CONNECTION OF CO-GENERATION PLANTS WITH THE MEDIUM-VOLTAGE NETWORK OF PUBLIC UTILITIES

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INTRODUCTION

Existing medium-voltage networks of public utilities have historically grown structures. Thus, they are designed with no respect to a later connection of dispersed power generation. As high investments are needed to increase the rated values of the existing equipment, they must be considered as a constraint for network operation and network extension.

A growing number of customers today detect the economic benefits of modern co-generation units integrated into their technical processes. This applies not only to new customers, but also to existing installations.

Whenever a customer intends to install on-site co-generation, the utility has to check the impact on the public supply network. Costly investments should be avoided, and proven operation principles should be maintained as far as possible.

It is under these aspects that system studies were performed based on the situation of Bewag, the Berlin utility. Their scope are the existing margins for the connection of new unit-type co-generation plants (UCP), considering the specific conditions in the distribution network.

NETWORK STRUCTURES

The following studies were performed on the model network shown in Fig 1.

The 10-kV cable networks of *Bewag* are typically designed as open loops, each of which supplying several medium-voltage/low-voltage (MV/LV) stations. The high-voltage/medium-voltage (HV/MV) transformer substations are equipped with redundant transformer capacity. Each part of the network fed by the same transformer and thus connected to the same MV busbar is called a "network group". The normally open connection in the loop is selected so that both halves of the loop are equally loaded under normal conditions.

High-power customers have direct cable connections to the 110-kV/10-kV transformer substation.

The data of the UCP modules used in this study were selected according to practical planning cases.

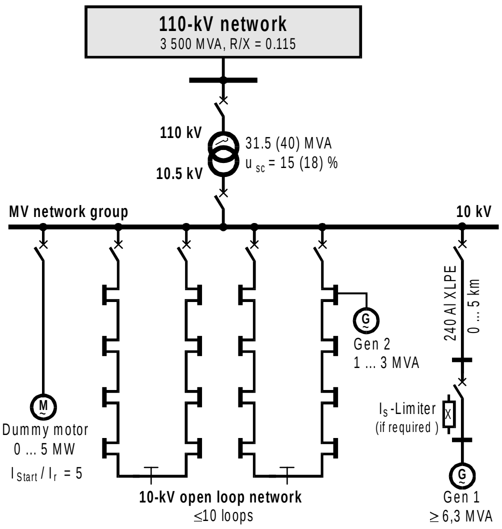

Fig 1: Model network for the studies

ADMISSIBLE RATED POWER OF UCP PLANTS

Short Circuit Currents

The generators of UCP plants contribute to the fault currents in the network. Their influence comes in addition to the short circuit power of the already existing sources (network infeed and motor loads).

The existing 10(6)-kV distribution networks of *Bewag* have different short circuit ratings, depending on the voltage level and on their erection dates. Accordingly, the amount of generation power that can be added to a network group without any technical modifications is different. The constraint for the admissible rated UCP generation is defined by the peak current i_p. The thermal fault withstandability of the network normally is no limiting criterion, as high-current faults are interrupted by instantaneous protection tripping.

Recommended values for the maximum dispersed generation per MV network group, with feeding transformers of 31.5 MVA and 40 MVA, are shown in Fig 2. The indicated installed power values apply to the connection of a single UCP device as well as to the sum power of several smaller modules.

When the motor load in a MV network group is not known exactly, an estimation of 10 % of the maximum customer load is recommended.

The curves in Fig 2 show, that an additional dispersed generation of up to 5 MVA is admissible for 10-kV-networks supplied by 31.5-MVA and 40-MVA transformers, for a peak current rating of i_P = 40 kA. In the case of smaller rated transformer power or of higher peak current rating in the network, the limits for the dispersed generation can be selected above the indicated values.

