Response of MV-connected Doubly-Fed Induction Generator Wind Turbines and CHP plants to Grid Disturbances

Citation for published version (APA):
Karaliolios, P., Slootweg, J. G., & Kling, W. L. (2010). Response of MV-connected Doubly-Fed Induction Generator Wind Turbines and CHP plants to Grid Disturbances. In *Proceedings of the IEEE Power and Energy Society General Meeting 2010, 25-29 July 2010, Minneapolis USA* (pp. 1-6). Institute of Electrical and Electronics Engineers. https://doi.org/10.1109/PES.2010.5589542

DOI:
10.1109/PES.2010.5589542

Document status and date:
Published: 01/01/2010

Document Version:
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Download date: 04. Oct. 2023

Response of MV-connected Doubly-Fed Induction Generator Wind Turbines and CHP-plants to Grid Disturbances

P. Karaliolios, *Student Member, IEEE*, J.G Slootweg, *Member*, *IEEE* and W. L. Kling, *Member, IEEE*

***Abstract*--Notwithstanding the positive environmental impact, the increasing penetration of Distributed Generation (DG) units connected to the distribution network raises new topics concerning the expected response of these during outages. Grid disturbances especially at the transmission level can cause the unwanted disconnection of large amounts of DG, leading to undesired power imbalances causing line overloadings and/or voltage and frequency instability. This paper examines how transmission network faults can affect the operation of DG units connected on to the distribution network, how these units currently contribute to the voltage support and what are the consequences of actual and possible Fault Ride-Through (FRT) behaviors.**

***Index Terms*--Decentralized Generation, Fault Ride-Through, Short-Circuit contribution, CHP-plant, Doubly-Fed Induction Generator.**

I. INTRODUCTION

THE continuous increase in energy consumption as well as the demand for clean and renewable energy is leading to fundamental changes in the way electricity is produced. Nowadays more and more generators are connected on to the distribution network and their share in the production is expected to be significantly increased in the near future. In the recent past, several grid codes would oblige immediate disconnection of DG units connected on to the distribution network, in order not to interfere with the installed protection scheme and to guarantee personal safety by avoiding unexpected energizing of the network from distributed generators. However, in many cases, the penetration level has increased to such an extent that DG units form a considerable amount in the energy production. As a result, immediate disconnection can lead to a severe mismatch between load and generation which can cause line overloadings and frequency or voltage instability in (parts of) the system. Therefore, the decision of disconnection or not of DGs has to take into consideration the load flow and branch capacities, frequency and voltage stability issues as well as fault current contribution and personal safety, which were the decisive considerations so far.

Thus, in order to ensure security of supply, several grid operators have adapted their codes, incorporating fault ride-through (FRT) requirements. However these apply for units connected on to the transmission network, e.g. wind parks, which have to be treated more or less as conventional power plants [1].

In this paper a comparison of the behavior of two different types of DG during disturbances in the transmission grid will be studied. The reason that it focuses on outages in transmission grid is due to the much more widespread effect that these have. The test grid used in this paper is an existing network in western part of the Netherlands. The grid is modeled in detail, including both the transmission and the distribution network. The modeled distribution network contains a large amount of combined heat and power (CHP)-plants. In [2], the effect of different fault types occurring in the transmission system on the FRT behavior of the CHP-plants is discussed. In this paper, in the same distribution grid CHP-plants have been replaced by Doubly Fed Induction Generator (DFIG) wind turbines, in order to make a comparison of these two types of DGs on the way that they react on short-circuits (S/C) from the perspective of ability to stay connected, voltage support and fault current contribution. It has to be mentioned that all units in practice are equipped with undervoltage protection, whose settings are not aiming towards voltage support; however, for study purposes, this has been changed, thus creating a situation which may exist in few years.

In the first part of the paper, a short discussion about the current practice for FRT requirements is made. According to this, the research question of the paper will be drawn. Then, the study case, consisting of the network and models for the DG will be presented. In order to evaluate the problem, critical cases are identified with static short-circuit calculations, according to IEC standards, and then dynamic simulations are performed in order to examine the real behavior of the generators. This procedure is described in the fourth part. Then, the results from the dynamic simulations are presented. Finally, the effect of the current FRT requirements as well as

---

This research has been performed within the framework of the IOP-EMVT research program ‘Intelligent Power Systems’ that is supported financially by SenterNovem. SenterNovem is an agency of the Dutch Ministry of Economic Affairs.

