# Analysis of D-STATCOM Impact on Protection of Distribution Network

K. Pandakov, E. Tedeschi, H.Kr. Høidalen

***Abstract*--Impact of the compensation devices on relay protection is an important issue affecting secure operation of transmission systems. Currently, solutions for this problem are widely demonstrated in literature and in practice. At the same time, application of these devices in distribution systems is increasing due to their ability to improve power quality. Nevertheless, less attention has been paid to questions related to the influence of the devices on the standard protective schemes in medium voltage networks. In this paper, investigation of this issue is performed for the time overcurrent relays and impedance-based protection utilized due to presence of distributed generation in the grid. The research method consists in analysis of transient characteristics of measured electrical quantities during fault situations. The results reveal negative impact of the D-STATCOM on the typical overcurrent protection, and impedance relays are proposed as a solution; furthermore, positive and adverse effects for them are also introduced. The findings help to disclose possible problems at planning stage and to establish directions for further studies.**

***Keywords*: D-STATCOM, time overcurrent relay, impedance relay.**

## I. Introduction

Distributed generation (DG) technologies are getting more popular in distribution networks to increase diversification and reliability of power supply, as well as due to a tendency of efficient utilization of local resources. Besides the well-known problems for the standard protective schemes caused by presence of DG [1], there are also voltage stability [2] and harmonic pollution issues in case of inverter-interfaced DG.

In case of sensitive loads, the last two concerns above must be eliminated and power electronic devices can be regarded as a local solution. Normally, they are referred to as the FACTS devices [3] and used at transmission level to enhance power transfer efficiency and stability. Nevertheless, they might be effective at distribution level. For instance, authors of [4] show how the Static Var Compensator for distribution network (D-SVC) can mitigate voltage fluctuations caused by the windfarm. Paper [5] illustrates application of the STATCOM in distribution network (D-STATCOM) as a voltage support device and as an active power filter (APF) in case of high harmonic contamination. At the same time, these devices may have positive effect during fault situations in the systems. Paper [6] proposes to use the D-STATCOM as a flexible power source during unbalanced faults in order to mitigate voltage dips and swells. Additionally, in [7] it is proposed to use the D-STATCOM to increase fault ride through capability of DG (the wind farm) and stability margins of the system.

One of the most important issues in application of the FACTS devices is the impact on relay protection. The main protective schemes at transmission level are based on impedance relays [8], therefore many research works are dedicated to only this type. For instance, [9] demonstrates how adaptive settings can reduce adverse effects from the STATCOM in front of the generator (particular case). Reference [10] examines different positions of the STATCOM and fault point with respect to the relay and reports about under- and overreaching problems [8].

In this work, the D-STATCOM is used in the test cases because it has multi-purpose application [5] – [7] in medium voltage (MV) networks. In literature, lack of publications related to its impact on protective schemes is observed. For example, paper [11] uses the one-feeder model of the distribution network (without DG) to investigate how impedance measurements are affected. Authors of [12] only examine the protection of the induction generator in island mode in presence of the D-STATCOM.

Distribution networks have multi-feeder structure, possibly DGs and different types of relays [13]; therefore, detailed study encompassing all these cases in presence of the D-STATCOM is required.

Thus, the main aim of the current work has become analysis of the D-STATCOM (two modes of operation are investigated: voltage control and APF) impact on the protection of the distribution network (two types are performed: the time overcurrent (TOC) and impedance relays) with DG for different fault locations and points of common coupling (PCC) between the grid and the device. The paper is organized as follows: the second section describes the test case network, the third is the investigation methodology and study cases, the fourth presents the simulation results with analysis, and the main findings and contributions are highlighted in the conclusion.

## II. Test case network

In this work, we deal with a simplified version of the real

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Norwegian distribution network illustrated in Fig. 1. It is a 22 kV grid with DG of a small capacity connected to Feeder 2. Numerous transmission lines are wrapped into TL1 – TL8, and dispersed loads are represented as concentrated load points S1 – S8 at the ends of each line. The current study is focusing on four relays: R1, R2 at the substation and downstream Rds1, Rds2.

