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Grid Interaction of MV-connected CHP-plants during Disturbances

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Abstract—Nowadays the amount of distributed generation (DG) units is increasing rapidly. Most dominant are combined heat and power (CHP) plants and wind turbines. At this moment, in most systems, there are no requirements defined for short-circuit behavior of such generators connected to the medium voltage grid. However in the future this situation will not be acceptable anymore, since with the present protection settings of DG a fault in the transmission grid may lead to disconnection of a large amount of DG over a large geographical area. This paper focuses on CHP-plants connected to the MV-grid. New settings for the under-voltage protection will be proposed. These settings will be based on voltage dip profiles and the fault ride through capability of the CHP-plants. With the aid of dynamic simulations it is shown that the new settings of the under-voltage protection can lead to a significant improvement of the availability performance without losing the stability of the generators.

Index Terms—Distributed generation, Voltage recovery, Fault Ride through, Stability, Medium voltage grids,

I. INTRODUCTION

THE share of distributed and renewable energy sources in the total energy production is growing. This is due to development of small on-shore and large off-shore wind farms as well as an increasing share of Combined Heat and Power plants (CHP-plants). Small wind farms and small CHP-plants are usually connected to the distribution system while large off-shore wind farms and large power plants with additional heat generation are connected to the transmission system. In order not to disturb the fault-clearing process wind turbines and small CHP-units are mostly disconnected immediately after a disturbance in the grid. For faults in the transmission grid this can lead to a disconnection of a large amount of generators which can cause a large power imbalance. To prevent this situation grid operators have set fault ride through requirements for wind farms connected to the transmission system.

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In the Netherlands local authorities has designated rural areas where horticultural activities can be developed. In these areas greenhouses are built and each greenhouse might contain a CHP-plant. The CHP-plant produces heat and CO₂ which is used in the greenhouse and the electricity is sold to the market. Because of the clustering of horticultural activities the CHP-plants are clustered as well which lead to a high penetration level of CHP-plants in the local Medium Voltage grid (MV-grid). In the Dutch grid code no fault-ride through requirements are set up for generation units smaller than 5 MW so the small CHP-units will disconnect at a voltage level of 0.8 p.u. if it holds for a certain time period.

Fault ride through requirements become standard for wind farms connected to the transmission grid. Smaller wind parks connected to the distribution grid are still exempted because they are spread out over the area. An important question is how large the amount of generation will be, that will be disconnected in case of a fault. Whether or not a plant will disconnect, will depend on the depth of the voltage dip in combination with the settings of the under-voltage protection. The aim of this paper is to study on what voltage dip the CHP-plants will disconnect. This will be examined for an existing MV-grid structure including a large penetration of CHP-plants. In the paper techniques are described to obtain voltage dip profiles which will be used to assess which disturbances lead to a disconnection of the CHP-plant. The paper ends with a recommendation for new protection settings for the under-voltage protection including coordination with the grid protection.

II. VOLTAGE DIPS

Voltage dips are caused by short circuits, overloads and starting of large motors [1]. These dips propagate through the power system and can lead to malfunctioning of equipment. Moreover in MV-grids including DG-units voltage dips can cause desirable or undesirable disconnection of these DG-units. In some standards disconnection of DG-units is even obliged in order not to disturb the fault-clearing process [2].

The CHP-plants connected to the MV-grid are equipped with an under-voltage protection. This protection disconnects the CHP-plant when a dip of a certain depth and duration occurs in the line-voltage. In this way, for grids operated with an isolated neutral disconnection on local single phase-to-ground faults are prevented. Common settings of the under-voltage protection are 0.8 p.u. with a clearing time of 100-200 ms.

A. Voltage dip characteristics

Voltage dips are characterized by the depth, duration and frequency of occurrence. The depth of the dip is determined by the fault location, feeder impedance and fault level. The dip duration is mainly determined by the fault-clearing time of the protection scheme. An exact definition of a dip and its characteristics can be found in [3]. In this paper only dips caused by grid disturbances are considered. To estimate the dip frequency a probabilistic approach is needed using network reliability data.

B. Propagation of unbalanced voltage dips

Severe voltage dips occur caused by balanced three phase faults however, most faults are unbalanced. These unbalanced faults lead to unbalanced voltage dips. The propagation of voltage dips through different types of transformer connections results in a different appearance of voltage dips at the secondary side of the transformers [4]. Also neutral grounding can have a significant effect on voltage dip propagation [5]. The effect of the transformer connection on voltage dip propagation is demonstrated with a simulation of a fault at the HV-side of the transformer which is shown in a simple test grid in Fig. 1.

