15. Symposium Energieinnovation, 14. bis 16. Februar 2018, Technische Universität Graz, www.EnInnov.TUGraz.at
ISBN 978-3-85125-586-7 DOI 10.3217/978-3-85125-586-7

Review on Network Restoration Strategies as a Part of the RestoreGrid4RES Project

Yi Guo[1](*), Elmira Torabi-Makhsos[1], Gertrud Rossa-Weber[1], Wolfgang Gawlik[1], Robert Schmaranz[2] , Philipp Hinkel[3], Martin Ostermann[3], Wolfram Wellßow[3], Ewald Traxler[4]

[1] TU Wien, Institut für Energiesysteme und Elektrische Antriebe, Gußhausstraße 25/370-1,1040 Wien; Tel.: +43-1-58801-370128; Fax.: +43-1-58801-370199; www.ea.tuwien.ac.at; {guo|torabi|rossa-weber|gawlik}@ea.tuwien.ac.at

[2] KNG-Kärnten Netz GmbH, Arnulfplatz 2, 9020 Klagenfurt, Österreich; Tel.:+43-(0)525 -1633; robert.schmaranz@kaerntennetz.at

[3] TU Kaiserslautern, Erwin-Schrödinger-Straße, 67663 Kaiserslautern, Deutschland; Tel.: +49 631 205-2021; Fax.: +49 631 205-2168; www.eit.uni-kl.de/esem; wellssow@eit.uni-kl.de

[4] Netz Oberösterreich GmbH, Neubauzeile 99, 4030 Linz, Österreich; Tel.: +43 59070-3193; Fax.: +43 59070-53193; ewald.traxler@netzgmbh.at

Abstract: Operation of electrical power systems, including normal and emergency operation, becomes more challenging because of a growing share of renewable energy resources, especially inverter-based distributed generation that generally has no inertia. Meanwhile a delay of the power system's enhancements results in an operation closer to its critical limits, which increases the risk of emergency conditions or even blackouts. The ability to restore the electrical power system after a wide-area blackout is a fundamental requirement. RestoreGrid4RES is a project that investigates new network restoration strategies to ensure a fast, coordinated and stable system restoration considering the impact of distributed renewable generation. In this paper, the impact of integration of renewable energy resources into electrical power systems undergoing restoration is analyzed. An overview of the ENTSO-E network code on network restoration process is presented. As a first step in the project, existing network restoration strategies, Top-down and Bottom-up, are reviewed. Furthermore, three new network restoration concepts, namely Build-down, Build-together and Build-up, clarifying the responsibility of distribution system operators are introduced.

Keywords: Distributed generation, renewable energy resources, ENTSO-E network code, network restoration strategies, Top-down, Bottom-up, Build-down, Build-together, Build-up

1 Introduction

The increasing amount of renewable energy sources (RES) changes operation of electrical power systems not only during normal, but also during emergency operation. In any network area that has a lower inertia the system frequency is more volatile. The integration of RES and related replacement of conventional power plants, which effectively provide inertia, reduces the total system inertia. This leads to an increase of the rate of change of frequency under unbalanced conditions. In case of power imbalances in a network with high penetration

ISBN 978-3-85125-586-7 DOI 10.3217/978-3-85125-586-7

of RES, frequency tends to change faster, which is a significant challenge for frequency control as well as power system operation. Combined with a delay of grid enhancements, electrical power systems are pushed to operate closer to their critical limits. This results in a higher risk of emergency conditions or even blackouts.

The ability to restore the electrical power system after a wide-area blackout is a fundamental requirement for network operators. Replacing conventional generation with partly uncontrollable distributed generation at distribution levels increases the risk of an unsuccessful grid restoration even further due to unforeseeable power injections in situations where an islanded system may be very sensitive to active power unbalances.

