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Protection, Transient Stability and Fault Ride-Through Issues in Distribution Networks with Dispersed Generation

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***Abstract*—This paper describes the transient stability analysis of a 10 kV distribution network with wind generators, microturbines and CHP plants. The network being modeled in Matlab/Simulink takes into account detailed dynamic models of the generators. Fault simulations at various locations are investigated. For the studied cases, the critical clearing times are calculated. Some network parameters which influence transient stability are also observed. The compliance of DG protection to stability criteria requirements is further studied. The ride-through capability of the DG units is also investigated through transient stability analysis and the equivalent CCT-voltage dip curves are derived. It is concluded that during fault DG unit availability can be increased through modification of undervoltage protection requirements.**

I. INTRODUCTION

NOWADAYS, intensive efforts are done to utilize both renewable energy sources (such as wind) and high efficiency Combined Heat Power (CHP) schemes to generate electric power. The generators are mostly integrated into utility networks at distribution voltage level and they are commonly referred to as 'Distributed Generators' (DGs). Various investigations conducted by industry and academia have shown that DGs could affect negatively the host distribution network in a number of ways.

This paper reports an investigation related to the determination of the Critical Clearing Time (CCT) of DGs when a variety of disturbances occurred on the network. Such CCT is determined by the onset of a DG becoming unstable. The study is conducted on a simulated system consisting of a distribution network (DN) with DGs using SimPowerSystems toolbox. Results obtained from several case studies are presented and evaluated. Calculation of CCTs is also provided for the most critical network element both for external faults and at its terminal. The derived curves are compared with typical used undervoltage protection requirements and meaningful conclusions are made. The compliance with the transient stability requirements in respect to the DG protection is additionally examined.

II. THE CONCEPT OF CRITICAL CLEARING TIME

In IEEE report [1] the critical clearing time (CCT) is defined as "the maximum time between the fault initiation and its clearing such that the power system is transiently stable". For synchronous generators (SG) there exists a maximum rotor angle (critical clearing angle) below which SG can retain a stable operation. The corresponding maximum clearing time is known as critical clearing time. However, the CCT for an induction generator is the maximum time of the fault to be cleared, within the time span that the induction generator is able to retain its stability. Stability of an induction generator can be evaluated based on its mechanical speed [2]. In this work, the CCT is defined as the smallest from all CCT values for different generators.

III. MODELING OF THE MV GRID USING MATLAB/SIMULINK

The analyzed system is shown in Figure 1. Modeling and simulations is done by using Matlab/Simulink and SimPowerSystems toolbox. Table I describes the type and the number of DGs.

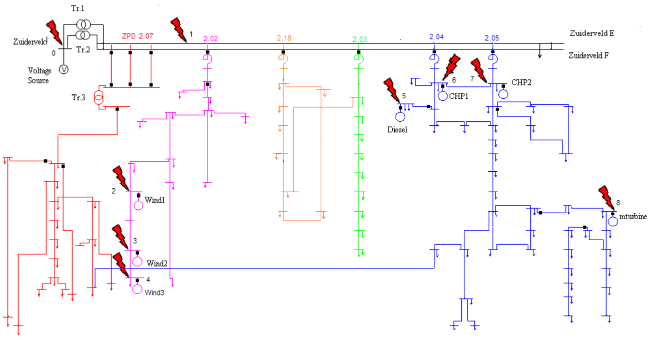


Figure 1. Schematic diagram of the investigated network with DG

A detailed description of the wind turbine models is shown in [3]. The diesel generator model [4] is characterized by the electrical and mechanical equations of a synchronous machine. Excitation and governor circuits of the generator are modeled as well. The model parameters of the split shaft microturbine and its detailed description can be found in [5]. Since the electromechanical behavior is of main interest for this study, the recuperator and the heat exchanger are not included in the model. The CHP model is an aggregated model consisting of 10 microturbines. All generators are connected to the distribution network through transformers. The loads are represented by constant impedances. The system, to which the DN is connected, is assumed to be an ideal voltage source.

TABLE I
DG POWER RATINGS

DG Type	**S_{nom} [MVA]**
Wind turbine 1	0.66
Wind turbine 2	0.66
Wind turbine 3	0.66
Diesel	3.125
CHP1	2.5
CHP2	2.5
m-turbine	0.25

IV. INVESTIGATED CASES

A. *CCT Calculation*

The system is subjected to various three-phase faults at different locations. In order to determine the critical clearing times of the DG units, simulations are performed for different fault durations. Protection of DG as well as network protection is omitted. We start first with long time duration of approximately 2 s, and then we halve the time duration. In Table II CCTs and critical generators are presented for various fault locations (shown in Figure 1). M stands for microturbine, CHP_1 stands for CHP_1 plant. For fault locations 2, 3 and 4, it turns out that all generators are stable even for maximum fault duration of 2 s. As it can been concluded from Table II, the critical system element is the microturbine and the critical fault location is the high voltage side of the substation. In the worst case the CCT=554 ms, and assuming that a normal DG protection tripping time is in the order of 200 ms and the breaker opening time in the order of 100 ms, DGs transient stability is not actually endangered.