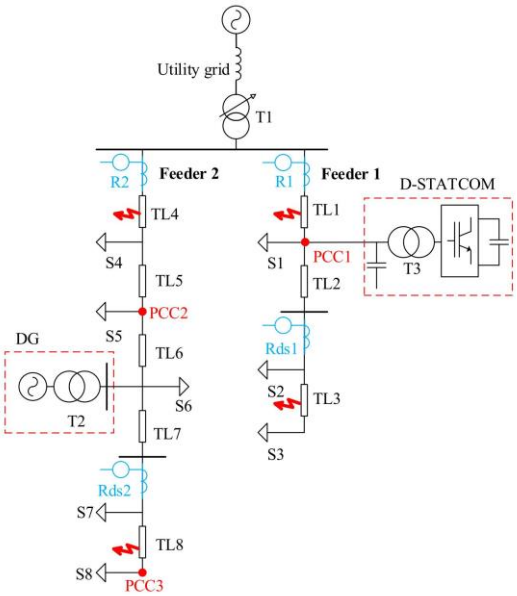



Fig. 1. 22 kV distribution network with DG and D-STATCOM.

The model is constructed in PSCAD/EMTDC as follows:

- The overhead lines are represented through PI-equivalent models, the loads are line-to-line resistive-inductive elements. Parameters can be found in Appendix.
- The utility grid is an ideal voltage source of 66 kV, short circuit capacity behind transformer T1 is 250 MVA.
- Main transformer T1 has 20 MVA capacity, 66/22 kV voltage ratio with DY windings (the grid is isolated), and leakage reactance $x_{T1}$=0.1 p.u.
- DG is represented through a synchronous (1.4 MVA) and an induction (0.623 MVA) generator. Transformer T2 of the synchronous generator is 1.6 MVA, 22/0.66 kV YD, and of the induction generator is 0.6 MVA, 22/0.38 kV YD. For both $x_{T2}$=0.1 p.u.

The D-STATCOM is modeled in two modes:

- Voltage support. It is capable of injecting 4 MVAr with maximum current 0.1 kA. It is connected to the grid through transformer T3 (4 MVA, 22/0.66 kV DY, $x_{T3}$=0.1 p.u.). A six-pulse-inverter is constructed using the standard model of the GTO thyristor (current is limited to 3 kA). The dc capacitor is 800 μF, the low-pass filter in Fig. 1 (transformer T3 and the shunt capacitor) has line-to-line capacitance 4 μF. Firing impulses are generated utilizing the control system illustrated in Fig. 2. F – the cascade of low-pass and notch filters, PI – the pi-regulator for an error between RMS voltage at PCC $V_{PCC}$ and reference $V_{ref}$, PWM – the pulse width modulation block controlled by angle shift (determines amount and direction of reactive power) between the device and the PCC. The full description of the control system in PSCAD can be found in [14].

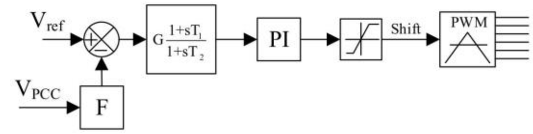



Fig. 2. Control system of D-STATCOM in voltage support mode.

- APF. It has the same scheme, but in order to simplify the control system (shown in Fig. 3), the dc side is modeled as a constant voltage source (0.185kV). Block IFP (interpolated firing pulses, the standard block in PSCAD) uses an difference between calculated in αβ-domain reference current $I_{ref}$ and instantaneous current produced by active filter $I_{AF}$ for operation.

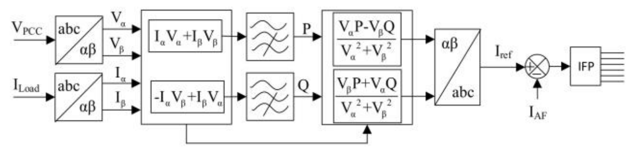



Fig. 3. Control system of D-STATCOM in APF mode.

The APF is used to mitigate current harmonics (up to 11$^{th}$) produced by a nonlinear load (instantaneous load current $I_{Load}$ is used for the control system) – a controllable six-pulse-rectifier (the standard block in PSCAD) supplying a 20 mOhm dc load and connected through a transformer (2 MVA, 22/0.2 kV DY, x=0.05 p.u.). Additionally, a fixed low-pass filter with line-to-line capacitance 6 μF is used in parallel with the load.