RestoreGrid4RES is a research project that investigates potential problems and challenges during the restoration caused by a high penetration of distributed generation, often in the form of RES. The aim is to support a fast and secure grid restoration in case of a blackout in networks with a high share of renewable energy generation. As a first step in the project, with consideration of the legal framework and technical requirements, existing network restoration strategies are reviewed and an analysis of the impact of high penetration of RES is conducted. Thereby, limitations of current practices are identified based on the vast experience of Austrian distributed system operators involved in the project. New grid restoration strategies are developed based on the review.

2 Impact of Integration of Renewable Energy Sources in Restoration State

As described in the introduction, integrating RES, particularly inverter-based distributed generation that has no inertia, into electrical power systems may increase the risk of emergency conditions or even blackouts. For instance, a power outage in Australia in September 2016 was caused by insufficient inertia [1]. Since networks are especially vulnerable during restoration state, large frequency deviations may cause another system collapse in the process of network restoration.

Furthermore, distributed generation has its own protection limits while operating. Once frequency exceeds certain limits, distributed generation is disconnected from the network automatically. For example, distributed generation does not remain connected if frequency is below 47.5 Hz or above 51.5 Hz following a typical frequency-dependent active power characteristic curve defined by the German VDE-AR-N 4105 standard [2]. If frequency returns to a certain value, e.g. 50.05 Hz for at least 60 s as given in [2], distributed generation is allowed to reconnect to the grid. Automatic reconnection of distributed generation to the network at a pre-defined value of frequency can have serious consequences in islands during restoration and poses a major challenge. This may result in a substantial increase of frequency, so that other generating units are disconnected, or as worst case, the system collapses again. One measure to avoid the automatic reconnection of RES is to start network restoration with a higher frequency. This has been successfully tested by Kärnten Netz GmbH during an island grid restoration test with a 51.5 Hz start-frequency [3].

ISBN 978-3-85125-586-7 DOI 10.3217/978-3-85125-586-7

3 Restoration Plan Defined in ENTSO-E Network Code

RestoreGrid4RES considers the future renewable-based generation structure within the transformation to a renewable and ecological power supply. Besides coping with a high share of RES in normal grid operation, grid operation in emergency situations has to deal with this progression as well. As the risk of blackouts persists with growing integration of RES, it is important for network operators to investigate existing network restoration plans and adjust them to the new challenges. A restoration plan is a set of coordinated technical and organizational actions to bring the system back to the normal state after a blackout. It consists of re-energization, frequency management and resynchronization procedures [4].

3.1 General Terms

According to the ENTSO-E network code on electricity emergency and restoration [4], the measures of the restoration plan are implemented in the transmission system by the transmission system operators (TSOs). TSOs in coordination with distribution system operators (DSOs), significant grid users (SGUs) and restoration service providers shall activate the process of its restoration plan in case of the system being in emergency or blackout state and keep the restoration plan updated. Each TSO has to inform to the transmission system connected DSOs of measures, which are to be implemented on DSOs installations as well as installations of SGUs, restoration service providers and DSOs that are connected to their distribution systems. Where a TSO notifies a DSO, the DSO shall immediately inform their SGUs, restoration service providers and connected DSOs in turn about the measures of the restoration plan so that each involved DSO, SGU and restoration service provider can execute the restoration plan instructions released by the TSO [4].

3.2 Obligations of TSOs for Network Restoration

According to Austrian Federal Law [5], TSOs are responsible for maintaining a safe, reliable and efficient electricity network. This means that TSOs have to provide all necessary ancillary services, including those necessary to meet the demand, in case that their provision is independent from other transmission networks that are interconnected. Furthermore, measures for re-energization after major transmission network disruptions need to be planned and coordinated by concluding contractual agreements to an extent that is technically necessary. These agreements have to be concluded with both directly and indirectly connected power plant operators to ensure necessary black start and island operation capability by the TSOs [5]. New arrangements define a combined approach of the Austrian's TSOs and DSOs, using the black-start capabilities at extra high voltage (EHV) and high voltage (HV) level.