TABLE II
CRITICAL GENERATORS AND THEIR CCT

Fault Location	0	1	5	6	7	8
t_{cct} [ms]	554	562	962	636	582	662
Critical generator	M	M	CHP_1	CHP_1	M	M

B. *Behavior of DGs During Fault Conditions and During the Post-Fault Period*

Once the critical clearing times are determined, the behavior of the generators during a disturbance and following the clearance of a fault is investigated. In this particular case, the microturbine, being the most critical generator in the network, is chosen. The behavior of the microturbine following a three-phase-to-ground fault with duration of 612 ms at locations #1 and #8 is examined. One of the most meaningful observations is related to the fact that a short-circuit at the terminals of the microturbine (fault location #8) is less critical than the fault at the common busbar of the substation (fault location #1). It can be observed that even though the transient behavior of the microturbine during a short-circuit is important, in particular cases the restoration of the voltage profile in the network after the disturbance is even more critical. In this sense the post-fault voltage restoration on the common busbar is crucial. Figure 2 illustrates the comparison of the variation of the substation voltage for both cases. For fault location #1 the substation voltage drops nearly to zero during the fault, then after clearance of the fault the voltage immediately rises and afterwards slowly restores to the pre-fault level. If this restoration is too slow, voltages in the network remain to be depressed and the stability of certain generators might be lost.

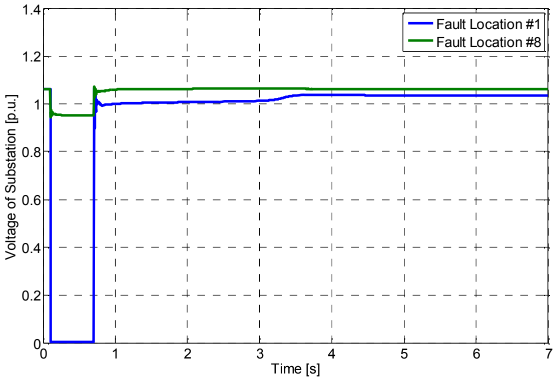


Figure 2. Substation voltage following a three phase 612 ms fault for fault location #1 and #8.

The variation of the microturbine terminal voltage for both cases is depicted in Figure 3. It can be observed that although the terminal voltage during the disturbance is lower for fault location #8 than for location #1, the situation is vice versa after the fault. The justification of this observation is strongly related to the nature of the post-fault common busbar restoration. Additionally, the magnitude of the substation voltage dip (for location #8 the common busbar voltage during the fault lies around 0.9 p.u., while for location #1 is nearly 0) plays a significant role.

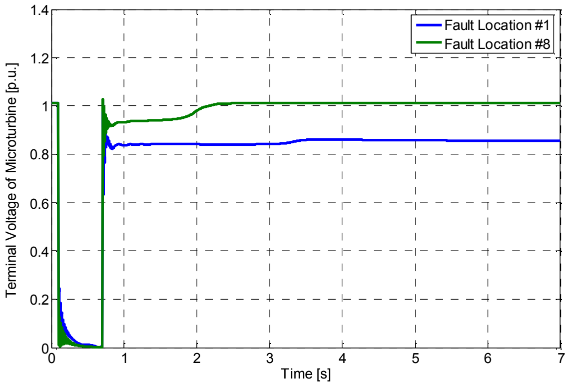
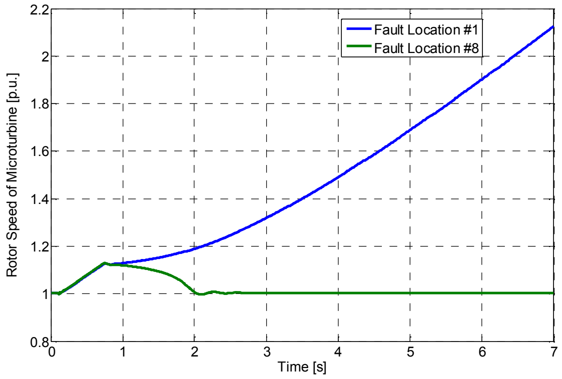
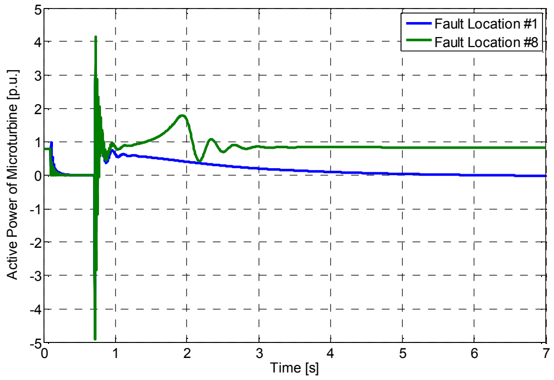


Figure 3. Terminal voltage of microturbine following a three phase 612 ms fault for fault location #1 and #8.