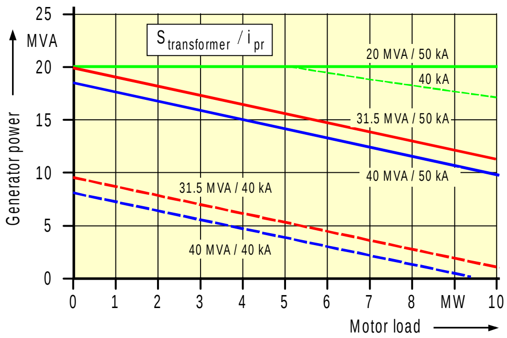

Fig 2: Admissible generator power in 10-kV networks

When dispersed generation of a higher power than admissible according to Fig 2 is requested to be connected to the network, additional measures become necessary. In most cases, an exchange and an upgrading of existing MV network equipment is too costly and can be excluded.

An alternative is the network connection of generators using I_S limiters [1] (see Fig 1). These are fuse-type devices that interrupt the alternator's fault current contribution before it reaches the peak value. When applying I_S limiters, exceeding short circuit power limits is no more constraint for installing dispersed generation. From the operational point of view, additional aspects have to be considered. But these will not be addressed here.

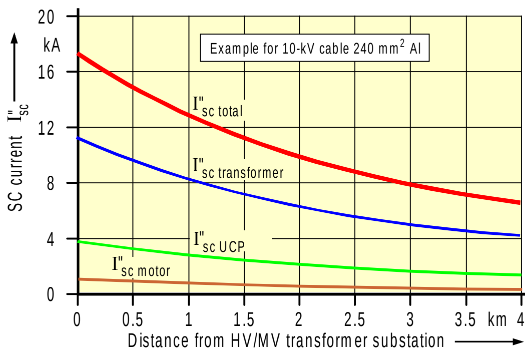

Fig 3: SC current contributions in the 10-kV network

Fig 3 illustrates the damping influence of the 10-kV cables on the short circuit current. It allows an easy check of the short circuit stresses on MV switchgear in the network.

FAULT LOCATING IN OPEN LOOPS

The open loops in *Bewag* MV network are equipped with fault current indicators (FCI), which allow locating the fault affected cable sections. The excitation current of the FCI for multi-phase faults is either 600 A or 1000 A.

FCI are not sensitive to the fault current direction. They simply react to the absolute current values. In networks without dispersed generation, their indication is always doubtless, as fault currents are only possible from the HV/MV substation to the fault location. Short circuit current contributions of motor loads, which also could come from any direction, normally are far below the FCI excitation values.

When UCP modules are connected to the network, their additional fault current flows from the alternator to the fault location. The possible consequences on the FCI operation are illustrated in Fig 4.

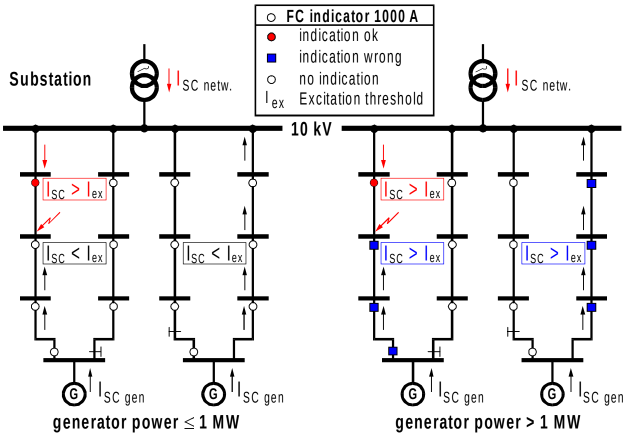

Fig 4: Dispersed generation - impact on SC indicators

To avoid misleading fault current indication, it is necessary to limit the dispersed generation power (and thus the value of additional fault currents) installed in a network loop. The criterion in this case is the peak current i_P if no detailed information about the operation principle of the FCI is available. The additional contribution to i_P should not exceed 80 % of the FCI excitation current.

This in practice leads to a maximal generation of 0.6 MVA in a MV loop for FCI operation currents of 600 A (or 1.0 MVA for 1000 A FCI values, respectively).