P. Karaliolios is with the Electrical Energy Systems group, Eindhoven University of Technology, 5600 MB Eindhoven, the Netherlands (e-mail: p.karaliolios@tue.nl)

J.G. Slootweg is with the Electrical Energy Systems group, Eindhoven University of Technology, 5600 MB Eindhoven, the Netherlands (e-mail: j.g.slootweg@tue.nl). He is also with the Asset Management Department of Enexis B.V., PO Box 856, 5201 AW ‘s Hertogenbosch, the Netherlands (e-mail: han.slootweg@enexis.nl).

W.L. Kling is with the Electrical Energy Systems group, Eindhoven University of Technology, 5600 MB Eindhoven, the Netherlands (e-mail: w.l.kling@tue.nl).

978-1-4244-6551-4/10/$26.00 ©2010 IEEE

the proposed ones together with new settings of the under-voltage protection, on the voltage support and S/C contribution for the two types of DG are discussed.

II. DG EFFECT ON DISTRIBUTION GRIDS

A. General

Due to the introduction of local generation, the distribution grid is currently changing from being passive to active. The various issues that have arisen, such as interference with the protection scheme, increase in short-circuit level etc. are discussed in [3].

Earlier standards, such as [4], in order to eliminate the interference of DG with the network during faults suggest their immediate disconnection in such cases. Newer approaches, incorporated especially in Transmission Grid Codes (e.g. [1]), set conditions according to which DG units should stay connected and support voltage recovery. These conditions are defined as the desired FRT behavior of the connected DG. However, it has to be mentioned that these approaches mainly focus in wind parks connected on to the transmission system, and not for individual generators connected to distribution networks. Given that large amounts of DG connected to "mixed" distribution networks also supplying MV and LV consumers interact with the system in a similar way as large wind parks, the question whether the limitation of generation connected to the transmission system is appropriate, or whether extension of FRT requirements should be extended to individual DGs connected to "mixed" distribution networks. This is the topic of this paper.

B. Problem Definition

In the Netherlands, there are currently no FRT requirements for units smaller than 5 MW connected in the MV network [5]. However, with the increased penetration of DG, it has to be examined how important it is to keep DG units connected and enforce a specific strategy towards active contribution in the voltage support during and after short-circuit (S/C) events. Therefore it is important to know how different types of DG behave during and after such events.

Based on this, the following research questions are posed:

1) How do different types of DG units react on S/C events?
2) How do currently adopted FRT strategies affect voltage support?
3) Is there a need for voltage support in the type of network examined?
4) What improvements can be made towards a more effective voltage support from certain DG units?

To answer these questions, a proper test network as well as models for the examined DG, are needed.

III. DESCRIPTION OF THE MODELS

A. CHP-Plant Model

A CHP-plant is a gas engine which drives a synchronous generator. Manufacturers of the installed CHPs provide data for the proper modeling of the generator, which are used as parameters in the synchronous machine model available in DIgSILENT Powerfactory. The model used is of 5th order. It has to be mentioned that the dynamics of the gas engine are neglected as for the time scale of the events considered in this paperand its inertia is incorporated in the inertia of the synchronous machine.

All CHP-plants are equipped with an Automatic Voltage Regulator (AVR), which is also modeled. However, currently, CHP-plants do not contribute actively to the voltage regulation and the AVR is used as a power factor controller.

B. DFIG Model

For the simulations with the DFIG wind turbines, the generic model provided by DIgSILENT is used as depicted in Fig. 1. In this model both mechanical and electrical parts are considered. The wind turbine is modeled with a two-mass shaft system, which for transient calculations is proved to have adequate accuracy [6].