Fig. 1. Test grid to determine voltage dip propagation

For various types of faults the propagation of the voltage dips to the secondary side of the transformer is assessed. Because the trip of CHP-plants is initiated by a dip in the line-voltage, dip propagation in the line-voltage is studied. In table I for various fault types and transformer connections the voltage dip propagation is shown. A detailed description of the results can be found in [4].

TABLE I
PROPAGATION OF UNBALANCED VOLTAGE DIPS

Fault type / transformer type	Yy	Yny	Yd	Ynd
Single phase-to-ground	No	No	No	Yes
Phase-to-phase	Yes	Yes	Yes	Yes
Double phase-to-ground	Yes	Yes	Yes	Yes
Three phase fault	Yes	Yes	Yes	Yes

Table I shows that the voltage dip caused by a multi phase fault always propagates to the secondary line-voltage independent of the transformer connection. For a single phase-to-ground fault this only holds for an Ynd connection. Due to the solid neutral grounding and the secondary delta winding this transformer connection has a low zero sequence impedance. Most MV-grids are connected via an Ynd transformer to the transmission grid hence single phase-to-ground faults can lead to disconnection of CHP-plants.

III. TEST NETWORK

Transmission systems normally have a ring or meshed grid structure. Faults in these systems can cause voltage dips which cover a large area. Therefore in a dip analysis the transmission

system has to be taken into account. In this paper an existing transmission grid of the western part of the Netherlands is used.

A. Transmission grid

In Fig. 2 the transmission system of the province of Zuid Holland in the Netherlands is depicted. The transmission system consists of a 150 kV grid and is connected to the national 380 kV transmission grid at three locations. Large power plants are connected to the transmission grid. From the 150 kV nodes the sub-transmission grids are connected via three winding transformers. In each substation the neutral point of at least one transformer is solidly grounded at the HV-side.

Fig. 2. Transmission system of the province of Zuid Holland, the Netherlands

B. Distribution grid

Voltage dips which cause disconnection of CHP-plants originate from grid disturbances at different voltage levels. Therefore the sub-transmission grid and the MV-grid of the area of interest are modeled as well. In this paper an existing distribution grid structure is considered built in a horticultural area where CHP-plants are connected to. An overview of the distribution grid is depicted in Fig. 3. The considered distribution grid consists of a 10 kV MV-grid which is connected to a 25 kV sub-transmission grid. The sub-transmission grid is via 150/25 kV transformers connected to substation 'sub 23' of the 150 kV transmission grid shown in Fig. 2. At the 25 kV side all transformers are grounded via a resistor of 10 Ω . The 10 kV distribution grid is operated with an isolated neutral point and radial feeders where the CHP-plants are connected to. The data of the load and generation connected to the 10 kV distribution grid is given in table II.

Fig. 3. Overview of the distribution grid in a horticultural area

TABLE II
DATA OF THE DISTRIBUTION GRID OF FIGURE 3

	Number of units	S [MVA]
Load 1	--	93.5
Load 2	--	26.8
Load 3	--	16
Load 4	--	38.6
Load 5	--	29.6
CHP 1	21	42.7
CHP 2	4	4.95
CHP 3	18	34.7

IV. VOLTAGE DIP PROFILES

In this paper a voltage dip analysis is applied to determine what voltage dip can be expected at the terminals of the CHP-plants. Based on the dip profile and the dip duration the effect of the voltage dips on the CHP-plants can be assessed and new settings of the under-voltage protection can be proposed. To obtain the voltage dip profile of the test system, this system is modeled in software package Power Factory. As mentioned earlier the voltage dip frequency is related to the failure rate of the components in the system. Based on statistics of the Netherlands for the failure rate of HV-lines and MV-cables respectively a value of 0.54 [times per annum/100 km] and 1.02 [times per annum/100 km] is used and incorporated in the model.