UCP of higher power should be directly connected to the HV/MV transformer substation. Another option is connecting different UCP modules units to different MV network loops.

When low-cost time-delayed FCI will be available in the future, the limits for the maximum generation power in the network loops can be exceeded. A possible option would be a delayed of the FCI excitation until the peak current has passed by. The limit for the generation power in each network loop, under protection aspects, then would be given by other criteria, e.g. the value for the overcurrent protection in the network feeders (at the HV/MV substation).

IMPACT ON THE VOLTAGE PROFILE

Public distribution networks traditionally have been designed for power transportation from the (central) power plants via the interconnected network and the distribution network to the end customer. The growing installation of dispersed generation on the distribution network has a distinct impact on the network operation.

"Backward" power injection in the network is generated, leading to reverse power flow. This power flow varies frequently, because of the operational behaviour of small generation modules (varying electric production, frequent determined and stochastic outages). This causes rapid voltage variations in the network which must not impair the power quality for the public customers in the network in above the technically admissible limits.

Normal operation. The voltage of the 10-kV busbars in the HV/MV substations is adjusted by the automatic tap changer control of the transformers. For the typical transformer rating, the installed dispersed generation in practise does not lead to any problems.
Generation within the MV network in principle can lead to voltage problems, depending on the injected power (see Fig **5**). But a limitation to 1 MVA per loop, found as the maximum value to prevent fault locating problems, does not cause any voltage problems.

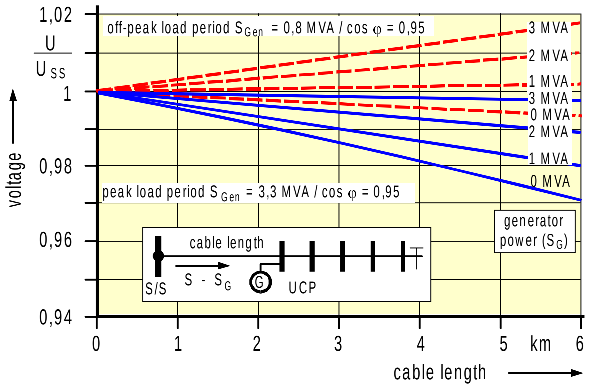

Fig 5: Voltage profile in open-loop networks during normal operation

Transient effects for UCPs connected directly to the HV/MV substation. Disturbances within the UCP and the impact of faults in the distribution network frequently lead to tripping of the protection system of a single generator or of all generators in the MV network. This results in rapid changes in the load flow, causing voltage drops in the supply of all customers in the MV network. The remaining voltage depends on the short-circuit impedance of the network close to the generator, to the interrupted generation power and its power factor cos φ.

Fig 6 shows the voltage variation, depending on the cited parameters, for UCP connected directly to the MV busbar of the HV/MV transformer substation.
It is according to the rules for the judgement of customer generated disturbances [2] and the rules for connecting UCP's to public distribution networks [3], that the voltage variation caused by the operation of UCP's at the PCC (point of common coupling) should not exceed 2 % of the nominal network voltage. This condition is fulfilled (see Fig 6), when the dispersed generation connected to the HV/MV transformer substation does not exceed 10 MVA, and when the UCP generators are operated at a power factor cos φ ≥ 0.95.

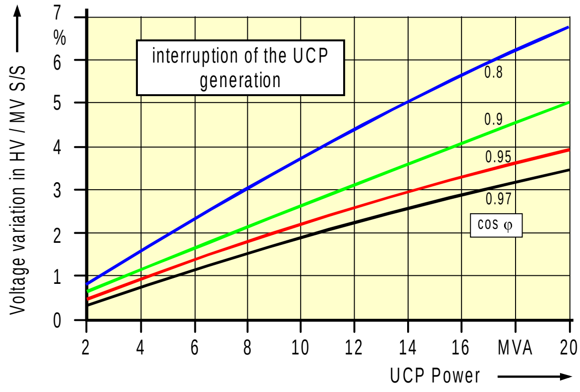

Fig 6: Voltage variation at the HV/MV substation

Transient effects for UCP within the network loops. The issue of voltage profiles requires detailed studies for the different PCC's in the network, because of the varying network impedances. But as already mentioned, the network fault location system requires UCP generation to be limited to 1 MVA per loop. UCP modules of this power will only lead to power quality problems in the case of cables with above-average lengths and limited conductor cross-sections.