## III. Investigation Methodology and Study Cases

The primary investigation methodology is an analysis of transient characteristics of electrical quantities measured by a corresponding relay (current for the TOC and impedance for the distance relays) during abnormal situation in the network (three-phase faults mainly) and their comparison with the typical settings for these types of relays [13]. The outcome is information about probability of malfunctioning of a relay for different study cases.

In order to get various study cases, three points of common coupling (PCC1 – PCC3 in Fig. 1) between the D-STATCOM and the grid are investigated. Faults are organized in four locations: TL1, TL3, TL4, TL8.

Simulations are carried out at high load in the system to handle extreme cases. Impedance calculations for three-phase faults (inter-phase measurements are needed in order to detect the fault) can be represented as:

$$z_{ab} = \frac{U_a - U_b}{I_a - I_b} = z_1 \tag{1}$$

where $U_{a,b}$ and $I_{a,b}$ are phase voltages and currents correspondingly; $z_1$ is a positive sequence impedance between a relay and a faulty point including the impedances of the transmission lines, loads, and a fault resistance (it is assumed that an electric arc has pure resistive character [15]). Impact of infeed currents (from the DG) on impedance measurements are out of the scope of this paper and can be found in [8], [15].

The grid is operated with isolated neutral of the main transformer and without earthing transformers. Application of impedance ground relays in such type of networks is a challenge and, therefore, it is out of the scope of this paper.

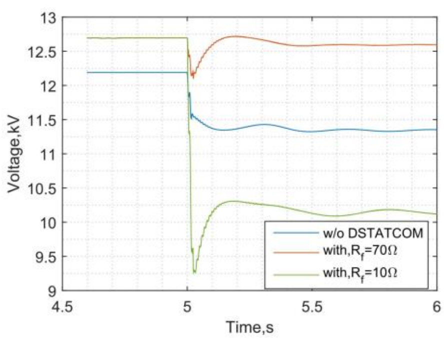
It is assumed that the TOC relays initiate tripping signals if current exceeds 25% of the high load level [13]. A time delay is not specified because it is not necessary for the study.

The settings of impedance relays are plotted according to [13], [15] as the quadrilateral characteristics taking into account arc resistance 15 Ohm (calculated according to [15] for the given short circuit network capacity): Zone 1 has 95% of the sum of the corresponding positive sequence impedances of the downstream transmission lines up to the next relay; Zone 2 reaches 120% of the same impedance (simplified settings because downstream devices at load points are not considered). The third zone is out of interest. Impedance trajectories are depicted during 500 ms that is comparable with the biggest coordination time interval (CTI) between zones [8], [13], [15].

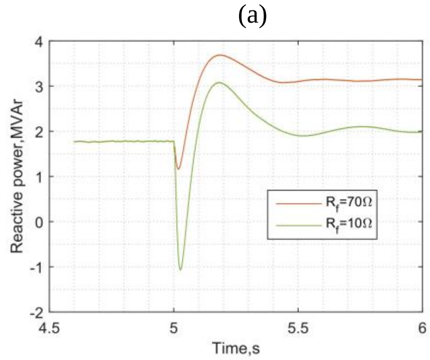
## IV. Results and Discussions

### A. D-STATCOM operation in voltage support mode

Firstly, PCC1 is considered, and relay R1 is TOC. This location of the D-STATCOM presents the cases for the feeder without embedded DG. First of all, it is of interest to observe behavior of the device under fault situations in the adjacent feeder. Three-phase fault (fault resistance $R_f$=70 Ohm) in transmission line TL4 is investigated (inception time is 5 s), see Fig. 4.




(a)




(b)

Fig. 4. (a) Measured RMS voltage at PCC1 and (b) reactive power injected by the D-STATCOM during fault in TL4.