A. Voltage dip analysis

In the simulation software the voltage dip analysis begins with a simulation of various faults at all relevant busbars. It starts with the selected busbar and proceeds to neighboring busbars until the voltage at the selected busbar does not drop below the exposed area limit. The voltage dip assessment continues with fault calculation at the middle of all relevant lines and cables. During the simulation all values of the remaining voltages are stored and the frequency of the voltage dips are determined with the aid of the failure rates of the various components. In the simulation software a tool is available to calculate voltage dip profiles. With the aid of this tool, the failure rate and fault distribution various voltage dip profiles are constructed for a busbar in the MV-grid of Fig. 3. In the voltage dip profile the depth of dip, frequency of occurrence and its origin is shown. For the fault type distribution the figures shown in table III are used.

TABLE III
OVERVIEW OF THE FAULT DISTRIBUTION

Component	3 ph	1 ph	2 ph	2 ph-ground
HV OH-line	15%	70%	5%	10%
MV cable	20%	80%	—	—

B. Effect of CHP-plants on voltage dip profiles

In [1] it is mentioned that the dip magnitude is mitigated by local connected generators. This holds for faults in the local MV-grids as well as for dips due to faults in the rest of the system. During such faults the CHP-plants keep up the voltage at its local bus by feeding into the fault. This is illustrated with the calculation of the voltage dip profile of busbar 28 in the distribution grid (Fig. 3). The voltage dip profile is obtained

for the case with and without all CHP-plants connected. In Fig. 4 the voltage dip profile excluding the CHP-plants is shown.

Fig. 4. Voltage dip profile of busbar 28 excluding CHP-plants

The voltage dip profile for the case including the CHP-plants is depicted in Fig. 5. It can be concluded that due to the contribution of the CHP-plants the number of deep dips is decreasing and transformed to more shallow dips.

Fig. 5. Voltage dip profile of busbar 28 including CHP-plants

In Fig. 4 and 5 it can be seen that most voltage dips are caused by disturbances in the transmission system. This is because of the meshed grid structure of the transmission system as well as the longer length of the HV-lines and cables. The MV-grid is operated radial and the feeder length is relatively short in comparison with the length of the HV-lines and cables. However, the most severe voltage drops are caused by disturbances in the local MV-grid.

C. Fault types

Besides the origin of the voltage dip the type of fault causing the voltage dip is also of importance. The voltage dip profile of Fig. 5 is converted to a dip profile with the distribution of fault types. This profile is shown in Fig. 6.

Fig. 6. Voltage dip profile including fault type distribution

When comparing Fig. 5 and 6 it can be seen that the dips with magnitude < 0.8 are mainly caused by three phase and single phase-to-ground faults. Comparing the share of dips

originating from the transmission system and the number of single phase-to-ground faults, it can be concluded that single phase-to-ground faults in the transmission system also causes dips in the line-voltage at medium voltage level. This is due to the transformer connections of the HV/MV transformers as mentioned in section II.

D. Dip duration

In general the duration of the voltage dip is determined by the fault-clearing time of the protection scheme. The fault-clearing time is strongly related with the type of applied protection. The transmission system considered in this paper is protected by distance and differential protection. The differential protection scheme has a clearing time of 90-120 ms. That also stands for the distance protection when the fault is cleared in zone 1. In this paper only faults cleared in zone 1 are considered. The sub-transmission and distribution grid of Fig. 3 are protected by over-current relays. The protection settings are given in table IV.

TABLE IV
OVERVIEW OF PROTECTION SETTINGS OF SUB-TRANSMISSION AND DISTRIBUTION GRID

Substation	$I_{pick-up}$	I [kA]	t_{clear} [ms]
Sub 26	$10 \cdot I_{nom}$	5	300
Sub 28	$2 \cdot I_{nom}$	1.2	900
Sub 30	$2 \cdot I_{nom}$	1.2	900
Sub 31	$2 \cdot I_{nom}$	1.2	900

Selective fault clearing in the sub-transmission and distribution grid is obtained by the differentiation in pick-up current. The setting of the pick-up current in the sub-transmission grid is such that the protection only picks up the fault current in the sub-transmission grid. The grid contribution of the sub-transmission grid to faults in the distribution grid stays below the pick-up current of the protection. In this way in the sub-transmission grid low fault-clearing times can be reached without loss of selectivity.

The fault-clearing times of table IV can be combined with the dip profile of Fig. 5. In fig. 7 a scatter plot of the voltage dip vs. fault-clearing time is given. In this plot it is assumed that voltage dips originating from the 380 and 150 kV grid have an average duration of 90 ms.