GENERATOR STABILITY

Dispersed generation power plants operate in parallel with the public distribution network. This is beneficial for normal operation, however it endangers the generator stability in the case of network faults. When the grading time of the network protection is too high, generators must be decoupled from the network after fault occurrence before they fall out of step to avoid mechanical damages. Based on the example network shown in Fig 1, extensive studies were carried out to evaluate this effect for different generator sizes and fault locations in the 10-kV network.

Short Circuits in the vicinity of substations. The clearing of a 3-phase fault direct behind the cable sealing end of a 10-kV feeder is done by the high current stage of the overcurrent protection within less than 0.5 s. It is assumed that the generators are not decoupled by their own protection during considered time range. The transient behaviour of generator Gen 1 is shown in Fig 7 for a simulation time of 2 s.
The generator looses synchronism about 230 ms after the short circuit occurrence. After fault clearing by the overcurrent protection of outgoing feeder from the S/S busbar, heavy voltage and power swings can be observed. The rotor angle crosses the stability limit of 180 degrees referred to the voltage of the 110-kV network (Fig 7). The generator is in asynchronous operation and should be disconnected from the network to avoid damages. It is not to be expected that the generator returns to synchronism.

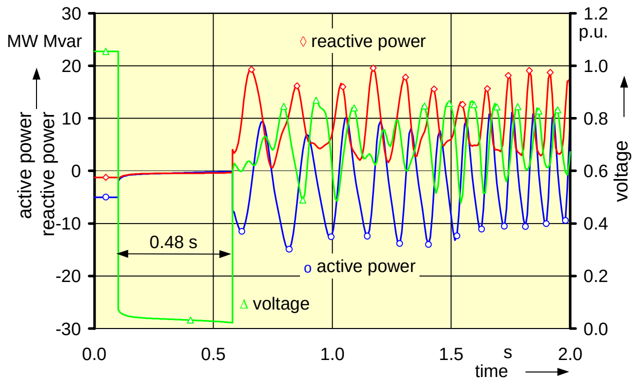

Fig 7: Generator behaviour for fault clearing by high current stage of feeder overcurrent protection

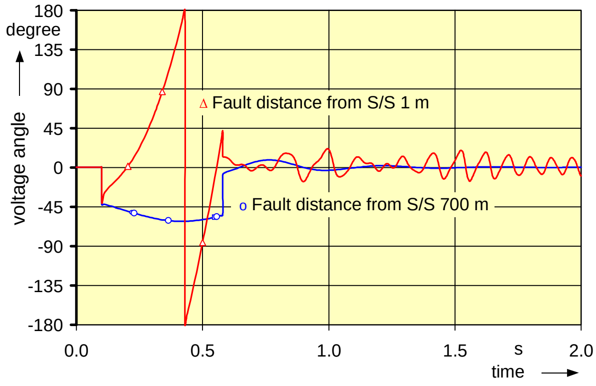

Fig 8: UCP busbar voltage angle for different fault locations cable feeder produced by s.c. current.

Out of step operation can be avoided, when UCP generators are decoupled immediately after fault occurance (e. g. due to I_s limiter). The generators remain in a stable condition and can continue in island operation e. g. to feed homeload of UCP. Speed control of the UCP then must be able to cope with load changes coming along with islanding. The power swings of the generators are drastically reduced by a fast decoupling from the network.

Alternatives for a fast decoupling of the generator from the network are voltage vector surge relays or protection relays based on the voltage magnitude, both tripping the generator circuit breaker.