From the pre-fault period, it is seen that the D-STATCOM injects reactive power 1.75 MVAr in order to boost the voltage at the desired level 12.7 kV (compare the cases with and without the device). It also helps to overcome the voltage dips during the fault. For comparison, Fig. 4 also demonstrates the low-ohmic fault with $R_f$=10 Ohm: the amount of reactive power is less and the voltage dip is more significant. These two circumstances are related to each other because reactive power produced by the D-STATCOM can be expressed as

$$Q = \frac{V_{PCC}(V_{PCC} - V_c \cos\delta)}{x_{T3}} \qquad (2)$$

where $V_c$ is RMS voltage at the compensator and cos$\delta$ is angle shift between $V_c$ and $V_{PCC}$. Hence, $Q$ is also restricted by voltage dips in the network depending on fault parameters and, consequently, more sustainable voltage support can be achieved for distant or non-metallic faults with high $R_f$ in vicinity of the device. Moreover, due to a significant voltage drop, the phase locked loop cannot synchronize the converter with the grid that leads to unstable operation and disconnection by the interior protection.

Reactive power produced by the D-STATCOM during balanced faults might lead to sympathetic tripping [1] of relay R1, as it can be observed from Fig. 5.

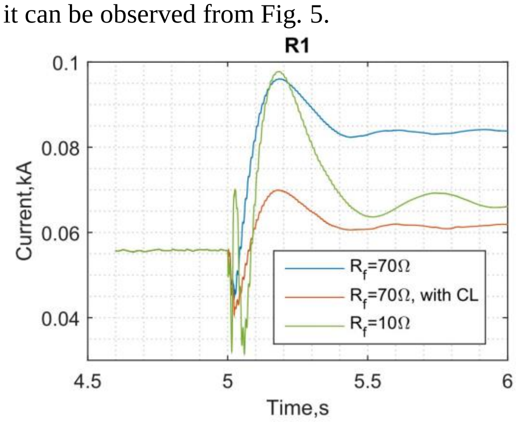



Fig. 5. Sympathetic tripping issue: RMS current in relay R1 during fault in TL4. CL –current limiting control strategy.

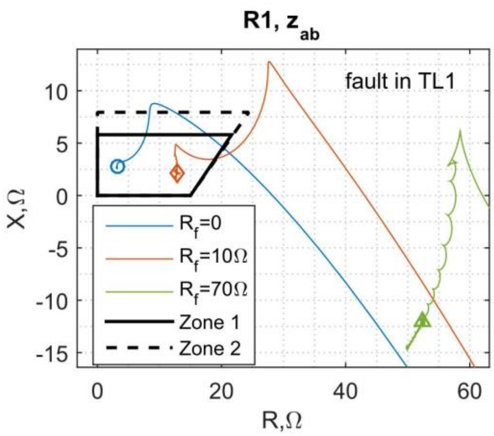
The current passing through this relay during the fault (the case with $R_f$=70 Ohm) is almost 2 times larger than during the pre-fault conditions. The reason is current transferred from the device to the adjacent feeder through the relay.

Such effect can be mitigated applying current limiting (CL) strategy in the control system (the saturation block in Fig. 2). As a result, decrease of current can be observed in Fig. 5. Additionally, it is seen that the peak current for the case with $R_f$=10 Ohm (without CL) is the same as for the high resistance despite the fact that injection of reactive power is decreased (Fig. 4b). Hence, for both cases, CL is needed in order to avoid misoperation of the feeder TOC relay.

From this point, it is proposed to use for feeder protection impedance relays because they have inherent feature of directionality: in [16] this solution is recommended for MV networks with DG; analogously, because of the similar issues, it can be utilized in case of presence of the D-STATCOM.

Similar to the cases with DG in [17], there is no possibility of misoperation of the TOC ground relays in case of presence of the D-STATCOM because it is isolated from the network by the DY coupling transformer and does not have significant influence on zero sequence currents. Hence, ground faults are out of interest.

Secondly, PCC1 is considered, and relay R1 is impedance type. Fig. 6a demonstrates the cases when the faulty point is inside Zone 1 (in TL1): for the case with the zero fault resistance, the impedance locus is inside Zone 1 as it is anticipated. Small fault resistance $R_f$=10 Ohm gives the shift handled by the quadrilateral characteristics. For high fault resistance $R_f$=70 Ohm, the injected reactive power from the device is significant and it moves the impedance curve out from the tripping zones; moreover, it becomes a capacitive impedance – the reactive part is below zero. The end points of the loci are pointed out by the special markers.

