York was shut down as late as 16 November 2007.

Within electrical distribution, it is essential to use as simple, robust and disturbance-insensitive technology as possible in order to achieve high reliability and low maintenance costs. The Edison system meets these requirements and may experience a revival in a modernised form.

It is now highly interesting to study and test this system again in practice with the design voltage level +/-400V in conjunction with so-called micro grid development with local generators. This allows bi-directional energy flows to be managed without special equipment. This means that generators, battery storage and load can all be connected directly to the network. A network of this kind can also be called a bus network.

Bus network principle



This can save a lot of energy, give better quality electrical quality and reliability and save cabling costs compared with three-phase AC system, for example [1]. The design voltage level 400 V is adapted to the voltage that all electronic loads can use with the highest energy efficiency. This voltage level is already in use in what is called the intermediate DC link inside of all electronic appliances. The operational supply voltage is set at a lower level. In the Glava network +/- 350V and main voltage 700V are proposed.

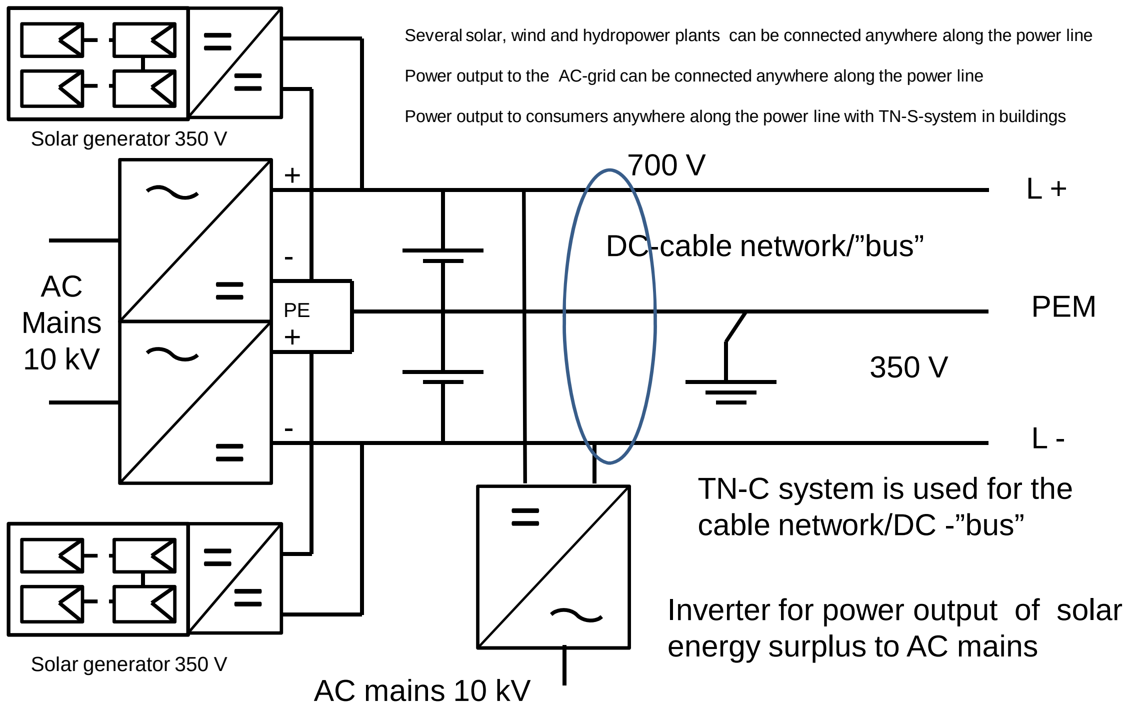
The problems one had with the Edison system when in use are associated mainly with current breaking. With modern technology this has been solved with the introduction of power electronics. Current breaking has become almost trouble-free. Semiconductor technology in general will further enhance the possibility of utilising the advantages of the DC system by enabling the development of new products that increase safety. Present-day insulating materials allow higher voltage than earlier without increasing the risks and thereby obtaining better energy efficiency. According to the visions of Philips and other manufacturers, mechanical switches will be replaced by semiconductor switches and touch control in ordinary electrical installations, as an example of new products.

The system has no transformation losses or cooling losses as in other systems for higher system voltage, for example [3], or in a superconducting system where constantly working cooling compressors are needed. In comparison with these, therefore, it will be very simple, reliable and efficient. At the power level under discussion in this project the system will be the optimal solution.

The system is very simply constructed. The main diagram is clear from wiring diagram 1.

DC–cable network at Glava and power station at new cowshed

DC –network design main voltage 800 V, 2-phase +/- 400 V
Operational main voltage 700 V, operational phase voltage 350 V



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Inverter for power output of solar energy surplus to AC mains

See specification IEC 60364-1 chapter 312,313 and 314 and 132.6 etc.

Wiring diagram 1

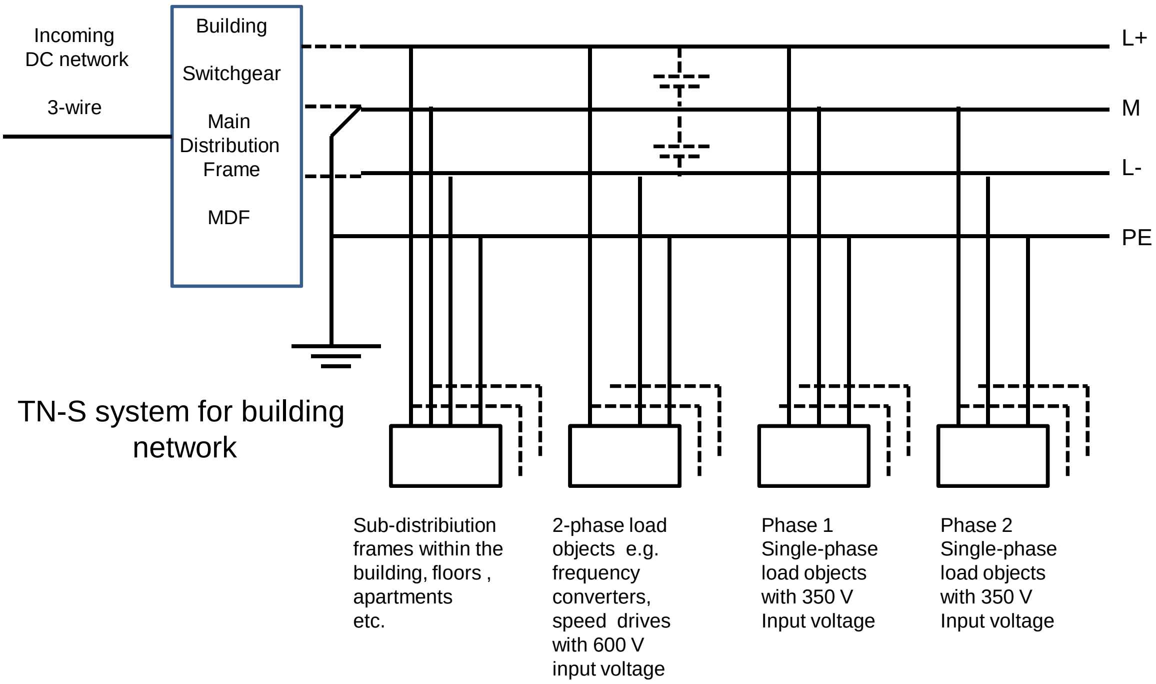
Along the cable bus, tap-off boxes with defusing to the switchgear and distribution box of the loading object can be mounted anywhere. Rectifiers and solar cell generators can similarly be connected anywhere after the cable. All of the generators have tuned constant output voltage and deliver power according to need at the time. Power that can be delivered in excess of this is fed into the batteries or out to the AC grid. The voltage on the DC bus can vary between 300V – 350V phase voltage and 600V – 700V main voltage.

Inside the buildings, two-phase residential networks are installed according to wiring diagram 2, or single-phase networks according to wiring diagram 3.

With regard to the proposed system solution and relevant IEC standards, see also Safety and Interoperability of DC Power Grid Systems [21], with a list of IEC standards. This preliminary document presents the same system solution as UPN does. (It is added to the present investigation after consultation with its author).

Building Networks in new cow shed and solar cell factory etc.