The short-circuit power of the MV network has only a minor influence on the critical fault clearing time. For a short circuit power of 100 MVA, the critical clearing time is about 210 ms. It increases to about 230 ms for a short circuit power of 230 MVA. That is due to the fact, that during voltage zero, the generator behaviour is not influenced by the network.

It can be derived from the results that generators in dispersed power plants must be disconnected from the network within short time for short circuits in the vicinity of substation. That can be achieved by a voltage vector surge relay or by voltage dependent decoupling when grading time of feeder overcurrent protection in the substation is above critical fault clearing time of 200 ms.

Short circuits in longer distance from substation. Additional calculations were carried out for 3-phase short circuits on a subloop in some distance from substation. Fault clearing is also achieved by the high current stage of overcurrent protection in the related feeder. In contrast to the behaviour for a nearby fault, generator remains stable for a fault distance of 700 m to the S/S. The maximum rotor angle amounts to 80 ^{0}. After short power swings a stable steady state is reached.

Fig 8 shows the busbar voltage angle of the UCP generator related to the 110-kV network.

The reason for the significantly improved operating conditions is the damping of power swings by watts loss in the cables.

A voltage vector surge relay, if installed, would trip the generator breaker also in this case.

Short circuits on direct cable links from the S/S to the dispersed generation power plant lead to a similar behaviour of generators as faults behind cable sealing end at outgoing feeders. A fast decoupling from the network is also required.

Behaviour of low voltage generators. Low voltage generators connected via transformers 10/0.4 kV to network loops show a similar behaviour like MV generators. The critical clearing time for faults nearby S/S and in subloops connected to UPC is in the range of 200...270 ms. For faults in other subloops in some distance from the substation, the critical fault clearing time increases to values above 1 s. A stable operation of generators can be possible also for fault clearing in the low current zone of the overcurrent protection (e.g. 1.5 s) in some cases with fault locations far away from substation.

Influence of protection devices of UCP. To avoid backfeed of generators to undefined islands ongoing with transformer outage and to protect other customers, additional protection functions besides usual generator protection are required ($\gtrless$ U, $\gtrless$ f, voltage vector surge relay) [3]. These additional devices are usually combined with a separate circuit breaker and lead in most cases to an undelayed decoupling (t<<200 ms). They prevent unstable operation conditions of the generator and thus represent necessary requirements for secure islanding of generators.

IMPACT OF UCP ON THE NETWORK RELIABILITY

Some customers need an additional Backup Power Supply (BPS) besides the normal network connection, e. g. for reasons of operating safety. The normal supply and the BPS must be as independent as possible. The BPS typically is provided by an emergency generating unit (e. g. diesel generator), in some cases also by a "especially secure network connection". This can be a connection to a second MV network group, which then should be independent of faults in the main connection.

An variant that is of growing interest for customers interested in combined heat-power production is the application of UCP modules for the BPS (see Fig 9).