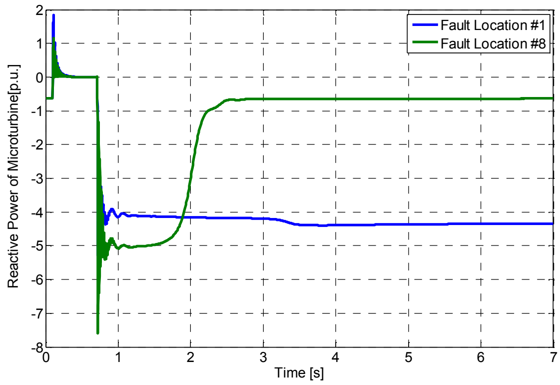
Figure 4 displays the variation of the active/reactive power and of the rotor speed of the microturbine for the different fault locations. It is shown that for fault location #1 the microturbine cannot retain normal operation because the clearing time is greater than 562 ms. It also shows that when the fault is cleared for time spans larger than the CCT, the mechanical speed of the induction generator continues to increase. While for the same fault location the generator is delivering power during the disturbance, after the clearance of the fault the active power of the microturbine becomes zero and no electric power is delivered to the grid. In the contrary, after the disturbance isolation of location #8 the generator retains its stability and regains its normal p.u. active power.



(a)



(b)



(c)

Figure 4. (a) Rotor speed of the microturbine following a three phase 612 ms duration fault for fault location #1 and #8. (b) Active power of the microturbine following a three phase 612 ms duration fault for fault location #1 and #8. (c) Reactive power of the microturbine following a three phase 612 ms duration fault for fault location #1 and #8.

C. *Microturbine CCT Calculation for External Faults*

Finally, the CCTs of the microturbine in case of different external faults are determined. The ideal voltage source of the grid model (which represents the external grid) is substituted by a three phase programmable voltage source accompanied by its equivalent source impedance. An iterative procedure is followed for the extraction of the CCT points. The value of the voltage dip magnitude is adjusted to a certain value and the duration of the voltage dip is modified repetitively until the determination of the stability boundary (CCT). The magnitude of the voltage dip indicates the distance to the fault in the external grid. When this iteration is completed the process starts all over for a different voltage magnitude. The results are illustrated in Table III (V_{grid} is the external grid voltage). It can be concluded that the CCTs in case of external short-circuits increase with the distance to the fault, and for a remaining voltage level of the external grid of 0.6 p.u. and more there is no problem with the transient stability.

TABLE III
CCT OF MICROTURBINE FOR DIFFERENT EXTERNAL FAULTS

V_{grid}, **p.u**	0	0.1	0.2	0.3	0.4	0.5	0.6
t_{cct} [ms]	539	573	652	777	1025	1767	stable

V. INVESTIGATION OF MICROTURBINE FAULT RIDE-THROUGH CAPABILITY

Nowadays, international standards and national grid codes specify requirements for the connection of DG units to distribution level grids. The common practise is to immediately disconnect the units. However, as the aggregate DG installed capacity increases, this will be no longer acceptable and new requirements for the integration of the

DG units will be needed. Thus it can become important to keep them connected to the grid. In this section the ride-through capabilities of the network related DG units are examined with the aid of their CCTs determination.

The Critical Clearing Times of the microturbine are determined for faults at each terminal. The ride-through capabilities of the microturbine are determined based on the method explained in [6]. The microturbine is connected through a 0.5 km cable to the programmable voltage source. The test network is implemented in Matlab / Simulink. For each amplitude value of the applied voltage dip, the duration value of the voltage dip is modified and the CCT times are determined. The results are illustrated in Table IV.

TABLE IV
CCT OF MICROTURBINE FOR FAULTS AT ITS TERMINAL

V_{grid}, **p.u**	0	0.1	0.2	0.3	0.4	0.5	0.6
t_{cct} **[ms]**	655	691	760	882	1130	1691	stable

The extracted points are utilized for the formulation of the blue curve in Figure 5. The green CCT-voltage dip curve, (depicted in the same figure) corresponds to the points extracted in section IV_C. The comparison of the two curves emphasises the fact that an external fault is worse from CCT point of view than a fault at the terminals of the microturbine. The typical Dutch undervoltage protection settings (0.8 p.u. for the voltage dip magnitude and 0.2 ms for the voltage dip duration) are also depicted on the same figure. Additionally, the undervoltage protection settings utilized by the German grid operator E.on Netz (for generating units with a high symmetrical short circuit current) are illustrated (red curve).