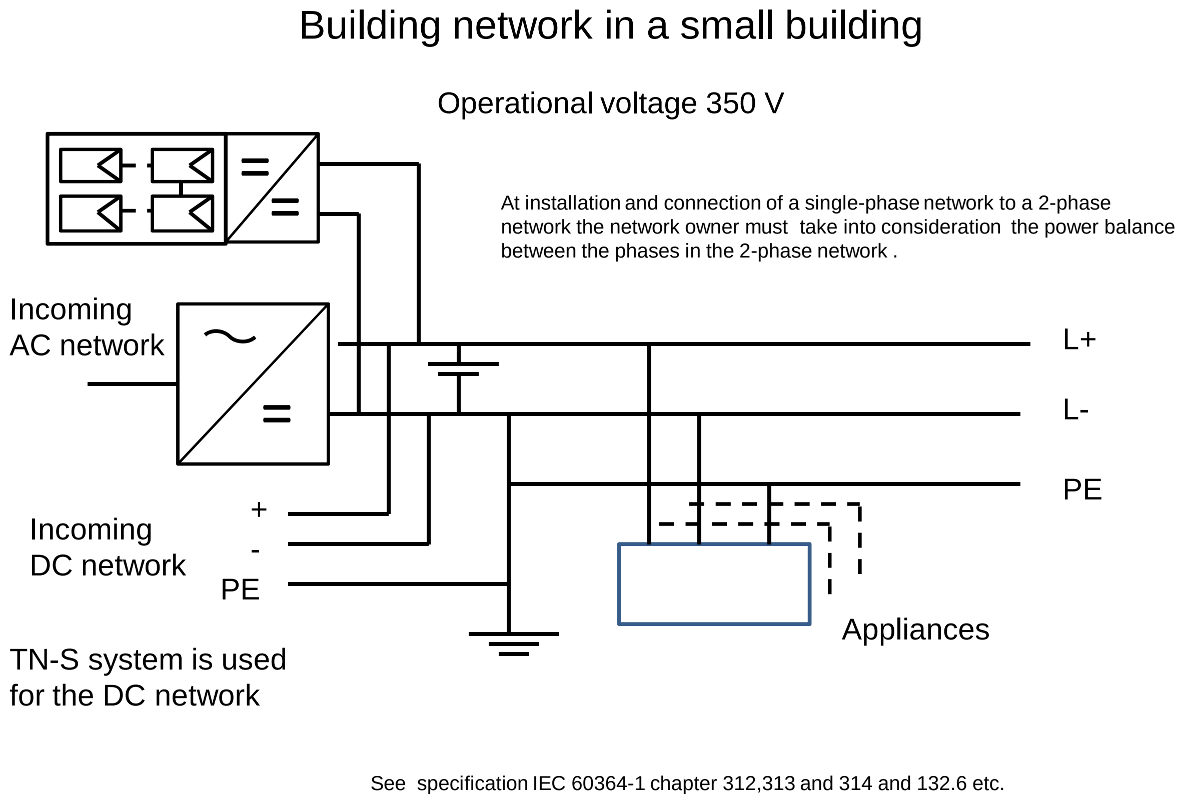
Operational main voltage 700 V, phase voltage 350 V



See specification IEC 60364-1 chapter 312,313 and 314 and 132.6 etc.

Wiring diagram 2

In smaller buildings, “only” a 400V branch of the network according to wiring diagram 3 can be installed, if preferred. In this context, however, the network owner must consider and take into account any uneven loads in the earth wire and the core cable of the two-phase main network. Furthermore, the network owner must keep a check on the earthing in the building always alternates between plus and minus. Otherwise the peak-shaving along the main line will not take place. This may be an administrative difficulty and safety risk. Therefore, bringing in the main voltage to the distribution box for the building might be considered, and also distributing the loads inside the building as evenly as possible to achieve the desired distribution so that zero current in the neutral wire can be achieved as early as possible. The problem is then shifted to the building, where the polarity check must be made during the installation. All wires are colour-coded and the sockets are “keyed” for the right polarity



At installation and connection of a single-phase network to a 2-phase network the network owner must take into consideration the power balance between the phases in the 2-phase network .

See specification IEC 60364-1 chapter 312,313 and 314 and 132.6 etc.

Wiring diagram 3

2.3 400V DC power grid single-phase

A “single-phase” 400V DC power grid cannot be implemented as a village power grid with 1.2 km total length and with the power required in Glava-Hillringsberg. The electrical range in such a grid for the power in question can in practice only be about 400-500 metres.

However, a 400V DC power grid is naturally the single-phase part inside the building of a “two-phase” DC power grid and is its natural sub-network in the same way as single-phase AC is in the three-phase power grid.

2.4 1500V DC power grid with AC/DC transformer station as in “Lappenranta”

This system is described in [5], [6], and [7] and also in [3]. It is claimed that AC/DC transformer stations and DC/AC inverters could reach 98% efficiency, and that an efficiency of 95% has been achieved today. The de facto efficiency for rectifiers and DC/DC converters with built-in insulation with an HF transformer is 95-96% in optimal operating mode. It is very difficult and costly to reach higher than this, and reaching 98% efficiency with transformer insulation and semiconductors on both sides of the transformer.. The article in [3]claims that even if the losses in the DC/DC converters can be halved compared to today’s technology, the losses will still be greater than in a traditional electrical distribution system. The best normal low frequency transformers have about 98% efficiency.

In summary, after quickly reading through the reports, the losses in the outlined HF DC/DC converters at the present time are at least approximately 5% in their best operating mode. This agrees with what the best technology for DC/DC conversion can offer. It is possible to reach a higher level for rectifying if expensive components can be used, such as transistors and diodes made of silicon carbide and amorphous material for the transformers. In real operation, most of the time the system will only have loads far below peak power where the best efficiency occurs. With only partial load in the converters, the efficiency falls below its best and will end up at maybe 90-93%.

Without having done any LCC calculation and comparison with a bipolar 700V system for a village power grid similar to that for Hillringsberg, it can be assumed that the system as a whole will be more expensive. For transmission in a more classical electrical distribution context and with longer distances, the system may be competitive. But the comparison must be made with available AC technology at different voltage levels.

The question is whether the system is not unnecessarily complicated with its higher voltage, which demands active electronics, which in addition will constantly generate losses. It will also be very vulnerable and sensitive to lightning strikes and/or lightning overvoltage from far away. The motive for investing in Lappenranta is most probably the problem of maintaining voltage levels in long rural cables. If, however, direct current is used in the buildings for voltage-sensitive loads, the cheapest solution would be with small constant-voltage rectifiers in every building. A small battery could deliver the peak power. Electric heaters that are not particularly voltage-sensitive could remain on alternating current.

The Lappenranta system is a high-technology track which can be questioned in an infrastructure system, which has to be very robust and reliable and also very easy to maintain.

The most important criterion for practical use in Glava is to choose a system that is suitable for enhancing the reliability in a process industry such as the solar cell factory in Hillringsberg.

The Lappenranta system is considered to be costly, vulnerable and not robust enough for this application. It is not recommended for testing in Hillringsberg.

2.5 Superconducting cable network for DC

In the initial discussions of the project, the idea thrown forward that maybe superconductivity could be worth trying. A superconducting cable has no noticeable voltage drop and in this project with low voltage can be independent of the voltage level chosen. A system for 400V “single-phase” could be built.

However, the products available are at the prototype stage and made for considerably higher power and currents than those that occur in Hillringsberg. The requisite ancillary system for cooling the cable also requires relatively high power. It is a high-technology system with ancillary systems for operation, which may be vulnerable and not reliable.

The goal of the project in Hillingsberg is to try to enhance the availability of electricity deliveries and reduce the disturbances in the solar cell factory processes.

Superconductivity is not recommended for the project in Glava /Hillringsberg.

2.6 Stability in the electrical power grid

In recent years, in the context of power quality, it has been discussed whether the prerequisites for stability, i.e. maintaining voltage in the AC electrical power grid are changing with the increased use of electronic load. Theoretically, there is a risk of what is known as self-oscillation or resonance between grid and load is the electronic load becomes dominant. The phenomenon can arise as much in alternating current grids as direct current grids. The PFC-electronic load has the property of drawing constant power regardless of voltage, i.e., it draws higher current when the voltage drops. In unfavourable condition the voltage would thereby begin oscillating rapidly and risk becoming much too high and damaging the appliances. Considering the earlier dominating non-electronic load the action is, when the power drops - the current drops. This provides stability in the system and keeps the voltage steady. See [10],[11] and [12]. This relationship is the fundamental and basic principle for the stability of the AC power grid.

Resonance may occur in LC circuits. The network represents an L (inductance) and electronic appliances represent a C (capacitance). It is important to ensure that L and C in network and load values cannot be tuned for resonance. The inductance in the network is well controlled, but there is no control over the magnitude of the capacitance that can occur in the load.