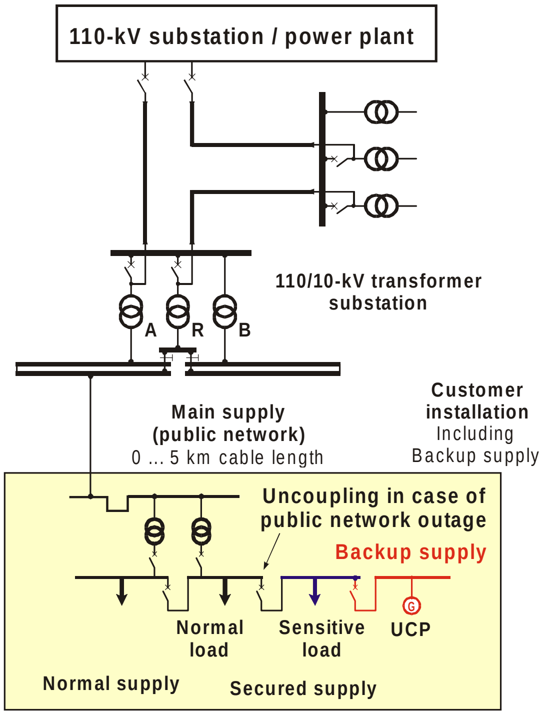

Fig 9: UCP module for Backup Power Supply

The reliability for different BPS concepts has been studied in great detail. The relevant parameter for the quality of a BPS solution is the frequency f_{Tot} of the total interruption of the customer power. This means the interruption of the normal and the backup supply. The calculations have been performed based on representative failure rates using a Markov model. The results are shown in Fig 10.

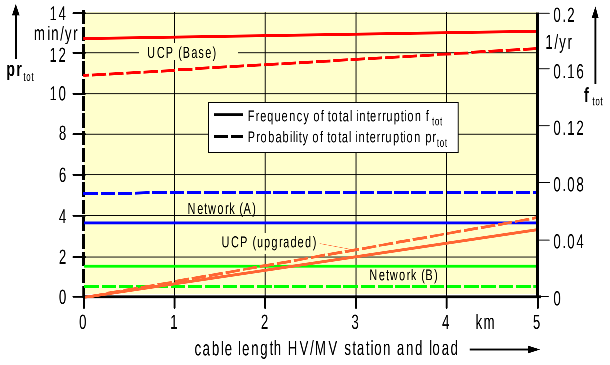

Fig 10: Reliability comparison of different BPS solutions

BPS via a second cable to the public network

The level of reliability gained by a backup supply is strongly depending on the stochastic independency for the common interruptions of both connections, that is the frequency of common-mode failures leading to an interruption of both supplies. The connection to two completely independent networks in practise is not possible.

The main factors for the probability of common-mode failures are the impact of MV cable faults and HV/MV transformer faults on both network connections.

A backup supply from a different loop of the same MV network group (A) thus offers the lowest total reliability. The supply situation is comparable to a parallel supply from the HV/MV substation via two dedicated cables. The interruption rates (1 interruption per 19 years) and the unavailability values are about the same. They equal the reliability of the MV busbar of the HV/MV station.

A significant increase is achieved when connecting the backup supply to a different MV network group (B) of the same HV/MV substation (that means, they are fed by different HV/MV transformers). The expected interruption rate reaches a value of only once per 43 years. This is comparable to the values of additional diesel emergency units.

Further calculations show, that an even higher degree of independency, e.g. by connecting the backup supply to the MV busbar of a different HV/MV substation, only leads to a marginal improvement of the reliability.

The cable length between the HV/MV transformer substation and the customer is of practically no importance in any of these cases (see Fig 10).

BPS provided by UCP modules

UCP modules - as opposed to emergency diesel units - typically are operated in permanent connection with the public network. Transient effects, like voltage drops during short circuits in the network, or short-term interruptions during switching manoeuvres, thus affect the secure operation of the UCP generators. They can lead to a disconnection of the generator from the network, typically by stochastic unintended operation of the protection system in these cases. But disturbances of longer durations can also force the generator to be uncoupled from the network. Both effects lead to a high rate of common network and generator faults, drastically reducing the value of the UCP generator for backup power supply. It increases the interruption rates and the unavailability of the sensitive load.

A summary of the effects typically affecting UCP generation reliability is shown in Fig 11. It can be concluded, that secure islanding is a pre-condition for the application of UCP modules as backup power supplies. Islanding in this context means the transition from the operation in parallel with the network to island operation.

Another important aspect is the parameter used as reference value for UCP power control. The conventional way uses the produced heat as the reference value for the UCP loading. The electric output thus is not correlated with the electric load of the system. In the case of network faults, the coupling between the sensitive load and the robust load is interrupted, and the generator finds itself in an electrical island together with the sensitive part of the electric load. The difference between generation and consumption may be drastic, like e.g. for rated UCP operation and minimal internal load. The UCP then is running into stability problems, and it is likely to be separated from the network by the generator protection. It is obvious that it cannot contribute to an increased reliability in this case, as desired.