Fig. 7. Overview of dip duration based on dip profile and fault-clearing time

To check the assumptions of the fault-clearing time of voltage dips originating from the 380 and 150 kV grids, in Fig. 8 a scatter plot of measured voltage dips is shown. This plot is based on ten year historical data of a fault recording database where all voltage dips at substation 3 are registered. The voltage dips are measured at a voltage level of 25 kV. In the

plot it can be seen that transmission grid faults are cleared in a time period of 90-120 ms. Voltage dips of the sub-transmission grid are also shown, however the duration of the dips strongly depend on the fault-clearing time of the local protection scheme. Because of the meshed structure of the transmission grid the same kind of voltage dip measurements can be expected at substation 23.

Fig. 8. Overview of voltage dip measurements at substation 3

E. Effect of voltage dips on CHP-plants

Current settings of the under-voltage protection are put at 0.8 p.u. with a clearing time of 100-200 ms. From Fig. 7 it is obvious that all CHP-plants disconnect during a disturbance in the sub-transmission grid. However, due to the resistor grounding, this only occurs during a three phase fault and a two phase-to-ground fault (see Fig. 6). For the fault-clearing time of the transmission grid faults a clearing time of 90 ms is assumed. Fig. 8 shows a scatter in the dip duration of transmission grid faults and especially fault-clearing time in the 150 kV grid can exceed 90 ms. This means that the setting of the under-voltage protection at a clearing time of 100 ms can lead to switching-off of a large amount of CHP-plants. In the next section new settings of the under-voltage protection will be proposed in such a way that unnecessary disconnection of CHP-plants is prevented as much as possible.

V. FAULT RIDE THROUGH OF CHP-PLANTS

During grid disturbances synchronous machines tends to accelerate. In the stable case after fault clearing the rotor swings via an oscillatory motion to the equilibrium point [6]. Small CHP-plants, consisting of a gas engine as prime mover and a synchronous machine as generator, show these dynamics as well. Immediate disconnection of CHP-plants during a voltage dip prevents instability of the generators. However this can jeopardize the security of supply. Hence new settings of the under-voltage protection have to be chosen in such a way that instability of the CHP-plants is prevented.

A. Critical Clearing Time

Keeping the CHP-plants connected to the grid means that the units have to withstand a certain voltage dip without losing synchronism. A measure for stability of synchronous machines is the Critical Clearing Time (CCT). The critical clearing time is the ability of a synchronous machine to withstand a voltage dip with a certain depth and duration and stay in stable operation. For all type of CHP-plants connected to the test system the CCT is determined. In table V the simulation figures of the CHP-plants are given.

TABLE V
SIMULATION FIGURES OF CHP-PLANTS

S [MVA]	P [MW]	H [s]	p.f.
2.475	1.98	0.817	1
3.767	3.01	0.869	1
4.156	3.32	0.862	1

In normal operation the CHP-plants are operated with unity power factor. In [7] it is described in detail how the CCT of the CHP-plants is obtained. In fig. 9 the CCT-curves are depicted.

Fig. 9. CCT-curves for the CHP-plants connected to the test system

B. New protection settings

Now the dynamic behavior of the CHP-plants and the expected voltage dips at the generator terminals are known the new settings for the under-voltage protection can be defined. The goal of the new settings is to prevent disconnection of a large number of CHP-plants. Faults in the MV-grid only affect the local distribution grid while the voltage dip does not propagate via the sub transmission grid to neighbouring MV-grids [1]. Also the dips in the local MV-grid do not cause disconnection of a large number of CHP-plant. To preclude islanding it is even desirable to disconnect the CHP-plants connected to the faulted MV-grid. For the new settings the following principles has been chosen:

- Transmission grid faults: Fault Ride Through of CHP-plants
- Sub-transmission grid faults: Fault Ride Through of CHP-plants
- Local MV-grid faults: Disconnection of CHP-plants

For the assessment of the new settings of the under-voltage protection the possible room offered by the worst case CCT-curve of figure 9 is used. In this study the CHP-plant of 2.475 MVA has the most critical CCT-curve and is taken as a reference. In figure 5 it has been shown that most voltage dips are caused by faults in the 150 kV transmission grid. As stated earlier it is assumed that the average clearing time of these faults is 90-120 ms. The disconnection of CHP-plants due to the dips of the transmission grid can be prevented by setting the first pick-up level of the under-voltage protection at 0.8 p.u. ~ 500 ms. Transmission grid faults are cleared faster than 500 ms so the CHP-plants stay connected.