According to Torbjörn Thiringer at Chalmers University of Technology [12],no problems have been seen in Sweden as yet, even though this is being discussed and maybe seen in Finland. To check this, a calculation should be performed in connection with the detailed planning of the grid for Hillringsberg. Furthermore, it would be interesting to carry out a provocation test before the system is brought into operation to see how the network performs as regards resonance in reality with different experimental loads.

2.7 Discussion and evaluation

The basic aim of the project is to improve efficiency reliability and availability in delivering electricity and to connect local alternative electricity production in the most economic and efficient way within the distances to be found in the area. Superconducting cable networks for DC and single-phase 400V DC power grids can be rejected from the discussion as the system choice for an industrial and village network, micro-grid, in Hillringsberg in view of the basic aim.

The decision to recommend a two-phase so-called Edison network instead of a 1500 V DC power grid as in Lappenranta is motivated by the following:

1. An Edison network is completely passive technology. No active components such as DC/DC converters are needed to reduce voltage. This means better reliability, low losses and lower maintenance costs.
2. In an industrial and village network micro-grid with a diameter of approx. 2 km, it is most probably more efficient, more reliable and cheaper to use an Edison network than a Lappenranta network.
3. In the case of larger network diameters, with longer distances than 2 km, it is not considered possible to use the Edison system, because voltage drops and cable costs will be too great. As long as it is economically acceptable to replace DC/DC converters, which are active technology, with passive technology as with cable area, this should be done for reasons of reliability and maintenance. What are called normal industrial and village networks or micro-grids built as star networks rarely need to have a wider range than about 2 km in diameter. It should therefore be practical to build new “cells” with new feed-in points from high voltage. Solar cell feed-in should be spread over the surface at suitable places. Namely house roofs in the area.
4. A Lappenranta network is considered to be a typical network for rural area electricity distribution, while an Edison network is considered to be a micro-grid for more built-up areas.

If this proposed network is built in Hillringsberg, it could be a platform for several research and development projects in the area of use of DC in electricity distribution, micro-grids and alternative energy. As far as we know, there is no corresponding DC power grid project anywhere in the world.

3 Hydropower plants and pumped-storage plants as energy stores

3.1 General

The greatest difficulty in economically utilising alternative energy is the large random variation in power from solar and wind power. The consumption does not vary to the same extent. For alternative energy to be a sound economic proposition, cheap and efficient storage of large surpluses from solar and wind energy are highly desirable.

In Glava at Hillringsberg, there is a good chance of arranging an energy store through water storage. The surplus from the solar and wind power plants can be stored in water reservoirs as an alternative to feeding it out to the electrical grid. The dam for the hydropower plant and the old dams higher up the valley on the river Glasälven can be used as diurnal peak-shaving water reservoirs, or the lake, Stora Glassjön, can be utilised for seasonal peak-shaving. By increasing the water flow in the river Glasälven in this way, the energy production of the hydropower plant can be increased.

Pumped-storage hydropower plants can reach an efficiency of 75-80% electricity to electricity while battery storage can reach 85-90%. However, the storage capacity in the water storage structures, depending on natural conditions, can be made many times greater at considerably lower costs by comparison. The cost per kWh for solar energy storage in batteries is about 3.75 SEK/kWh, excluding the solar cells, as analysed in [14].

3.2 Energy storage for diurnal peak-shaving – rough estimate

A diurnal peak-shaving water storage structure could be arranged at the dam in Hillringsberg. The height difference to Glafsfjorden is 7m. Available water storage area is assumed to be 800x50m= 40 000m2. Assume 0,5m permitted water level variation. This gives 20 000 m3 or 20 000 000 kg water (G) for a head (h) of 7 m over Glasfjorden.

This corresponds to a potential energy and an energy store of Wp=Gxh= 20 000 000x7= 140 106 kpm. – [1 kpm=9.81 Ws].

Wp=140 106 kpm=140 106 9.81 Ws = 1.37 109 Ws = [1 kWh = 103 3600 Ws=3.6 106 Ws] 1.37 109 / 3.6 106 kWh= 381 kWh.

With 75% efficiency, approximately 286 kWh usable energy store for diurnal peak-shaving and half-a-metre water variation.

3.3 Energy storage for seasonal peak-shaving – rough estimate

A seasonal peak-shaving water storage structure could be arranged in the lake Stora Gla above Hillringsberg. The height difference to Glafjorden is 100 m. For the energy need outlined in this project, the variations in water level would probably be negligible. Available water storage area is assumed to correspond to a circle of 3.0 km = pi x 32 km2 = 28 km2 = 28 million m2. Assume 0.1 m permissible water level variation. This gives 2.8 million m3 or 2800 106 kg of water (G) for a head (h) of 100 m over Glasfjorden.

This corresponds to an energy store of Wp= Gxh= 2800 106 x 100 = 2.8 1011 kpm. –[1 kpm=9.81 Ws).

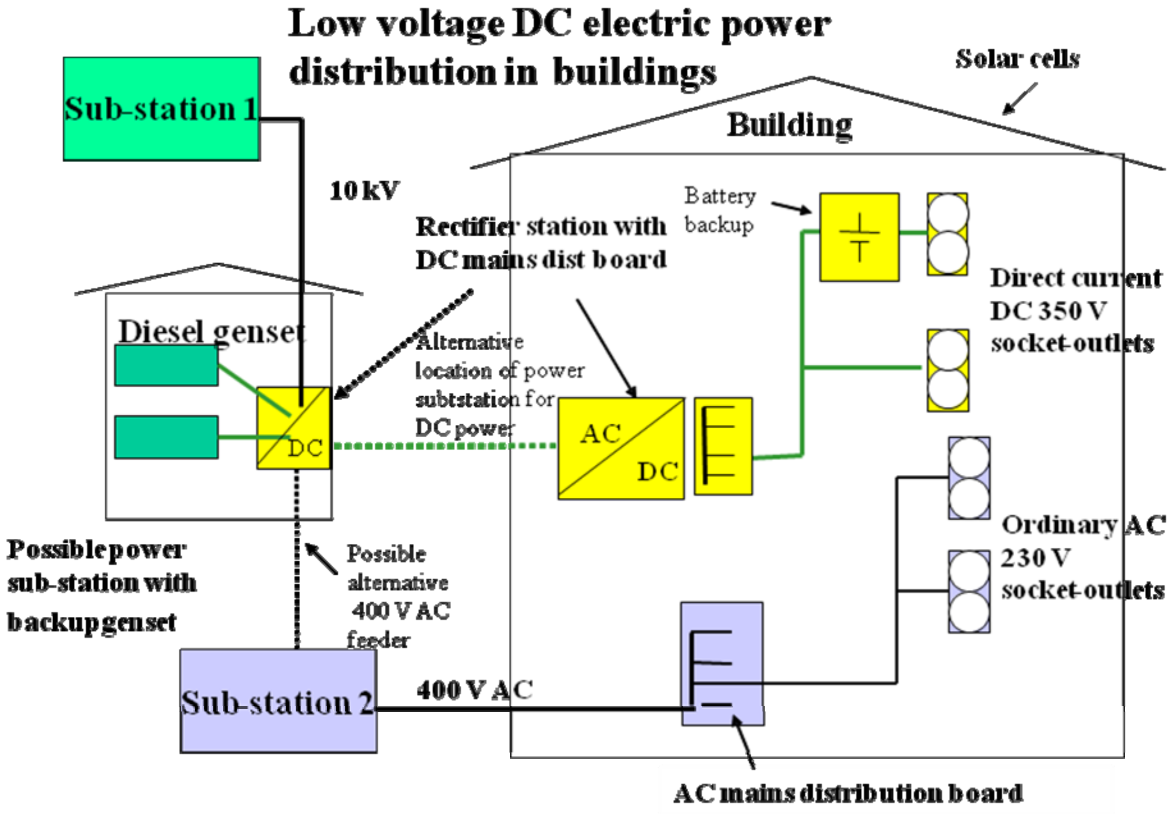
Wp= 2.8 1011 kpm = 2.8 1011 9.81 Ws = 27.5 1011 Ws.[1kWh = 103 3600 Ws= 3.6 106 Ws], 27.5 1011 /3.6 106 = 7.64 105 kWh = 764 000 kWh.

With 75% efficiency, approximately 573 000 kWh usable energy store for seasonal peak-shaving per dm of water variation.

Photographs of the dam and the old power station building.