Grid and rotor-side converter are represented as standard six-transistor bridge voltage sources in the fundamental frequency and sinusoidal pulse width modulation is applied. All the internal controls are also modeled in detail. The grid-side converter also incorporates routines to contribute to voltage support as proposed in [7]. Wind turbines have various protection systems, in order to ensure their proper operation during fault conditions such as over-speed, over-voltage and under-voltage protection. Apart from the basic protection routines, which are incorporated in the model, the DFIG uses also a crowbar in order to protect the converter from excessive currents which occur during severe transients, such as voltage dips and S/C clearances. The effect of crowbar protection in the enhancement of the stability as well as the fault ride-through capability of the generator has been discussed extensively in [7]. In [8] it is also shown that it affects the S/C contribution of the generator; therefore, it is also incorporated in the model used for the simulations presented in this paper.

C. Network Model

In order to investigate the behavior of different types of DG during various voltage dips, an existing grid that is currently operated in Netherlands is used as a study case. In this model a

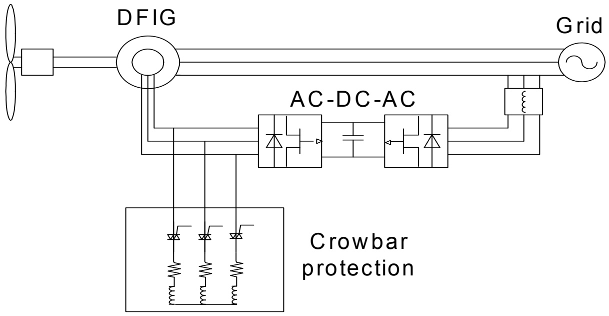


Fig. 1. DFIG schematic

large area is covered, which, as it can be seen in Fig. 2, consists of a national transmission grid operating at 380 kV, with connections to the local transmission grid at 3 points (substations 1, 2 and 23 respectively).

The local transmission grid operates at 150 kV. On this level, several heavy industries like refineries, chemical plants etc are connected. In most of them large CHP plants rated up to 60 MVA are installed.

The distribution grid connected to the substation 23 (see Fig. 2) is located in a greenhouse area and contains a large penetration of CHP-plants. The substation 23 is connected to the transmission grid via 150/25 kV transformers. The 25 kV side of the transformers is grounded through a 10 Ω resistor.

The local distribution network, which is of radial structure, is operating at 10 kV, with the neutral point of the transformers ungrounded.

It has to be pointed out that Dutch electrical grids do have some special characteristics that differentiate them from other countries such as the high S/C level, extended cable network and small feeder distances due to exceptionally high load density. The validity of the results presented here is of course limited to cases with similar characteristics, but the applied method is generally applicable. In both CHP-plants and DFIG the current protection strategy adapted was used as a starting point.

D. *Load model*

There are various ways to represent loads in power system studies [9]. As mentioned above, the model of the network includes the transmission and distribution system down to 10 kV level. Industrial loads as well as local residential network are aggregated and modeled as constant power load, as is normally done in power system dynamics simulations. This modeling approach neglects the interaction of the loads with the network during a transient period. A more accurate representation would require a detailed modeling of the loads which would take into consideration dynamic aspects such as load tripping, voltage dependence [10], but is considered beyond the scope of this paper .

IV. DESCRIPTION OF THE STUDY PROCEDURE

A. *Assessment of Voltage Dips to S/C Events*

In order to be able to investigate the reaction of various DGs in different abnormal conditions, it is important to know how various S/C events are associated with specific voltage dips. S/C can happen in every level of the grid, however, S/C occurring in a transmission system have a characteristic that makes their examination from stability point of view more important than others. They cause a much more widespread disturbance, which makes them much more critical.

In the examined network, all DG units are connected in the distribution network fed by “Substation 23”, therefore preliminarily through static S/C calculations an assessment of 3-ph S/C to voltage dips in this substation is made. The duration of the S/C was 100 ms, which is the time that reclosers need to clear a disturbance in the transmission system and was applied in the middle of the lines. This first approach was chosen as due to the detailed modeling of the system, it would be extremely time consuming to perform dynamic simulations for every faulted case.

A fast and reliable method for S/C studies is to use IEC standards [10]. The accuracy of this method has shown to be adequate for networks that have traditional types of generators, however, it can lead to over-estimation in case that converter interfaced DG are installed. In [8] a way to cope with this over-estimation is presented, which has shown to lead to results much closer to those obtained by electromagnetic transient simulations.