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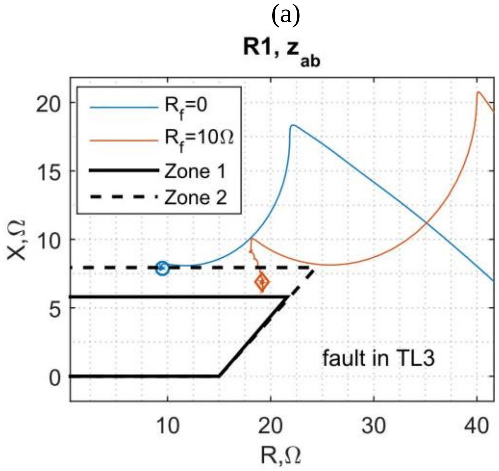



(b)

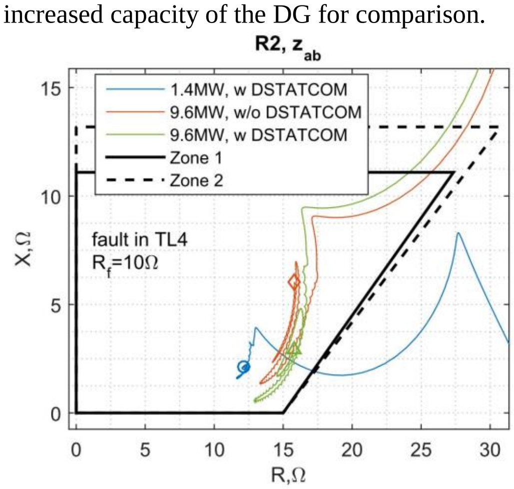
Fig. 6. Impedances measured by R1 for fault in (a) TL1 and (b) TL3, the cases for PCC1.

For higher ratings of the compensator, the last case can appear even for small fault impedances provoking underreaching effect [8] with capacitive character.

Such impact can also lead to overreaching problems [8] and it is demonstrated in Fig. 6b. The fault is applied in TL3 at the location corresponding to the boundary of Zone 2: the impedance locus with $R_f$=0 falls exactly on it. The curve with $R_f$=10 Ohm comes into Zone 2 due to decreasing of the reactive part. For higher ratings of the D-STATCOM, the locus can even fall into Zone 1 leading to miscoordination between relay R1 and downstream Rds1. Apparently that the same can occur for the given rating and fault locations in vicinity of Zone 1.

The main reason of this overreaching effect is compensation of the inductive part of the line impedances by injected reactive power from the D-STATCOM. It is not present for zero fault resistance due to significant voltage drop in the system and, consequently, lack of reactive power according to equation (2).

Thirdly, PCC2 is considered, and relay R2 is impedance type. This case investigates impact from the DG and the D-STATCOM. Relay R2 is impedance type due to the presence of the DG and sympathetic tripping issues [16]. It has been found that the actual capacity of the DG (1.4 MW) is insufficient to affect impedance measurements of relay R2 and, therefore, presence of the D-STATCOM in Feeder 2 leads to the same consequences described above. Hence, Fig. 7 illustrates the impedance loci for fault in TL4 for the actual and an increased capacity of the DG for comparison.

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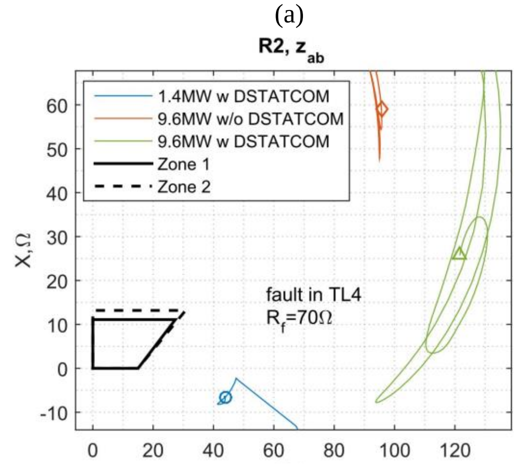


(b)

Fig. 7. Impedances measured by R2 for fault in TL4 with (a) $R_f$=10 Ohm and (b) Rf=70 Ohm, the cases for PCC2 and different capacities of the DG.