For deeper voltage dips the time setting of 500 ms exceeds the CCT of the CHP-plants which lead to unstable operation. Therefore extra settings have to be added to the under-voltage protection. The second level of the under-voltage protection is set to 0.5 p.u. ~ 400 ms. This setting prevents disconnection during faults in the sub-transmission grid. In accordance with

the voltage dip profile of fig. 5 the deepest voltage dip of a sub-transmission grid fault is 0.4 p.u. In table IV it is stated that the fault-clearing time of faults in the sub-transmission grid is 300 ms. The under-voltage protection will sense the voltage dip but the fault is cleared before the under-voltage protection trips the CHP-plants.

Although switching-off of CHP-plants because of faults in the (sub)-transmission grid is prevented by the two defined levels, for deep voltage dips the CHP-plants still can become unstable. Therefore two extra levels are defined. For faults in the MV-grid deep voltage dips are expected. Moreover the fault-clearing time in the MV-grid is set to 900 ms. In fig. 9 it is indicated that for deep voltage dips the CCT is rather low and cannot meet the fault-clearing time. To prevent instability of the CHP-plants the two extra levels of the under-voltage protection are set to 0.35 p.u.~200 ms and 0.2 p.u.~100 ms. In case of a fault in the MV-grid these levels are exceeded and the CHP-plants are disconnected. In table VI the settings are summarized and depicted graphically in fig. 10.

TABLE VI
PROPOSED SETTINGS OF THE UNDER-VOLTAGE PROTECTION

	Pick-up voltage [p.u.]	Clearing time [ms]
Level 1	0.8	500
Level 2	0.5	400
Level 3	0.35	200
Level 4	0.2	100

Fig. 10 Proposed protection settings for the under-voltage protection

VI. SIMULATION RESULTS

In order to check the effect of the proposed relay settings on the availability of the CHP-plants after a grid disturbance dynamic simulations are performed. The simulations are carried out with the aid of the test network as described in section III. The cases of interest are:

- Transmission grid disturbance
- Sub-transmission grid disturbance
- Distribution grid disturbance

The model of the CHP-plants is based on a fifth order synchronous machine model which is available in Power Factory. The model is equipped with a generic IEEE type 1 voltage controller. Machine and controller parameters are provided by the manufacturer. The proposed settings for the under-voltage protection are implemented in the relay model which is incorporated in the model of the CHP-plant. In the simulations the behavior of the rotor angle is taken as a stability index. The line-voltage of various busbars in the test

system is used to check if the simulation results are in compliance with the expected behavior of the new settings of the under-voltage protection.

A. Transmission grid faults

The fault in the transmission grid consists of a line fault between sub 22 and 23. In fig. 2 the simulated fault location is indicated. The simulated fault types are a three phase, double phase-to-ground and a single phase-to-ground fault which are simulated for 120 ms. In fig. 11 the line-voltages of sub 23, 26 and 28 are depicted during a three phase fault.

Fig. 11. Voltage dip at various busbars due to a three phase fault in the transmission grid

In fig. 11 it can be seen that the voltage of sub 28 drops below 0.8 p.u. This means that for the conventional setting of the under-voltage protection of 0.8 p.u.~100 ms, it is expected that all CHP plants disconnect. The under-voltage protection with the new proposed settings does not disconnect the CHP-plants during the voltage dip. Fig. 11 also shows the contribution of the CHP-plants to the disturbance. The CHP-plants try to keep up the voltage of sub 28. Because of the decaying DC-component in the current contribution of the generators the voltage starts to drop. After fault clearing the recovery of the voltage of sub 26 & 28 is delayed because of the grid interaction of the CHP-plants. In [8] similar simulations are carried out and the results also show the delayed voltage recovery but is not mentioned explicitly.

A single phase-to-ground fault results in a shallow voltage dip which propagates in the line-voltage as discussed in section II. However it does not lead to a disconnection of CHP-plants. In table VII for all fault types the results are given. For all fault types the fault-clearing time and the accompanying voltage dip is such that the CHP-plants stay in stable operation.