The results of these calculations are presented graphically in Fig. 3, where it is shown how S/C applied in the middle of the lines create voltage dips in Substation 23, categorized in the following cases:

1.1 $0.5< U_{Sub23} < 0.6$ p.u.
1.2 $0.6< U_{Sub23} < 0.7$ p.u.
1.3 $0.7< U_{Sub23} < 0,8$ p.u.

B. *Simulation Approach*

From the static simulations, the case which results in the

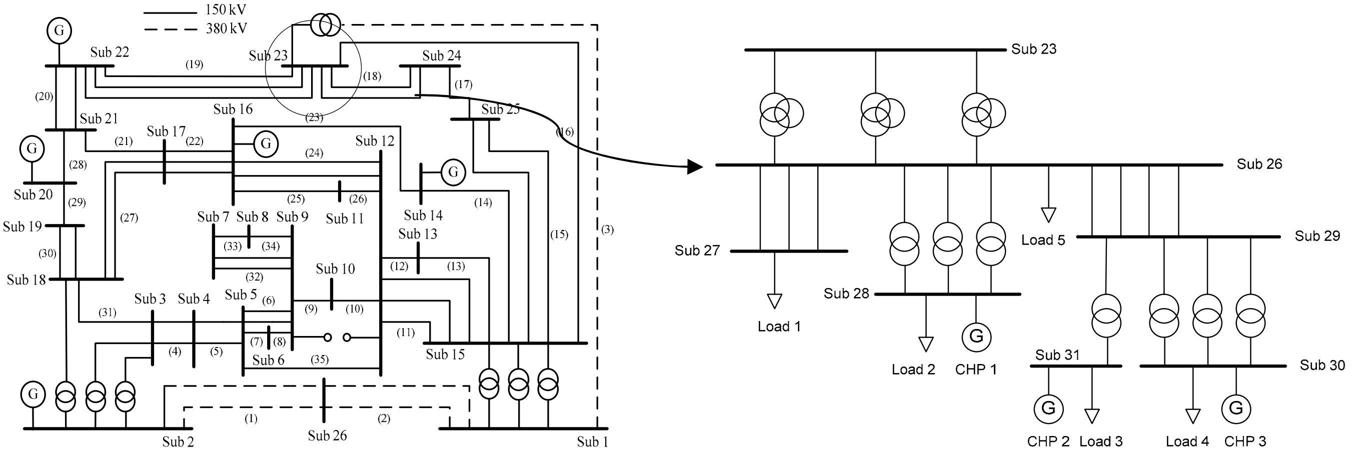


Fig. 2. Network schematic

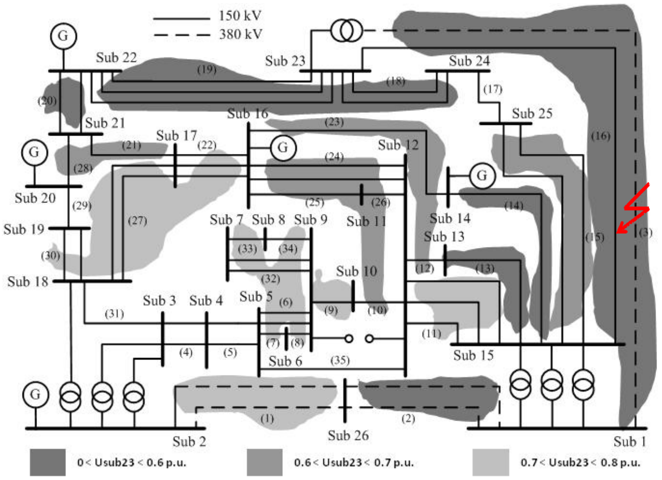


Fig. 3. Effect of S/C on voltage level of Substation 23

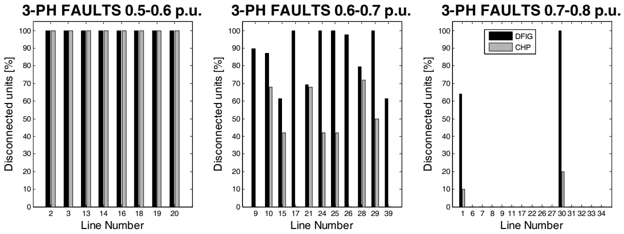


Fig. 4. Number of disconnected DGs

severest voltage dip was selected for further investigation in order to have an overview of the reaction of the DG.