4 Building Networks for 400V DC according to discussions in International Electrotechnical Commission (IEC)

4.1 General

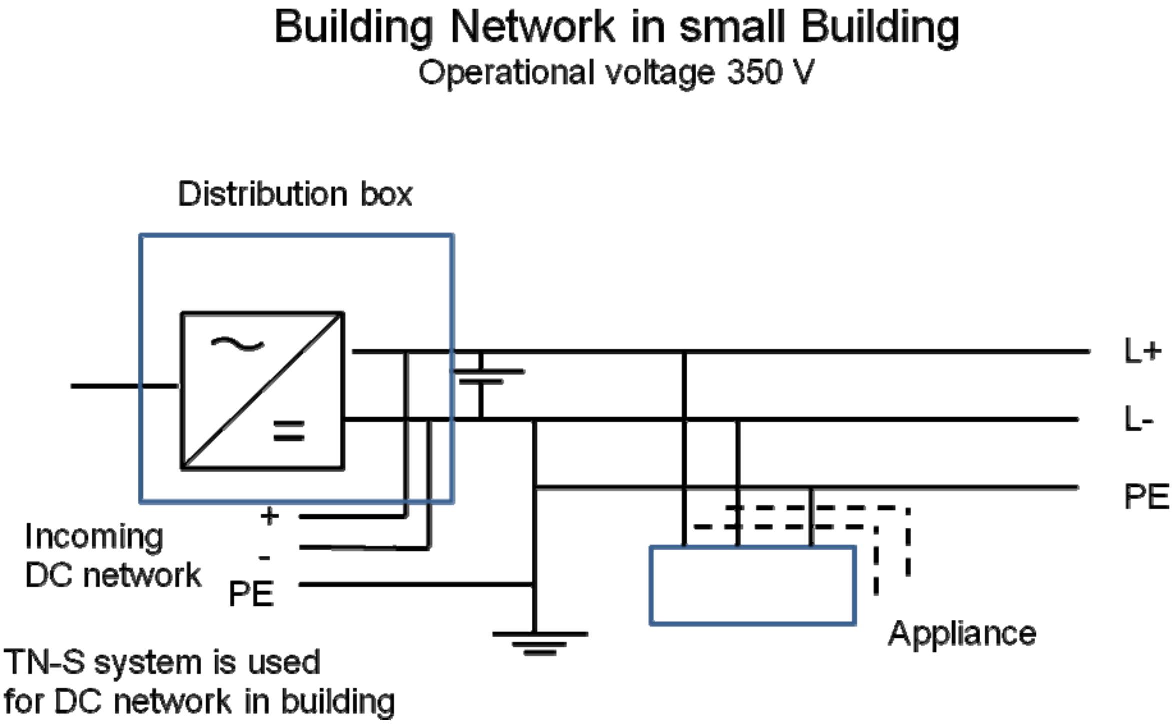


From distribution boxes with earth fault (RCD) and electric arc circuit breakers (Arc Fault Disconnect, AFD), building - networks are built in the same way as single-phase AC residential area networks. Standard installation cables can be used for 700V and 1000V. These can be used in both AC and DC systems. Dimensioning of the building network with regard to fuse size and cable area follows the same rules as for AC according to the electrical installation rules. In IEC, the introduction of electric arc detectors (AFD) with circuit breaking for both AC and DC installations is being discussed. There are already standards for this in solar cell plants.. However, particularly in DC installations in buildings this will probably be a future requirement. Products are available and new ones are also under development.

As regards fuses, circuit breakers and MCCB breakers for higher power are also available for DC. However, ordinary household melting fuses are the most suitable and cheapest choice in a smaller building network unless there are special reasons for the extra expense of circuit breakers. Melting fuses are a “relic” from the time, when DC was the standard before AC arrived. It is well proven and very safe and reliable. These fuses are certified for 500 V AC and DC.

With regard to circuit breakers and contactors, three-phase variants of these can be used in DC equipment via series connection of the three contact breaker units. Examples of electrical material for DC from ABB are to be found in ref [9].

For lighting purposes, the so-called DALI system with touch control and remote control and contactor control for switching on and off is recommended. Certain new wall switches are also about to be developed for DC for electronic loads. Low-energy lamps and light tube with HF ballasts can be used for 350V DC voltage.



The distribution box should contain Residual Current Disconnect (RCD) and Arc Fault Disconnect (AFD).

With regard to the building network in a cow shed, special attention must be paid to the corrosive environment with high ammonia content in the air. This applies to the use both of DC and AC.

4.2 Appliance and supply voltage of 350V DC or 380V DC

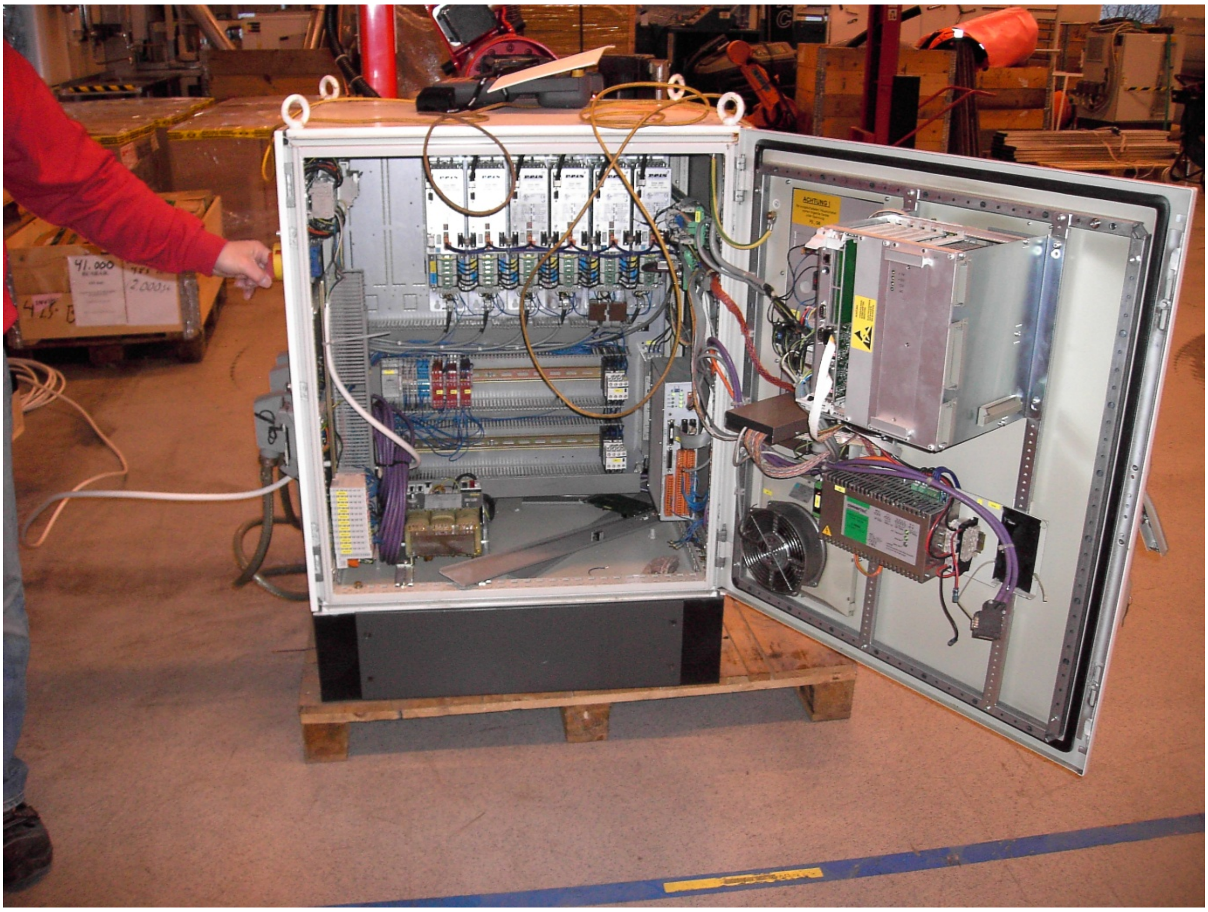
In the discussion on direct current feed, the issue of different voltages arises. A voltage of 400V is mentioned. This voltage is the design voltage level for which appliances and the grid must be designed. The desired operational voltage for use in the network or system is chosen below this level.