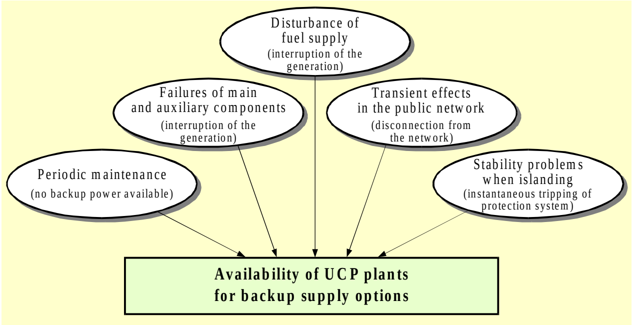

Fig 11: Factors influencing UCP backup supply reliability

The consequence is, that a UCP module with thermal reference operation has no significant impact on the reliability of a sensitive customer. It is no appropriate solution for the backup supply. The resulting reliability lies in the range of a MV network supply via a single cable between the HV/MV transformer station and the customer.

To improve the conditions for successful islanding, the electric power of the UCP can be used as the reference value for the power control. The aim is to adapt the UCP power to the internal electric consumption of the sensitive load, so that the load before and after islanding correspond to each other. This however requires a load management system and a high dynamic performance of the generator control. Practical experience shows that unsuccessful islanding also occurs in these cases. Besides that, this way of UCP operation in most cases is uneconomical.
A significant impact of UCP on supply reliability can only be achieved, when a stabilised protection system only disconnects the generator and the secured load from the network in cases of auto-reclosure and in cases of faults between the generator and HV/MV transformer substation. The number of islanding manoeuvres and the unavailability of the UCP would be strongly reduced, thus increasing the potential for secured supply. The achieved level of reliability then would be equal to an emergency diesel unit or to network supply from a different MV network group (see Fig 10).

A comparably high level of reliability is also achieved when the generators are equipped with a device that initiates a quick re-start after unsuccessful islanding. In this case, the secured load is separated from the insensitive load and the UCP is re-started within the admissible transfer time of 15 s.

The decision for the most suitable upgrading variant of the control system depends on economic considerations.

SUMMARY

The connection of UCP to existing MV networks, like those of *Bewag*, must consider the rated values of the installed network components and the admissible impact on the supply quality of the remaining customers.

Typical 10-kV networks are rated for short circuit values $I''_{SC''(3)}$ / i_p = 16 / 40 kA, and they are supplied via 110/10-kV transformer substations with 31,5(40)-MVA transformers. In this case, only UCP with a maximal power of 5 MVA can be installed within each MV network group in order not to exceed the short circuit limits. The installation of I_S limiters however allows higher UCP values.

The admissible values for the power flow variations in the case of changing electric generation or outages of UCP define a limit of 10 MVA maximal rating installed in a network group.

Another constraint is the excitation threshold of the fault current indicators in the 10-kV loops for multi-phase faults. As consequence, a maximal UCP generation of 1 MVA can be installed per loop, whose cables are equipped with 1000-A indicators.

When operating UCP generators and public distribution networks in parallel, the frequent short circuits in the distribution network jeopardize the stability of the generators. To avoid problems, network faults close to the generator must be cleared within 200 ms.

The UCP modules typically use thermal reference operation. Conventionally designed and controlled devices cannot be directly used as Backup Power Supplies, because the probability of successful islanding strongly depends on the thermal load situation and is typically rather low. An improvement of their value for backup power purposes can be achieved by additional equipment, e.g. for short-term restart. Also possible, but economically questionable, is the operation with electric power instead of thermal production as the control reference value. Alternatively the secured network can be permanently re-configured, so that the electric power resulting from the thermal production corresponds to the actual load in the secured network.

When discussing UCP upgrading for a backup power supply, the well-tried option of a backup connections to a neighbouring MV network group should be included.

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