TABLE VII
SIMULATION RESULTS OF A TRANSMISSION GRID FAULT

Fault type	Disconnection of CHP-plants	
	Conventional setting	Proposed setting
3 phase	Yes	No
2 ph-to-gnd	Yes	No
1 ph-to-gnd	No	No

B. Sub-transmission grid faults

The effect of the proposed settings of the under-voltage protection on the CHP-plants is also checked for sub-transmission grid faults. In fig. 3 the simulated fault location is given. The definite over-current protection in the sub-transmission grid determines the dip duration and is set to 300 ms. In fig. 12 for a three phase fault the line-voltage of substation 28 and 29 is shown. The voltage dip exceeds 0.8 p.u. and the under-voltage protection does disconnect all CHP-plants within 100 ms. During the fault, level 1 and 2 of the under-voltage protection are exceeded. After fault clearing the voltage rises above the pick-up value of level 2 and only level 1 stays triggered. Due to the grid interaction of the CHP-plants there is a delay in voltage recovery. Because of this delayed voltage recovery the settings of level 1 are exceeded and at 500 ms the CHP-plants are switched off. Simulations have shown that disconnection of CHP-plants only occurs due to a three phase fault at a certain location. For other locations the CHP-plants do not disconnect. During the simulation of all other types of faults the CHP-plants stay connected and in stable operation. For all types of faults the results are given in table VIII.

Fig. 12. Voltage dip at substation 28 & 29 due to a three phase fault in the sub-transmission grid

TABLE VIII
SIMULATION RESULTS OF A SUB-TRANSMISSION GRID FAULT

Fault type	Disconnection of CHP-plants			
	Conventional setting		Proposed setting	
	Sub 28	Sub 29	Sub 28	Sub 29
3 phase	Yes	Yes	Yes	Yes
2 ph-to-gnd	Yes	Yes	No	No
1 ph-to-gnd	No	No	No	No

C. Distribution grid faults

In this section the effect of the proposed settings are checked with simulations of a fault in the distribution grid. In fig. 13 the MV-grid of sub 28 is shown in more detail. To sub 28 radial MV-feeders are connected including the CHP-plants. The MV-feeders connected to sub 29 are more or less similar to the MV-feeders of sub 28. In fig. 13 the simulated fault location is depicted.

Fig. 13. Details of the MV-grid of substation 28

In fig. 13 in the busbar of substation 28 two coupling breakers are incorporated. For limitation of the fault level the substation is operated with open coupling breakers. However, to study the effect of the coupling breakers the simulations are also carried out for the situation with closed coupling breakers. In fig. 14 the results of the simulation of a three phase fault is given for the case with the closed coupling breakers. The fault duration is 900 ms which is in accordance with the fault-clearing time mentioned in table IV.

Fig. 14. Voltage dip at substation 28 & 29 due to three phase fault in MV-grid of substation 28 (coupling breakers closed)

The voltage dip at substation 28 exceeds the conventional setting as well as the new proposed setting of the under-voltage protection. Hence for both settings all CHP-plants connected to substation 28 will be disconnected. In fig. 14 it can be seen that the CHP-plants of substation 28 are cleared after 200 ms (Level 3 of the under-voltage protection). Because the CHP-plants try to keep up the voltage not all under-voltage protections are triggered at the same time. Therefore there is a small scatter in fault-clearing time of the individual CHP-plants.

The fault also causes a voltage dip at substation 29. The voltage drops below 0.8 p.u. which triggers level 1 of the under-voltage protection. Because of the fault-clearing time of 900 ms, all CHP-plants connected to the MV-grid of substation 29 disconnect in 500 ms. In fig. 14 after 500 ms the busbar voltage of substation 29 shows a sudden decrease which is the moment of the disconnection of all CHP-plants.

The simulations are repeated for the case with the open coupling breakers. Fig. 15 gives the voltage dips at faulted section of substation 28 and the busbar voltage of substation 29. Due to the opening of the coupling breakers only the CHP-plants of the faulted section of substation 28 are disconnected. Therefore there is no significant jump in the voltage of the faulted section of substation 28. For CHP-plants connected to substation 29 level 1 of the under-voltage protection is not triggered.

Fig. 15. Voltage dip at substation 28 & 29 due to three phase fault in the MV-grid of substation 28 (coupling breakers open)

In table IX for the case with the closed coupling breakers the results for all simulated fault types in the MV-grid of substation 28 are shown. The results for the case with the open coupling breakers are given in table X.