The International Electrotechnical Commission (IEC) and the European Telecommunications Standards Institute (ETSI) are discussing whether to choose a supply voltage of 350V DC or 380V DC. The present proposal recommends 350 V as supply voltage. A voltage of 350V allows today’s ordinary AC appliances to be connected to the grid. These are designed for standard AC voltage with its tolerances up to 375V DC voltage internally (240V plus 10% times the root of 2 = 375V). A supply voltage of 350V gives plus 7% tolerance, which is advantageous. If instead a voltage of 380V is chosen, ordinary appliances cannot be connected, only those specially designed for 380V DC. When in the future 380V DC appliances are available, these can later be connected to a 350V DC grid, since 380-volt appliances can, of course, be connected to the lower voltage.

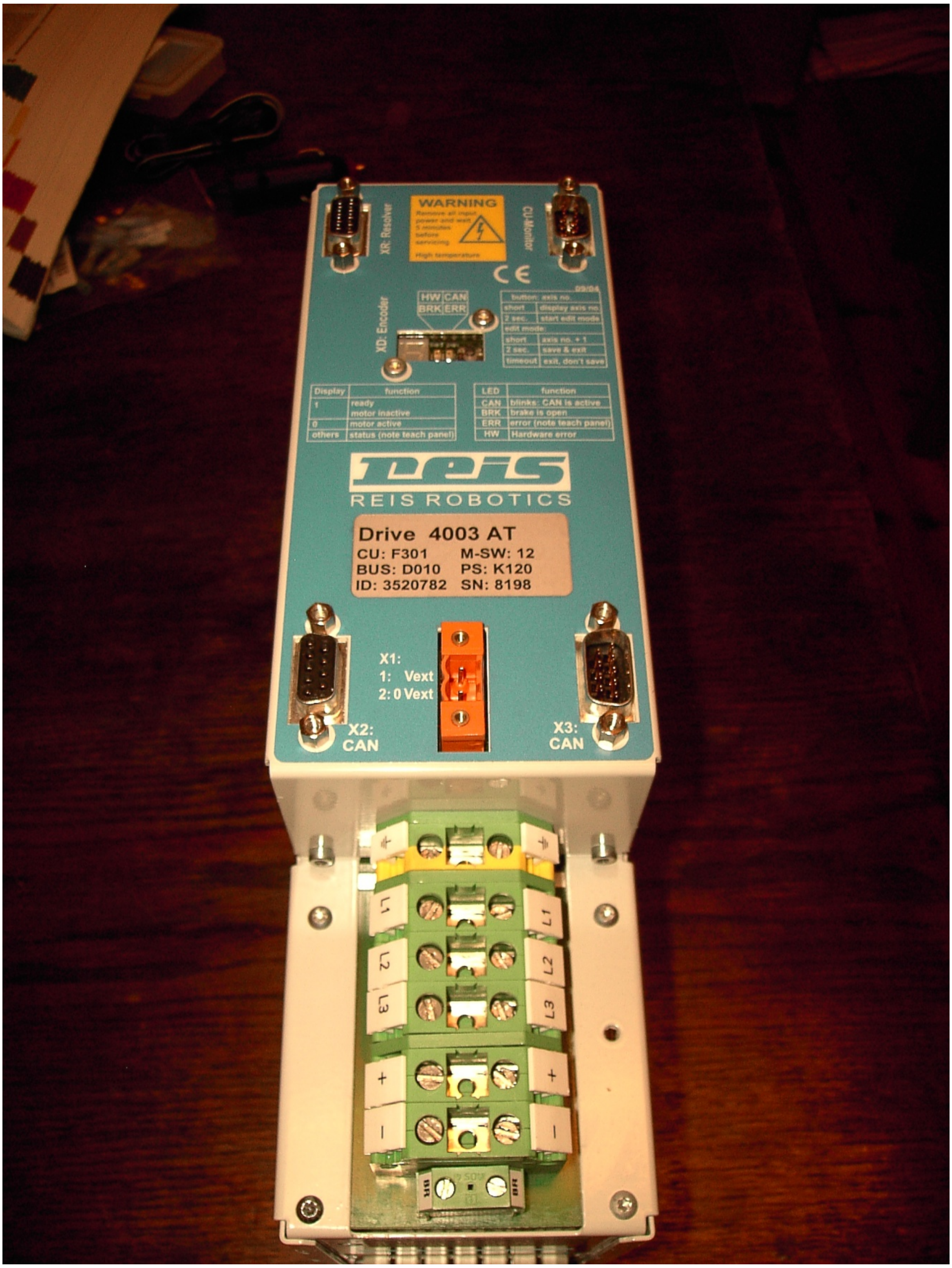
5 Power feed of the solar cell factory robots with 700/350V DC

In the solar cell factory, there are between 30 and 40 robots. About 20 of them are made by Reis Robotics, 10 are from ABB Robotics and the remaining four are from German KUKA. In the lines, there are also a number of automatic machines for different tasks, such as soldering machines. In the factory, there is also a free-standing robot from Reis outside the production lines. It has been used for training and practice purposes. On 22nd November, during a check-up of the electrical installations in the solar cell factory, the robot control cabinet containing all of the drive and control electronics was inspected.

At the top of the cabinet are six of the important drive units. On the lowest green connection blocks, the connection to the DC-link capacitors and their voltage is 600V DC is possible. These capacitors are the largest energy store in the drive unit.



Georg Berberich, Leiter Steuerungsentwicklung Hardware/Manager Control Development Hardware, Reis GmbH % Co. KG Maschinenfabrik in Germany, has been asked about the possibility of supplying the robot with 350V/700V DC (e-mail communication) [18].See also the operating manual and the technical manual, [19] and [20].The answer from Reis was that modifying the equipment for DC feed was not uncomplicated. It would have the scope of a minor development project. However, the details in the answer are open to interpretation. After close reading of the manuals in [19] and][20], it can be interpreted as meaning that making the necessary modifications would probably not be a particularly large project. It is more a question of costs for changing software so that certain watchdogs are disabled and possibly making certain hardware changes in the circuit boards in the drive units. None of this should be impossible for experienced electronics engineers to do. The drive units in Glava may be possible to use. What is needed is collaboration with Reis where the company under a non-disclosure agreement with Glava Energy Centre instructs us in making the required changes and is paid to make the necessary software changes in control parameters. UPN has the required competence to implement such a project in collaboration with Reis Robotics. Magnus Nilsson has expressed interest in rebuilding a line with robots and automatic machines to run on DC to compare them in operation with the usual AC feed.

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6 Power feed of solar cell factory refrigeration and ventilation systems and circulation pumps with 700/350V DC

In order to test the power feed of frequency inverters for running of induction motors with direct current in a systematic and controlled fashion, we visited Gunnar Englund and GKE Elektronik in Granbergsdal outside Karlskoga on 19 December 2011. Gunnar Englund and GKE Elektronik have world-leading knowledge of all the properties and problems of frequency inverters for drive systems in electric motors.

During the visit, an initial experiment with battery and direct current operation was to be carried out. At the same time, qualified registration of currents and voltages to the frequency inverter during DC operation and AC operation respectively were to be made to show and clarify the difference this would make to an electrical power grid for both operational cases.

For the results, which were very successful, see Motor inverter Granbergsdal [video 2]. The experiment shows that supplying a single-phase frequency inverter for 230V AC with 350V DC works excellently. Gunnar, who is an expert in frequency inverters, testifies that it should also be possible to supply a 400 V AC three-phase frequency inverter with direct current if the voltage is regulated to 560-600 V DC. This can be done from 700 V with a small DC/DC converter.