With the current adopted no FRT requirements, DGs would disconnect for a sustained voltage dip of more than 0.8 p.u. if it lasts longer than 100 ms. The consequences of this protection strategy in case of S/C in the transmission system are a disconnection of large amount of DG, depending on the severeness of the voltage dip and the type of the DG, as it is summarized in Fig. 4 and described more in detail in [11].

Considering this strategy as a starting point, in case of deep voltage dips <0.6 p.u. all the DG are disconnected. As it has been proven in [2], it is possible here to keep CHPs connected for a prolonged period of up to 200 ms, depending on the voltage dip, without endangering their stability By adopting these alternative settings, practically all DG units will survive any S/C occurring in the HV grid and stay connected, as protection will clear the fault in time. Based on this, results of DG support during and after S/C are presented bellow. A S/C event occurring in line 3 which results in a voltage dip of 0.5 p.u. in Substation 23 is simulated (Fig. 2).

For this S/C, 5 different scenarios where considered. Firstly no DGs were incorporated in the network, in order to have a view of the reference situation. Then the network is simulated in its current situation with the CHPs installed with undervoltage protection triggering at 100 and 200 ms. Finally, all CHPs where replaced with DFIGs, dispatched with the same output power as the former DGs, operating at 3 different modes (Fig. 5).

Wind turbines installed at the distribution network level, for cost reduction, do not incorporate any voltage support through reactive power, as it is obliged for wind turbines installed in wind farms in HV network. For this type of wind turbines, the rotor side converter is able to provide reactive current during voltage dips according to a predefined pattern. Therefore, for the DFIG, two different situations are simulated, one corresponding to the current situation and one assuming voltage support through reactive power. The implementation of this strategy is possible by controlling the reference signals in the converter and in effect the reactive current reference signal so as to correspond with the output mentioned in [1].

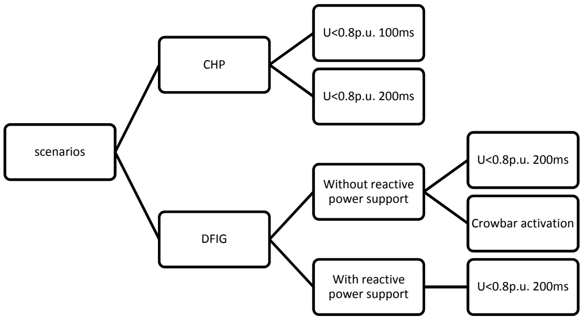


Fig. 5. Simulation scenarios

C. Simulation Results

In Fig. 6 the effect of this S/C in the 10kV level is shown. As it can be seen, the voltage levels during and after the S/C, depend on the type of DG. The S/C event can be divided in three periods, the subtransient period, during the first cycles, the transient period and the clearance of the S/C, where the voltage recovery occurs. The different S/C behavior is the main cause for the different voltage profiles throughout the S/C event as well as the period which follows after the clearance. As it can be seen in Fig. 6 the CHP-plants which act as synchronous generators are able to provide a much higher voltage support in the beginning of the S/C event. This is a result of the high S/C current that it is fed from the generator (Fig. 7), however is still not enough to prevent the triggering of the undervoltage protection with the 100 ms pick up time. On the other hand, the DFIG in the subtransient period has a much more limited S/C power and the voltage decrease is stiffer.