As it is seen from Fig. 7a, the 9.6 MW DG leads to increase of the active and the reactive (mostly) part of the impedance even for the small fault resistance (compare the cases 1.4 MW with and 9.6 MW without the compensator). For an extreme location (close to the end of Zone 1), it can cause underreaching problems [15]. Presence of the D-STATCOM compensates impact of the DG diminishing this reactance rise.

Fig. 7b shows the same cases for $R_f$=70 Ohm. It is seen that the D-STATCOM can also increase the active part of the measured impedance (compare the cases with and without the device and 9.6 MW DG) if system voltage drop (the high fault resistance and the DG boost it) allows to inject considerable amount of reactive power. The broad sweeping impedance trajectories are stipulated by power swing phenomenon in the system with the big DG.

Studying of faults in TL8 has indicated similar possibility in misoperation between relay R2 and downstream Rds2 as the described earlier for R1 and Rds1; however, for the big DG, underreaching issues become prevailing.

Finally, PCC3 is considered. It has been revealed that this location of the D-STATCOM causes similar impact on an impedance measured by relay R2 as before. Therefore, location of the device in Feeder 1 is not important for creation of the compensating effect against the DG. Impact of the device on relay Rds2 is the same as shown above for relay R1 and PCC1.

### A. D-STATCOM operation in APF mode

This section presents the study when the D-STATCOM is used as an active power filter in order to eliminate harmonics produced by the previously mentioned controllable rectifier: it is connected to the grid instead of load S5, firing angle is set $25^0$. The APF is connected in parallel at the same place – PCC2.

Fig. 8 demonstrates the frequency spectra (FS) of pre-fault load current, generated current by the D-STATCOM and total current consumed from the system. From the load FS, 200 Hz cut-off frequency of the high-pass filters (see Fig. 3) was chosen. From the D-STATCOM FS it is seen that the APF generates counter harmonics of the same frequencies. Finally, the resulting current contains only fundamental 50 Hz.

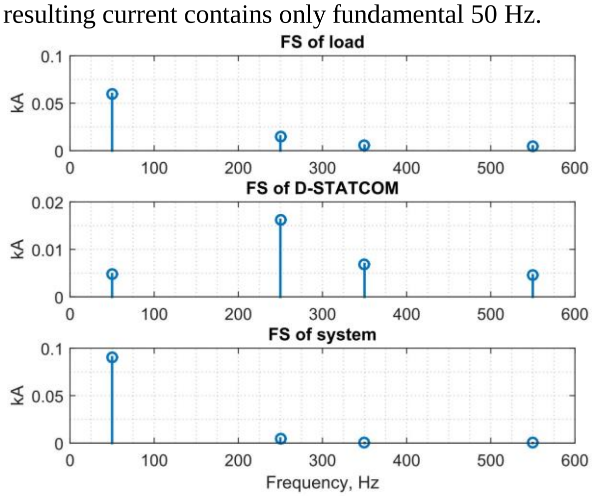


Fig. 8. Frequency spectra (FS) of pre-fault load current, generated current by the D-STATCOM and consumed current from the system.

Fig. 9 shows the behavior of the device under the abnormal situation (low-ohmic fault in TL4) in the term of the active and reactive powers. It is observable that, in both pre- and fault periods, the D-STATCOM consumes power (it has the negative sign).

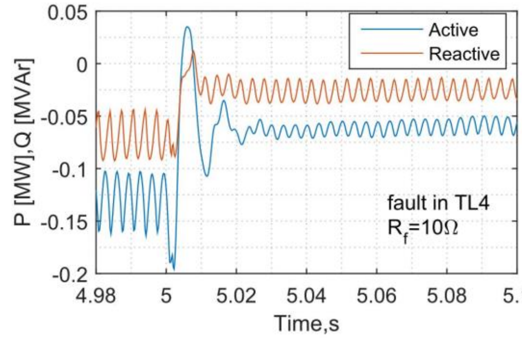


Fig. 9. Active and reactive power of the APF during abnormal situation in the grid.

Thus, from the impedance relay point of view, behavior of the APF resembles passive loads during faults. As a result, it provokes disappearing of the over-/underreaching problems, as well as other effects described above.