The next step in the testing was a test run of one of the fan motors in one of the ventilation units in an empty office in the solar cell factory in Hillringsberg. This test was performed on 10 January 2012. The aim of the test was to show that it is possible to feed the fan motor with DC without having to modify the complicated control electronics in the ventilation system. In that case, most of the energy for the ventilation and its motors is taken from a DC power grid, but the control remains on the AC power grid. Possibly, the control and monitoring electronics could be transferred later to DC, but this requires a more extensive effort to investigate. This test, too, was conducted successfully and a single-phase fan motor was driven by a battery with a voltage of about 300V; see [video 3], Solar cell factory fan room open, [video 4], Solar cell factory fan room closed

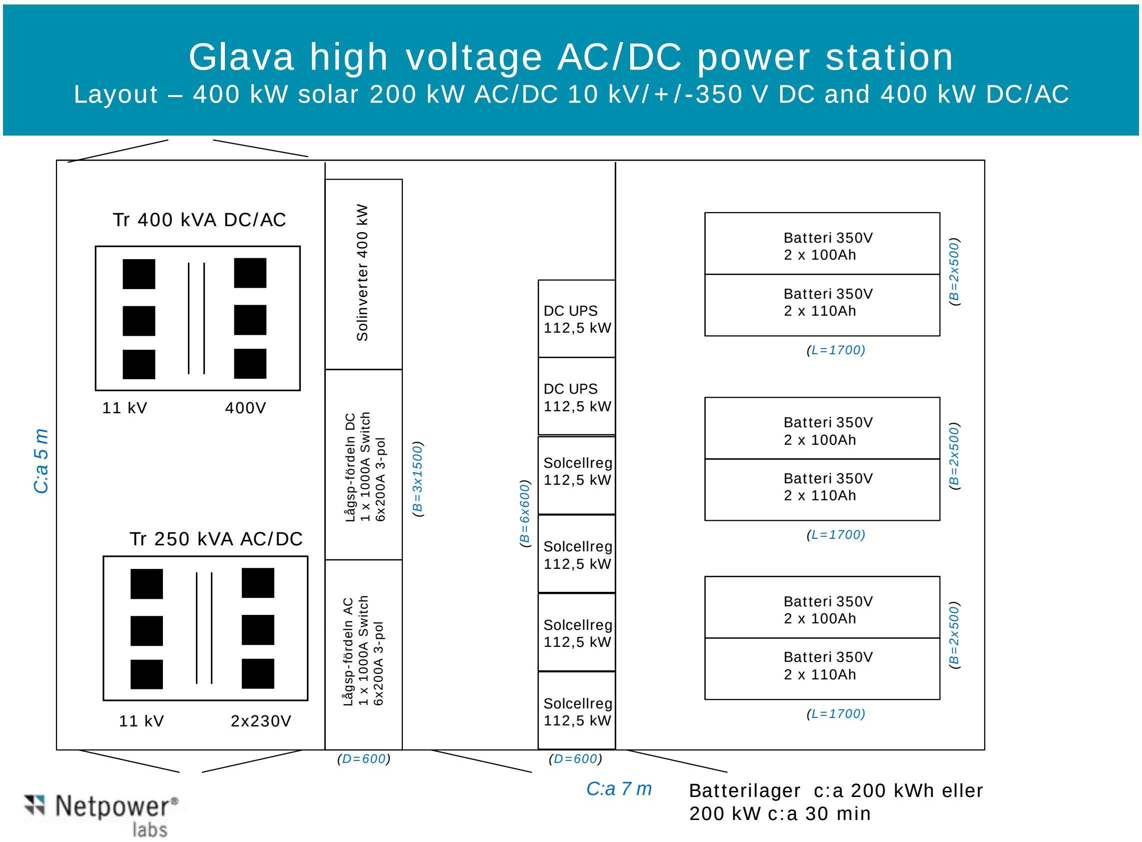
7 Power supply of the milking robots with 700/350 V DC

An interview with Bengt Johansson at Lely (telephone communication 070/3444781) shows that:

- The logic is current-fed with 24V DC. This allows its rectifier to be fed with 350V DC voltage.
- There is a single-phase frequency inverter. This can be fed with 350V DC.
- There is a three-phase motor that is directly def with three-phase 400V AC voltage with 3.7 kW power. It can be fed with a three-phase frequency inverter that can be plugged into the milking robot. A three-phase frequency inverter can be fed with 560-600V DC. With a small DC/DC converter, the 700V main supply voltage can be lowered to 560V. This DC/DC converter is a somewhat modified solar cell regulator for DC systems.

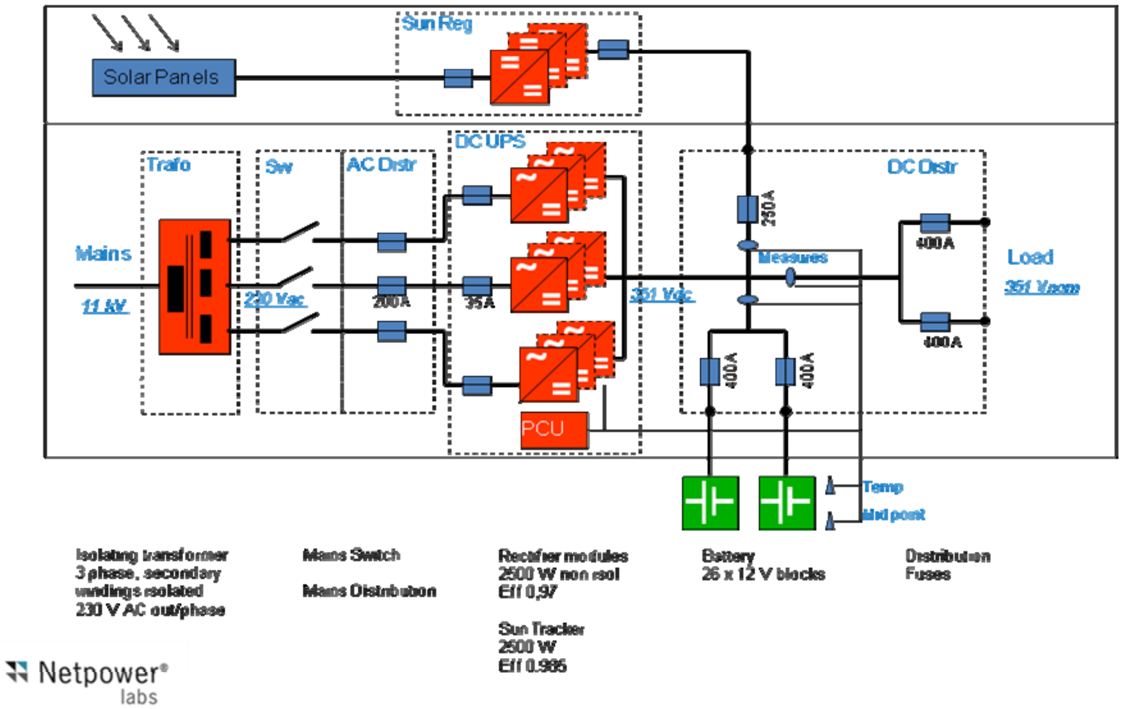
The conclusion is that the new milking robots can be adapted to DC operation.

8 Pre-planning of new power stations in Glava Hillringsberg



Glava high voltage AC/DC power station

Layout – 400 kW solar 200 kW AC/DC 10 kV/+/-350 V DC and 400 kW DC/AC



When choosing power equipment, equipment without “unnecessary” transformer insulation should be preferred. Every transformer insulation that is removed saves approx. 2% of the constant conversion losses.

A question under discussion is to what extent there should be a two-way (bidirectional) inverter or two one-way inverters at the connection point to higher-level networks. One argument put forward is that the highest possible efficiency is important. Just as important, if not most important is that the technology should be robust, reliable and maintenance-friendly. The efficiency in one-way inverters can be made a little higher than in two-way inverters. The reliability of a one-way inverter can be made considerably higher than in a two-way inverter, since the latter has more components and is more complicated.

Above all, it is important that the power feed from higher-level networks has the highest possible efficiency and robustness. Therefore, the feed-in equipment should be made as simple and robust as possible.

As regards feed -out of surplus electricity from the solar cell installations, it is not as important either with respect to efficiency, robustness or reliability. The feed-out equipment is also a much more complicated and sensitive piece of equipment than the feed-in equipment, which can be made very simple and robust in a one-way design.

The reliability of the feed-in should not be reduced by complicating it with a two-way device, or make the feed-in dependent on the feed-out. In such a case, two-way equipment that develops a fault can knock out both feed-in and feed-out and can cause power cut in the DC power grid for an extended period of time.

The most reliable and efficient system should be built with separate one-way devices, one for feed-in and one for feed-out. A fault in the most complicated device, which for feed-out, will not then be able to cause a power cut in the feed-in.

9 Pre-planning of distribution network in Glava

9.1 Discussion

A “bus” network of the Edison type can reach its greatest range if the largest power feed-in takes place in the middle and can be stretched farther if power feed-in can take place along the line. If we analyse the structure found in Stockholm and Gothenburg during the DC period, we see that the distribution radius round the power stations was 700 m – 1000 m at a system voltage of 440V, which is 60% of that now under discussion: 700V. At that time, there was no feed-in to the grid along the lines or on the periphery in the same way as in Hillringsberg. A distribution diameter of up to perhaps 2.5 km should be economic without requiring the provision of higher voltage than plus or minus the maximum appliance voltage for present-day power supply units for electronics (350/700V). Then we obtain a very simple, energy-efficient, economic and robust micro-grid for local energy production and consumption. No transforming or active electronics or cooling equipment is needed, which means high availability and simplified maintenance.