During the transient period, the controller of the DFIG

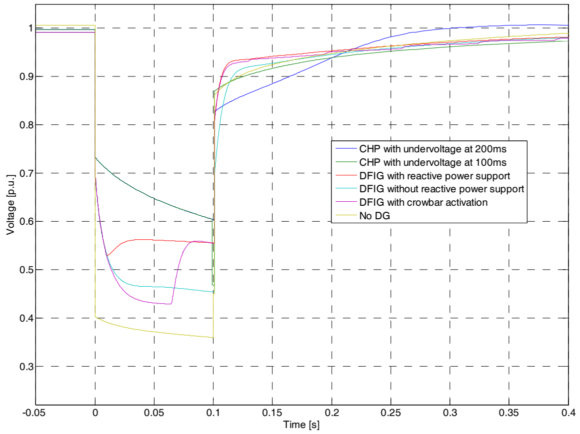


Fig. 6. Voltage at 10 kV

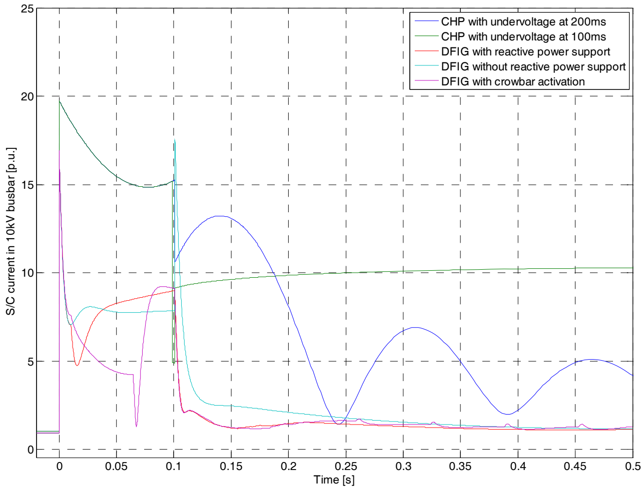


Fig. 7. S/C contribution of different operation scenarios

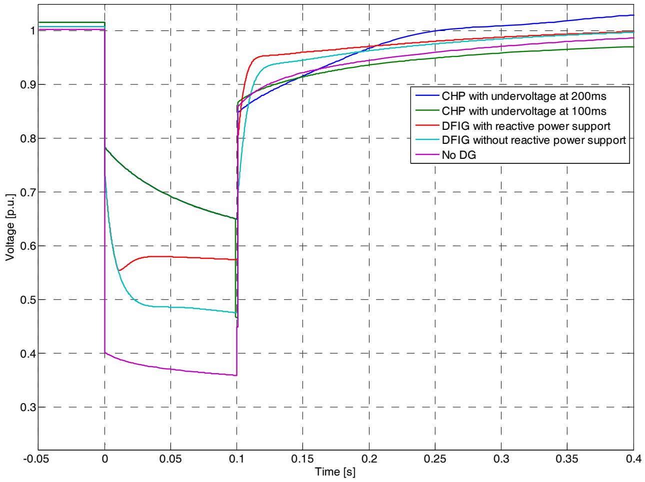


Fig. 8. Voltage at DG terminals

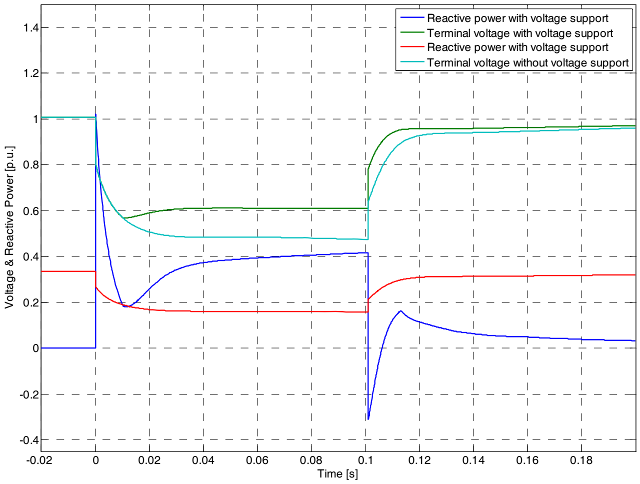


Fig. 9. Application of active voltage support

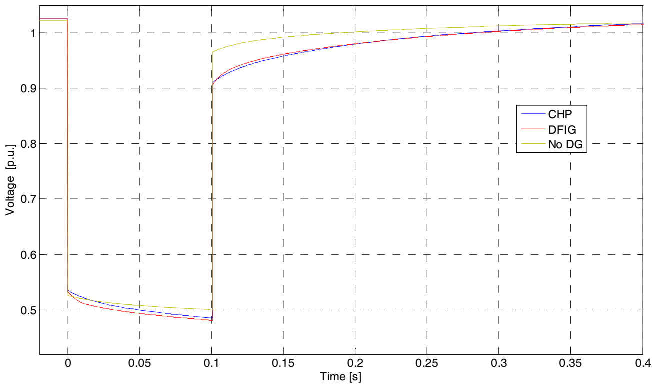


Fig. 10. Voltage at 150 kV level in Substation 23

detects the voltage drop (Fig. 8) and starts to provide reactive power if it incorporates voltage support routines. Since the dip is not very low, voltage support through reactive current is still possible. According to [1] during voltage disturbances that exceed 0.05 p.u., the generator should provide reactive current up to 1 p.u. for a limited time. In this case, as it can be seen from Fig. 9, the generator provides the rated reactive power of the converter (converter is rated at 33% of the turbine output power). This results in an increase of the terminal voltage of 0.1 p.u. (Fig. 8).

After the fault clearance, in case that the new protection settings are used, the CHP-plants stay connected and consume reactive power which results in delaying the voltage recovery in the generator's terminals [12]. According to the Grid Code applied in the Netherlands, voltage in distribution network should return to values above 0.9 p.u in 10 minutes. For the last regulation, the tap changing in the distribution transformers is fast enough so that the only risk not to meet with the norms is because of the loss of local production. However, even with the CHPs disconnected the voltage settles before the reaction of the tap changers to 0.97 p.u. It has to be mentioned that this rapid re-establishment of the voltage levels is also due to the very strong connections with the high voltage network, together with the available S/C power. This can be seen by observing the effect of the DG in the voltage level of Substation 23, which is rather insignificant (Fig. 10).

D. DG Impact on Fault Current

Although from the voltage support perspective, the contribution of the DG on the local level is positive, the increase in the S/C currents fed in the network can be a significant bottleneck. A thorough comparison between the two types of DG can be found in [8]. As it can be seen in Fig. 9 the biggest impact is from the CHP plants, as it is expected from a synchronous generator. On the other hand the contribution of the DFIG is lower, especially in the transient period. During this period, the implementation or not of voltage support through reactive power by injecting reactive current from the grid side converter gives an increase of the S/C transient current of up to 25% just before the clearance of the S/C. In case a more sensitive setting is used in the triggering of the crowbar protection, it is possible to reduce even more the transient current.