## V. Conclusions

The current work illustrates possibility to use the D-STATCOM as a voltage control device in MV networks enabling mitigation of voltage dips and swells mainly caused by abnormal situations. At the same time, it reveals the negative impact of the device on the standard protective schemes used in MV networks. The main findings are as follows:

- TOC relays are subjected to sympathetic tripping issues in case of presence of the D-STATCOM (voltage support mode) in front of a relay and a faulty point is behind. This complication can be resolved applying current limiting strategy in the control system of the device.
- Reverse power flow can be registered by impedance relays, therefore they can serve as a solution as well. Furthermore, if the compensator is behind of a relay, it does not affect impedance measurements.
- Impact of the D-STATCOM is present when it is situated inside a zone of protection of an impedance relay. It increases the reactive part of a measured impedance providing capacitive character. For high fault impedances (or big ratings of the compensator), it leads to underreaching problems. For low-ohmic faults, overreaching issues are emerged due to compensation of transmission line inductances. Decrease of Zone 1 might be required that causes delayed fault clearance. It is worth noting that extended tripping times for Feeder 1 leads to disconnection of the generators by the undervoltage relays as it is required in [18].
- For faults in the feeder with the DG, it has been revealed that the D-STATCOM is capable to compensate

underreaching effects brought in by the generator infeed. Besides influence on the reactive part, it can also increase the active part of a measured impedance in case of high impedance faults or bigger ratings (sufficient reactive power is required).

- Amount of reactive power drawn from the compensator depends on network voltage dips and, consequently, on fault parameters.
- Operation of the D-STATCOM in APF mode does not affect the protective schemes of the network.

The main solution against underreaching problems caused by high impedance faults (of high ratings of the compensator) requires involvement of communication links in order to compensate impact of the D-STATCOM and the DG on impedance measurements. Low-ohmic fault issues (loss of coordination with downstream devices) can be handled through modification of settings and adjustment of CTIs.

Voltage support during faults might also be a challenge for the undervoltage relays used for the DG protection [18]. In case of permanent faults in the upward part of Feeder 2 (transmission lines TL4 – TL7), the generators must be disconnected by them to avoid islanding situation; however, due to non-violation of the voltage limits, it stays coupled with the grid. These problems require further investigations.

These findings disclose the main complications arising with application of the compensating device in the MV network. Taking them into account at planning stage will help to increase dependability and security of the protective schemes.

## VI. Appendix

TABLE I

Transmission line parameter

| Name | Length, m | $Z_{s1}$[1], mΩ/m | $Z_{sh1}$[2], MΩm | $Z_{s0}$[3], mΩ/m | $Z_{sh0}$[4], MΩm |
|---|---|---|---|---|---|
| TL1 | 14530 | 0.43+i0.37 | 300 | 0.6+i1.6 | 650 |
| TL2 | 1854 | 0.36+i0.37 | 325 | 0.5+i1.6 | 650 |
| TL3 | 20380 | 0.58+i0.49 | 350 | 0.75+i1.6 | 675 |
| TL4 | 15015 | 0.36+i0.37 | 310 | 0.5+i1.6 | 665 |
| TL5 | 4820 | 0.36+i0.37 | 325 | 0.5+i1.6 | 660 |
| TL6 | 9767 | 0.5+i0.38 | 340 | 0.7+i1.6 | 665 |
| TL7 | 1619 | 0.54+i0.39 | 350 | 0.7+i1.6 | 670 |
| TL8 | 7643 | 0.72+i0.4 | 345 | 0.9+i1.6 | 675 |

1, 2 – positive sequence series and shunt impedances correspondingly.

3, 4 – zero sequence series and shunt impedances correspondingly;

TABLE 2

Loads

| Name | Total Power,MVA | Name | Total Power,MVA |
|---|---|---|---|
| S1 | 0.67+i0.23 | S5 | 2.27+i0.26 |
| S2 | 0.78+i0.23 | S6 | 0.29+i0.08 |
| S3 | 0.2+i0.05 | S7 | 0.13+i0.025 |
| S4 | 2.14+i0.38 | S8 | 0.13+i0.025 |

## VII. References


[1] K. Kauhaniemi, L. Kumpulainen, "Impact of Distributed Generation of the Protection of Distributed Networks," in *Proc. 2004 8th IEE International Conference on Developments in Power System Protection*, pp. 315-318.