Because the MV-grid is operated with an isolated neutral the CHP-plants do not disconnect during single phase-to-ground faults. In systems with an isolated neutral these faults do not lead to a voltage dip in the line-voltage.

TABLE IX
SIMULATION RESULTS OF A FAULT IN THE MV-GRID OF SUBSTATION 28
(COUPLING BREAKERS CLOSED)

Fault type	Disconnection of CHP-plants			
	Conventional setting		Proposed setting	
	Sub 28	Sub 29	Sub 28	Sub 29
3 ph	Yes	Yes	Yes	Yes
2 ph-to-gnd	Yes	No	Yes	No
1 ph-to-gnd	No	No	No	No

Unnecessary disconnection of the CHP-plants of substation 29 can be prevented by reducing the fault-clearing time in the MV-grid. The unnecessary disconnection of CHP-plants in substation 29 is initiated by exceeding level 1 of the proposed settings which switches off the CHP-plants in 500 ms. When in substation 28 the fault-clearing time is reduced from 900 ms to 300 ms the CHP-plants of substation 29 stay connected. Reducing the fault-clearing time to 300 ms reduces the voltage dip duration and unnecessary disconnection of CHP-plants is prevented. The fault-clearing time can be reduced by applying an extra pick-up level in the definite over-current protection which is also mentioned in [8]. The settings are such that the protection only picks up severe fault currents.

TABLE X
SIMULATION RESULTS OF A FAULT IN THE MV-GRID OF SUBSTATION 28
(COUPLING BREAKERS OPEN)

Fault type	Disconnection of CHP-plants			
	Conventional setting		Proposed setting	
	Sub 28	Sub 29	Sub 28	Sub 29
3 ph	Yes	No	Yes	No
2 ph-to-gnd	Yes	No	Yes	No
1 ph-to-gnd	No	No	No	No

VII. CONCLUSIONS

In this paper the fault ride through behavior of MV-connected CHP-plants is discussed. It is shown that the conventional settings of the under-voltage protection lead to disconnection of CHP-plants during grid disturbances. To define new settings for the under-voltage protection the approach of voltage dip profiles is chosen. The voltage dip profile shows that most voltage dips are caused due to transmission grid disturbances. For these dips there is no need to disconnect the CHP-plants and the settings of the under-voltage protection are chosen such that this is prevented.

For the new settings of the under-voltage protection four levels are defined. The settings of these levels are based on the expected voltage dips at the terminals of the CHP-plants and the CCT of the CHP-plants. With the aid of dynamic simulations the proposed settings are checked. It can be concluded that the approach of the voltage dip profile is a good starting point but the dynamics of the voltage dip have also be taken into account. The simulation results show that the new settings prevent disconnection of CHP-plants during faults in the transmission grid. For the sub-transmission grid most faults do not lead to a disconnection of CHP-plants. Because of the short feeder length in the sub-transmission grid for some three phase faults the CHP-plants are switched off.

As proposed, for faults in the distribution grid a limited number of CHP-plants disconnect. This number can be further reduced by reducing the fault-clearing time for faults in the MV-grid.

In general the approach described in this paper can also be applied to other transmission and distribution grids. Different voltage dip profiles can lead to different trigger levels of the under-voltage protection. Moreover, different fault-clearing times of the transmission and distribution grid protection schemes in combination with the critical clearing times of other types of rotating DG can lead to different clearing times of the under-voltage protection. However, the approach still holds.

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Wil Kling (M'95) was born in Heesch, the Netherlands in 1950. He received the MSc. degree in electrical engineering from the Technical University of Eindhoven, the Netherlands, in 1978. From 1978 to 1983 he worked with KEMA and from 1983 to 1998 with Sep. Since then he was with TenneT, the Dutch Transmission System Operator, as a senior engineer for network planning and network strategy. Since 1993 he is a part-time Professor at the Delft University of Technology and since 2000 he was also a part-time Professor in the Electrical Power Systems group at the Eindhoven University of Technology, the Netherlands. At the end of 2008 he is appointed as a full-time professor and chair of the EPS group at the Eindhoven University of Technology. He is leading research programs on distributed generation, integration of wind power, network concepts and reliability. Mr. Kling is involved in scientific organizations such as Cigre and IEEE. He is the Dutch representative in the Cigre Study Committee C6 *Distribution Systems and Dispersed Generation*.