After the clearance of the S/C it can be observed that when response of the converter, the current settles to its pre-fault values almost immediately, in contrast to the CHP where the return of the voltage to its nominal values causes a swing in the rotor angle which results in an exchange of power and thus the transients that appear in the current. The different impact of directly connected or decoupled through a converter DGs in the stability of large systems has been also discussed in [13].

V. CONCLUSIONS

As it has been shown by the simulations, S/C events occurring in the transmission network can lead to a disconnection of a large amounts of DG connected to “mixed” MV networks, also supplying loads. This depends on the fault type, the dip and the duration of the S/C event, as well as the settings of the under-voltage protection.

For common faults that occur in the HV network, the differential or distance protection manages to clear them within 100 ms. It has been shown that current under-voltage strategy for CHP which imposes disconnection of the unit for a fault which results in a voltage dip of 0.8 for 100 ms or more, leads to unnecessary interruption of both CHP-plants and DFIGs.

DFIGs are much more sensitive to under-voltage tripping, due to their limited voltage support capability. In any case, an adaptation of a 200 ms pick-up time for the protection has proven to ensure both the uninterrupted supply of the units as well as their stability. The result of the strategy to keep the DG connected was finally examined with respect to voltage support and S/C contribution. It was shown that the S/C contribution of CHPs is high throughout the S/C duration and also that the dynamics of the synchronous generator result in high currents after the clearance of the S/C. On the other hand the contribution of the DFIG is lower, and its behavior in the transient period depends on the FRT strategy that is implemented as well as the triggering or not of the crowbar. An important conclusion is the fact that even with the FRT implemented, the voltage support is not significant. Therefore, from S/C contribution point of view, it is better to remain connected but passive during the fault, since one of the major problems in distribution system in the Netherlands is the fault currents exceeding the S/C capacity of the substation components.

VI. ACKNOWLEDGMENT

Our colleague Edward Coster is acknowledged for his valuable contributions.

VII. REFERENCES

[1] "German Grid Code: Transmission Code 2007 – Network and System Rules of the German Transmission System", August 2007.