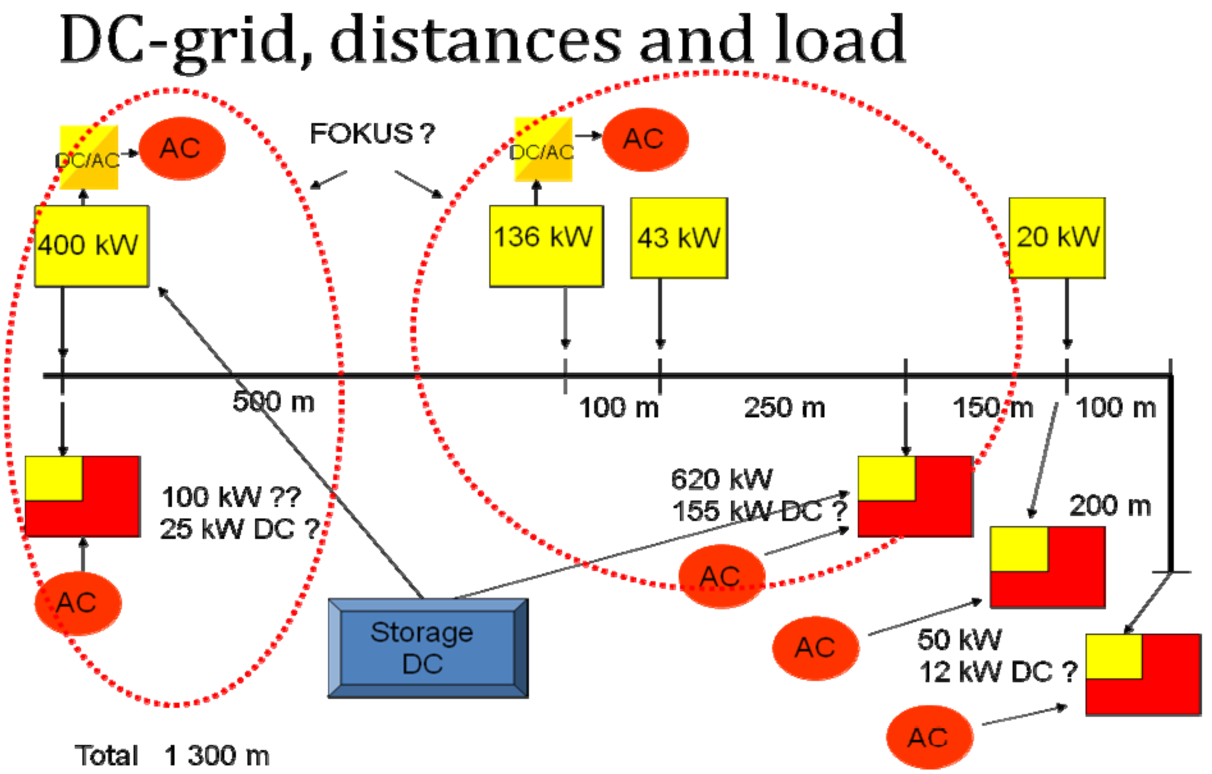
A “bus” network with feed-in and feed-out points along the entire cable is assumed not to require calculation in order to cope with the need for peak power transmission for the whole length. The reported need of peak power mainly in the solar cell factory cannot and need not be covered by DC power alone. There, a great deal of the need for peak power goes to the heating units of the laminators. This heating power should continue to be taken from the AC power grid. A calculation should be possible to make for 200kW and still give reasonable voltage drops even at the lowest supply voltage of approx. 300V per phase or 600V main voltage.

It is assumed that the rectifier capacity and battery storage for supply to the DC power grid is placed both at the new cow shed and at the existing solar cell installation: at the new cow shed approx. 200 kW and at the existing solar cells or in the solar cell factory approx. 100 kW. Batteries for 660 Ah at the new cow shed and possibly the same number at the factory to protect the process for about one hour and/or to store solar energy for night consumption.

Solar cell regulators for feeding to the DC grid are placed by the solar cell installations.

A voltage drop calculation is made assuming 5% voltage drop during the assumed transmission of 200 kW for the entire length as a mean drop for power transmission. Different load situations, power feed-in along the whole length and the time of the largest power requirement make a real-life worst case hard to identify. The standard value 5% voltage drop is old and based on the lighting and motor loads of the old technology. It is no longer as critical for modern electronic loads. Many of the modern electronic loads, including lighting, withstand, without a negative effect on the performance, minus approx. 20% (190V AC and 270V DC) and plus at least 10% of 240V AC (265 V AC and 375 V DC), which most modern appliances are designed for.

9.2 Discussion on mains connection for input and output supply along the network



The total peak power for DC consumption is estimated at 210 kW.

At the consumption points, no DC/DC converters are needed for feeding the load according to the outline of the Edison system with main voltage 700 V and phase voltage 350 V. This phase voltage can be distributed via ordinary distribution boards or fireboxes directly to all ordinary electrical appliances and lighting. The normal power supplies in modern electronics have a wide input voltage range. At battery-operation the systems voltage drops from 350V and down to 300-270V, which is the lowest that can arise. Low-energy lamps can also take the lower limit without the light intensity being particularly affected.

NB. During the detailed planning, it must be checked that all protection (fuses) are bidirectional, i.e., they work for currents in two directions.

9.3 Total power need for Glava Hillringsberg DC power grid

Production:

- The existing solar cell installation is expanded to a peak power of 130 kW. The measured energy production is 120 000 kWh per year. Mean power over the year: 13.7 kW.
- The solar cell installation for the new cow shed is 400 kW. According to measured production, 400/130x120000 kWh=370 000 kWh per year. Mean power over the year: 40.0 kW.
- Wind power plant 43 kW peak power for short duration. Annual energy production unknown and hard to calculate but is estimated at 100 000 kWh.

- Hydropower plant peak power of 20 kW. Estimated production 90 000 kWh per year. Mean power over the year : 10.0 kW.
- The sum of the maximum peak power in the generator capacity is 593 kW. The maximum mean power over the year : 65.7 kW.
- The sum of the estimated maximum annual production if all energy produced can be utilised: 680 000 kWh.

Consumption:

- The new cow shed is assumed to have the same peak power of 75 kW as the present cow shed. The same consumption of 420 000 kWh per year. Mean power over the year: 48 kW.
- The solar cell factory has a peak power of 620 kW. Consumption during full operation 2 300 000 kWh per year. Average power over the year: 262 kW. The present status in the factory is 30% production. This indicates a peak power of, say, 310 kW and consumption 767 000 kWh per year. The average power over the year is 87 kW. A large part of the peak power is in the heating units in the laminators and cooling machines for air conditioning during the summer. How this is divided between AC and DC consumption is hard to judge, but depends on how extensively the building network can be rebuilt.
- Hillringsberg Manor House has a peak power of 50 kW and a consumption per year of 165 000 kWh. The mean power over the year is 19 kW. It is still unclear whether the manor house is to be supplied with DC, but the proportion of DC will depend on how extensively the building network can be rebuilt. Lighting and fans should be possible to connect to DC without large costs.
- Total maximum peak power in consumption: 435 kW. Maximum mean power over the year is 154 kW.
- Total estimated maximum annual consumption is 932 000 kWh.

9.4 Voltage drop calculation

Assume that 200 kW needs to be transmitted over the whole distance of 1200 m with a maximum voltage drop of 5%. According to the cable manufacturer, the cheapest aluminium cable in the largest production volume is N1XE 4x95, 4x150 and 4x240 mm2 unshielded [8]. Three cables may be the most economical, depending on the power we finally wish to transmit. The intended system is a three-wire system but the fourth wire could be used as an extra PE /protective earth wire along the whole network in the system, which could raise the safety level. This could be compared with the five-wire system for three-phase. However, it is doubtful whether the need for a protective earth wire throughout is as large in the case of direct current as in the three-phase system of alternating current. This could perhaps be the object of a special study. According to the regulations, however, it is permitted to connect PE wires to the neutral or centre core in a DC three-wire system. Which cable to use finally in a grid must be specially studied along with cable suppliers in the final planning.

Calculation:

Assume for the calculation 2 or 3 parallel cables.