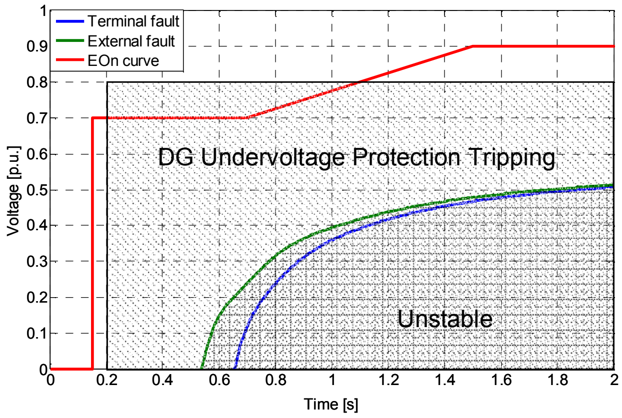


Figure 5. CCT of the microturbine as a function of the voltage dip (remains voltage) for different external faults and for faults at its terminal. Comparison of both the typical Dutch undervoltage protection settings and the equivalent settings of the grid operator E.on Netz with the derived CCT-voltage dip curves.

A comparison between the typically used undervoltage protection settings and the derived CCT-voltage dip curves reveals that while in most cases the DGs are immediately disconnected, from stability point of view they could actually remain connected to the grid and support it after the clearance of the disturbance. In this sense, the adjustment of the DG undervoltage protection settings according to the CCT-voltage dip curves can significantly increase the availability of the generation units.

However, special attention has to be paid during this adjustment since the CCT-curve, which is determined based on the simulation of the three-phase fault on the terminals of generator, does not necessarily represent the worst case situation. External faults sometimes might be more critical. Therefore to prevent instability for such situations (for the points in between green and blue curves on Figure 5) certain safety margin has to be introduced to the settings of undervoltage protection of DG.

Exactly the same procedure was repeated to determine the CCT curve of the rest DG units. The derived CHP CCT-voltage dip curve is approximately identical to the microturbine one. Simulations concerning the wind turbine and diesel generator models reveal that these generators are always stable even for the worst voltage dip depth and duration.

VI. OPERATION OF DG PROTECTION

The DG units' protection of the Lelystad network is implemented. The following DG protections are implemented: instantaneous overcurrent, definite overcurrent (positive sequence), current unbalance, undervoltage (positive sequence), overvoltage (positive sequence), voltage unbalance (negative sequence), voltage unbalance (zero sequence), underspeed and finally overspeed [7].

After that, simulations are implemented for faults at different locations in the network and the minimal fault durations, for which the protection trips, are determined for the different generators. The results are displayed in Table V. The columns correspond to the fault locations, the rows to the generators. The fault durations are given in milliseconds. In most of the cases the protection operates around 200 ms and the undervoltage protection trips first.

TABLE V
MINIMAL FAULT DURATIONS THAT LEAD TO GENERATOR TRIPPING

	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Wind1	189	187	189	190	190	-	210	211	-
Wind2	189	187	189	189	189	-	210	211	-
Wind3	189	187	189	189	189	-	210	211	-
Diesel	191	187	-	-	-	-	-	-	-
CHP1	189	187	-	-	-	192	188	215	-
CHP2	188	187	-	-	-	-	211	188	207
turbine	187	187	-	-	-	335	208	187	187

Comparison between the results of the protection operation and the DG's CCT calculation reveals that in any situation the protection of the DG prevents their transient instability. However, the results also verify the fact that even for an extremely short disturbance, tripping of all generators in the area can occur.

VII. CONCLUSIONS

Several studies have been carried out to determine the effect of the clearing time of a fault on the network stability of DGs. Results obtained from the studied cases are presented and discussed.

Simulations have shown that transient stability of DG units in the studied network is in general not endangered. Microturbine appears to be the most critical element due to its low inertia. Then transient stability analysis for microturbine in case of external faults (distant faults in transmission network) was performed. Based on the analysis it can be concluded that severe external faults are even more critical than the fault on the terminals of generator. External faults resulting in remains voltage of 0.6 p.u. and higher do not endanger transient stability at all.

Present settings of DG undervoltage protection (0.8 p.u., 200 ms) might lead to massive tripping of DG units over large areas in case of short-circuits at the transmission level. Therefore adjustment of DG undervoltage protection is necessary to comply with fault ride-through requirements. This adjustment can be based on CCT-voltage dip curve of generator, which represents the case of fault on the terminals of generator (as proposed in [6]). By doing this, availability of DG units can be significantly increased. However, as illustrated in this paper, some external faults might be more critical than the terminal one. Therefore, certain safety margin has to be introduced to the DG undervoltage protection settings in order to avoid possible instabilities.

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