[2] E. J. Coster, J. M. A. Myrzik, and W. L. Kling, "Effect of Grid Disturbances on Fault-Ride-Through Behaviour of MV-connected DG-units, in especially CHP-plants," Integration of Wide-Scale Renewable Resources Into the Power Delivery System, 2009 CIGRE/IEEE PES Joint Symposium, 2009.

[3] T. Ackermann and V. Knyazkin, "Interaction between distributed generation and the distribution network: operation aspects," EEE/PES Transmission and Distribution Conference and Exhibition Piscataway, NJ, USA: IEEE, pp. 1357-1362, 2002.

[4] "IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems," IEEE Std 1547-2003, pp. 0-16, 2003.

[5] NMa Energiekamer, "Systeemcode," *http://energiekamer.nl/images/Systeemcode_28_februari_2009_tcm7-127999.pdf*, Febr. 2009.

[6] J. G. Slootweg, "Wind Power: Modelling and impact on power system dynamics," PhD Thesis Technical University of Delft, 2003.

[7] I. Erlich and F. Shewarega, "Modeling of Wind Turbines Equipped with Doubly-Fed Induction Machines for Power System Stability Studies," *Power* Systems Conference and Exposition, 2006.PSCE '06, pp. 978-985, 2006.

[8] P. Karaliolios, A. Ishchenko, E. Coster, J. M. A. Myrzik, and W. L. Kling, "Overview of short-circuit contribution of various Distributed Generators on the distribution network," 43rd International Universities Power Engineering Conference, UPEC 2008, pp. 1-6, 2008.

[9] P. Kundur, Power System Stability and Control McGraw-Hill, 1994.

[10] L. Ning, X. Yulong, H. Zhenyu, F. Puyleart, and S. Yang, "Load component database of household appliances and small office equipment," Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE, pp. 1-5, 2008.

[11] "IEC 60909-0 Calculation of currents," IEC Std, 2001.

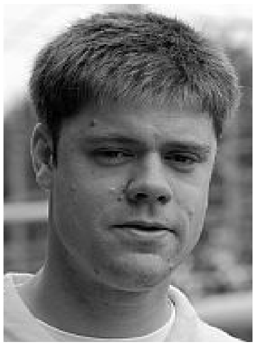
[12] P. Karaliolios, E. Coster, W. L. Kling, and J. M. A. Myrzik, "Fault Ride-through Behavior of MV-connected Wind Turbines and CHP-plants during Transmission Grid Disturbances," UPEC 2009, 2009.

[13] E. J. Coster, J. M. A. Myrzik, and W. L. Kling, "Grid Interaction of MV-connected CHP-plants during Disturbances," PES General Meeting, Calgary AB, Canada, 2009.

[14] J. G. Slootweg and W. L. Kling. Impacts of distributed generation on power system transient stability. 2, 862-867. 2002.

VIII. BIOGRAPHIES

Karaliolios Panagiotis (M ’08,) received his Electrical Engineering diploma from Technologival University of Patras, in 2007 Since November 2007 he is with Electrical Power Systems Group at Eindhoven University of technology, working towards his PhD. His research interest are: short-circuit behavior and safety in distribution networks with a high penetration level of distributed generators.



J.G. (Han) Slootweg (M ’00) received the M.Sc. degree in electrical power engineering in 1998 (cumlaude) and a Ph.D. degree in 2003, both from Delft University of Technology. He also holds a M.Sc. degree in business administration. He is currently manager of the Innovation department of Enexis B.V., one of the largest Distribution Network Operators of the Netherlands. His spearheads are energy transition (including distributed generation and smart grids), asset condition assessment and increasing workforce productivity through new technologies. Han also holds a professorship in Smart Grids at the Electrical Power Systems group at the Eindhoven University of Technology. He has (co-)authored more than 100 papers, covering a broad range of aspects of the electricity supply.

Wil L. Kling (M ’95) received the M.Sc. degree in electrical engineering from the Eindhoven University of Technology, 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 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 is also a part-time Professor in the Electric Power Systems Group at the Eindhoven University of Technology, The Netherlands. From December 2008 he is appointed as a full-time professor and as chair of EPS group at the Eindhoven University of Technology. He is leading research programs on distributed generation, integration of wind power, network concepts and reliability. Prof. 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.