[2] S. Repo, H. Laaksonen, P. Jarventausta, O. Huhtala, M. Mickelsson, "A case study of a voltage rise problem due to a large amount of distributed generation on a weak distribution network," in *Proc. 2003 IEEE Bologna Power Tech Conf.*, vol. 4, 6 p.

[3] N.G. Hingorani, L. Gyugyi, *Understanding FACTS, concepts and technology of Flexible AC Transmission Systems*, Wiley-IEEE Press, 1999.

[4] K. Tsunedomi, Y. Imazu, S. Tamura, T. Sodeyama, T. Omori, D. Cheung, M. Parr, S. Gough, "Effectiveness of D-SVC on rural networks," in *Proc. 2013 22nd International Conference and Exhibition on Electricity Distribution (CIRED 2013)*, pp. 1-4.

[5] D. Kalyankumar, Dr. V. Kirubakaran, "D-STATCOM Based Voltage Regulation and Harmonic Damping," *International Journal of Computer Applications*, vol. 7, num. 4, 5 p., 2010.

[6] A. Nazarloo, S. H. Hosseini, E. Babaei, "Flexible D-STATCOM performance as a flexible Distributed Generation in mitigating faults," in *Proc. 2011 2nd Power Electronics, Drive Systems and Technologies Conference (PEDSTC)*, pp. 568-573.

[7] E. E. C. Moraes, S. J. de Mesquita, R. P. S. Leao, M. B. M. Neto, K. Q. da Silva, R. M. C. Correa, H. A. dos Santos, L. Cajuaz, K. P. dos Santos, F. R Leite, "The application of D-STATCOM in smart distribution grid with wind power plants," in *Proc. 2012 10th IEEE/IAS International Conference on Industry Applications (INDUSCON)*, pp. 1-6.

[8] *IEEE Guide for Protective Relay Applications to Transmission Lines*, IEEE Standard C37.113-1999, 1999.

[9] S. Raman, R. Gokaraju, A. Jain, "An Adaptive Fuzzy Mho Relay for Phase Backup Protection with Infeed From STATCOM," *IEEE Trans. Power Delivery*, vol. 28, issue 1, pp. 120-128, 2013.

[10] X. Y Zhou, H. F Wang, R. K Aggarwal, P. Beaumont, "The Impact of STATCOM on Distance Relay," in *Proc. 2005 15th Power Systems Computation Conference (PSCC05)*, 7 p.

[11] A. Kazemi, S. Jamali, H. Shateri, "Effects of D-STATCOM on measured impedance at source node of distribution feeder," in *Proc. 2008 IET-CIRED Seminar SmartGrids for Distribution*, pp. 1-8.

[12] F. Sulla, O. Samuelsson, "Analysis of island-operated distribution networks with distributed induction generation under fault conditions," in *Proc. 2008 43rd International Universities Power Engineering Conference (UPEC08)*, pp. 1-5.

[13] A. Sinclair, D. Finney, D. Martin, P. Sharma, "Distance Protection in Distribution Systems: How It Assists With Integrating Distributed Resources," in *Proc. 2013 IEEE Rural Electric Power Conference (REPC)*, pp. B3-1 – B3-12.

[14] A. B. Kunya, T. Yalcinoz, G. S. Shehu, "Voltage sag and swell alleviation in distribution network using custom power devices; D-STATCOM and DVR," in *Proc. 2014 16th International Power Electronics and Motion Control Conference and Exposition (PEMC)*, pp. 400-405.

[15] J. L. Blackburn, T. J. Domin, *Protective relaying. Principles and applications*, 4th ed., New York: CRC Press, Taylor&Francis Group, 2014.

[16] Joint Working Group B5/C6.26/CIRED, "Protection of Distribution Systems with Distributed Energy Resources," Final Report, 2015.

[17] L. K. Kumpulainen, K. T. Kauhaniemi, " Aspects of the effects of distributed generation in single-line-to-earth faults," in *Proc. 2005 International Conference on Future Power Systems*, 5 p.

[18] *IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems*, IEEE Standard 1547-2003, 2003.