- N1XE 4-wire 240 mm2 resistance 0.125 Ohm/km
- 2or 3 cables in parallel can be chosen
- Main voltage 700 V, 5% max. voltage drop=35 V
- Cable length 1.2 km 2// 0.075 Ohm one way 3// 0.05 Ohm

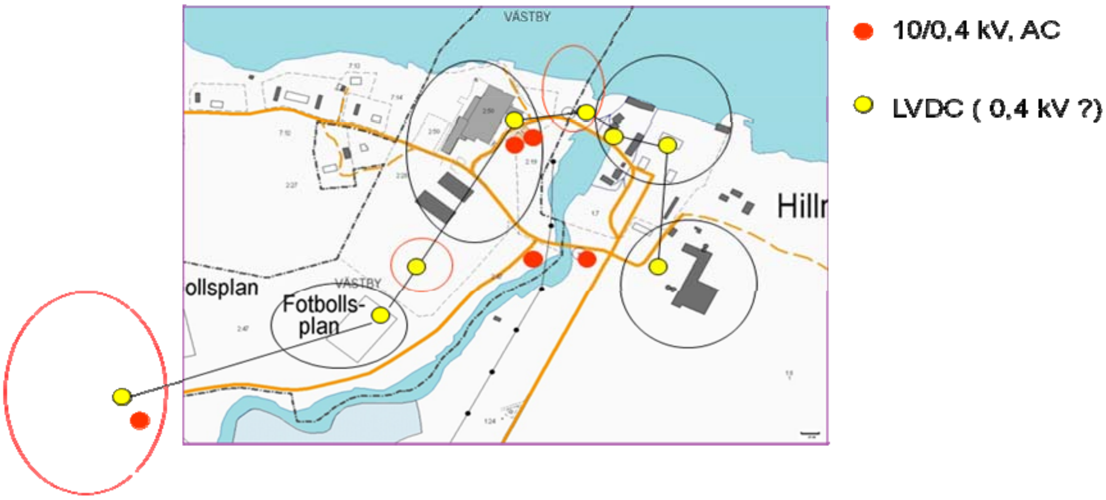
- Assume transmission of max 200 kW or 333 A at the lowest voltage 600 V, battery operation, and 285 A for 700 V during normal operation
- Assume transmission of max 300 kW or 500 A at the lowest voltage 600 V, battery operation, and 429 A for 700 V during normal operation
- 2 cables (200 kW) //give the voltage drop (two-way) of 2x0.075=0.15 Ohm x 333 A=50 V (8.3%) voltage drop at 600 V and 0.15 Ohm x 285 A=43 V (6.1%) at 700 V.
- 3 cables (200 kW)// give the voltage drop (two-way) of 2x0.05=0.1 Ohm x 333 A=33 V (5.5%) voltage drop at 600 V and 0.1 x 285 =28.5 V (4.0%) at 700 V.

With regard to the voltage drop of 5% as a norm, it can be stated that modern electrical appliances, including lighting, can take at least +10% and approx. -20% in voltage variation from nominal 230 x the root of 2=1.42 = 325 V DC. In the grid, 200 kW only needs to be transmitted the entire length in exceptional cases, since 30% of the supplied power can come from the solar cells a short distance from the factory if rectifier capacity is also installed there.

NB. It is very important that there are plus and minus wires in each cable when they are being laid, even when cables are connected in parallel. It is not permitted to lay plus wire in one cable and minus in another if several cables are used. This is very important for ensuring as low inductance as possible in the cable bundle. The inductance in a cable bundle is linear due to the area that the current encloses, - hence the area between the plus and minus wires in a cable. This is seen as a protective parameter in conjunction with short-circuits. Unnecessarily large inductance in a cable bundle can lead to unnecessarily large plasma arcs, which may be hard to extinguish in the event of short circuits. This inductance may also cause damaging over voltages in the event of short circuits and blown fuses.

It is suggested that two or three parallel cables are laid according to the proposal in the outline map. Tap-off boxes or cabinets are located in suitable places during later planning. Each phase is equipped with a suitably-sized fuse. The choice of type and size is determined during later detailed planning.

Local ”DC-grid”
within the area



10 Pre-planning of a building network in the solar cell

It is suggested that a new transformer station fort direct high-voltage conversion from 10 kV to 350 V DC is built beside TR 1 and TR2; see "Factory layout" below. The new transformer shed also houses rectifiers for 100 to 200 kW. A battery the same size as the one suggested for the new cow shed is placed inside the factory in a space near the transformers. In the same room, the new DC grid is drawn in and DC switchgear for distribution to the fuse boxes is placed there.

Inside the building, a DC distribution grid is installed parallel to the existing AC grid. As far as possible, existing cable ducts for AC cables to the fuse boxes are used for the DC grid. These are installed at the side of the present AC fuse boxes in suitable places. Cables and fuse boxes are clearly marked with DC signs to avoid confusion.

It is suggested that all the lighting, all ventilation fans and selected robots are connected to the DC grid—not, however, the laminating robots.

10.1 Lighting

Inside the factory premises, there are two types of light-tubes: the more modern T5 (very thin tube), which has HF ballast and can be fed with 350 V DC without modification; the older type, which has magnetic ignition and a thicker tube. These cannot be fed with DC.

Now under development are new LED light fittings both for street lighting and, for instance, factory premises and offices. Philips in the Netherlands has these and would like to have reference installations for demo and long-term testing in different environments. Philips is prepared to develop a drive unit that can be fed with 350 V DC for LED light fittings. In Sweden, Fagerhults in Småland are developing a corresponding device mainly for T5 light-tubes. Fagerhult is collaborating with the Finnish company Hellvar to develop a certified HF ballast device that can be fed with 350 V DC.

The areas to be lit are:

Office: 1582m^2

Production: 3454m^2

Store: 1290m^2

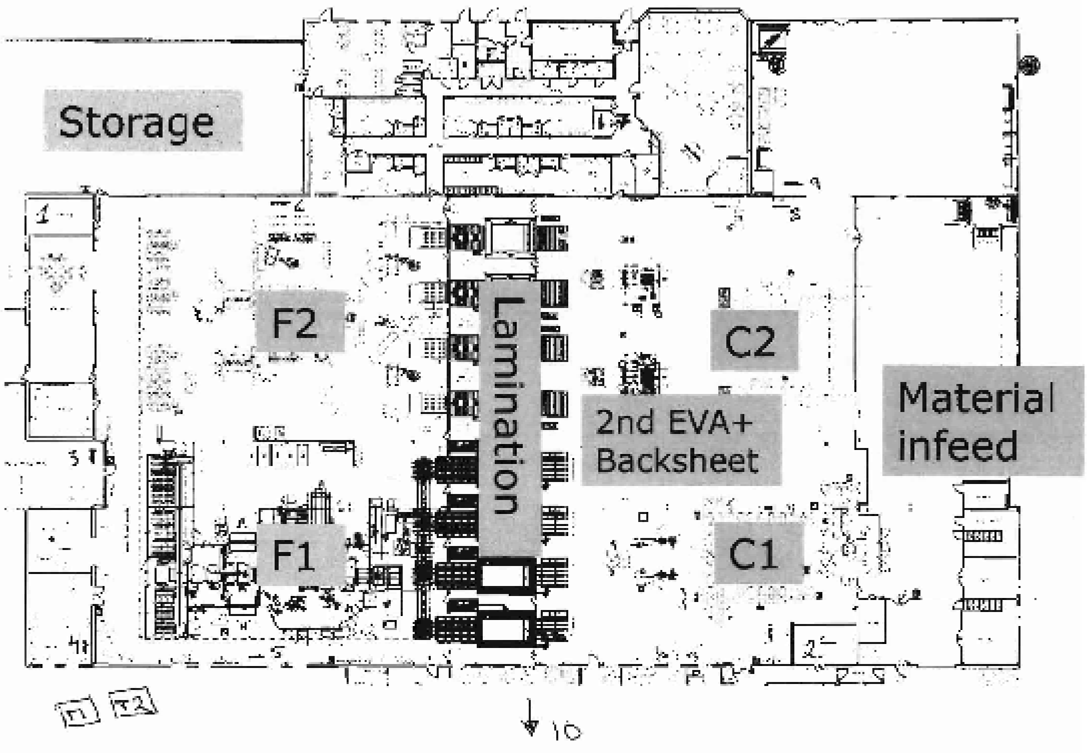
Staff areas and canteen/restaurant:678m^2

Laboratory: 400m^2

1. STÄLLVERK FRÅN T1
2. STÄLLVERK FRÅN T2
3. UNDERFÖRDELNING KOMPRESSORER/VENT.

4.-9 UNDERCENTRALER
10. UNDERCENTRAL KONTORSDEL.

Factory layout



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