3.3 Re-energization Procedure and Frequency Management

In case of a blackout, one or more TSOs need to re-energize the disturbed network. Taking into account the availability of power sources capable of re-energization, the duration of restoration strategies and the conditions of the power system, each TSO shall decide to apply either a Top-down or Bottom-up re-energization strategy, or a combination of both in

ISBN 978-3-85125-586-7 DOI 10.3217/978-3-85125-586-7

parallel for network restoration. Each DSO shall reconnect the announced amount of demand from the TSO on the distribution network during re-energization [4].

In case of a Top-down strategy, the TSO connects load and generation with the aim to regulate frequency towards nominal frequency with a maximum tolerance of frequency deviation. Each TSO informs other TSOs about its capability to support the Top-down strategy. This support may be assistance for active power. The TSO that is required to support re-energization activates its available balancing energy to provide the requested power [4].

If there is no available TSO providing assistance, Bottom-up strategy should be implemented. In this case, the restoration procedure contains managing voltage and frequency deviations, monitoring island operation and resynchronization of islands. Each TSO shall connect load and generation and activate the frequency management procedure with the aim to reach the target frequency. After a frequency deviation, the frequency leader shall set off the operated load-frequency control operated by each TSO of the synchronous area, and activate frequency restoration reserves manually. In this case, the TSOs re-energize the system with their respective black start units [4]. A black start unit shall operate and deliver power without external electrical energy supply. It has island operation capability with the ability to run from a shutdown condition to an operation mode [6].

3.4 Resynchronization

The resynchronization process includes appointment of a resynchronization leader, measures allowing the TSO to apply a re-energization strategy and maximum phase angle, frequency and voltage differences for connecting lines. Before resynchronization, the resynchronization leader shall define the target frequency value for resynchronization, the maximum frequency difference between two synchronized regions, the maximum exchange values for active and reactive power and operating mode for load-frequency control. When all of these requirements are fulfilled, the resynchronization leader shall initiate the resynchronization [4].

4 Network Restoration Strategies

In the (unlikely) event of a system-wide blackout, restoration strategies have to be available, which define how to restore the electricity system.

4.1 Top-down and Bottom-up Re-energization Strategies

As stated in Policy 5 “Emergency operations” of the ENTSO-E Continental Europe Operation Handbook, the related network restoration process for re-energization is mainly based on two principles, namely Top-down and Bottom-up re-energization strategies [6]. Their definitions in [6] are presented as following:

- Top-down re-energization strategy: “using external voltage sources from tie lines (the power from a secure system that can be the main ENTSO-E regional group continental Europe system) to re-energize a separated severely disturbed system”.

ISBN 978-3-85125-586-7 DOI 10.3217/978-3-85125-586-7

- Bottom-up re-energization strategy: "from self-reenergizing of parts of its own load-frequency control area to be ready for resynchronization with another area (that can be with the ENTSO-E regional group continental Europe main system)".

According to Article 27 of the ENTSO-E Network Code on Emergency and Restoration, in case of blackouts, each TSO is entitled to combine Top-down or Bottom-up re-energization strategies as needed [4].

For the sake of clarity, a distinction of Top-down, Bottom-up and a combination of Top-down and Bottom-up is made as follows:

- Top-down strategy exclusively requires the assistance from neighboring TSOs to reenergize the system of a TSO;
- Bottom-up strategy requires no assistance from other TSOs, but uses power sources with black start capability being available in the own control area of a TSO or subordinated DSOs for self-re-energization;
- Combinations of Top-down and Bottom-up re-energization strategies use the assistance of other TSOs as well as power sources with black start capability being available in the own control area of a TSO or subordinated DSOs for re-energization.

4.2 Build-down, Build-up and Build-together Re-energization Strategies

The ENTSO-E network code only addresses the coordinated action and relationship between TSOs of different control areas during network restoration state. However, the responsibility of DSOs is in this code not yet described [3].

In the definition of the Bottom-up strategy, it is not defined whether black start is possible in the grid of the TSO, a distribution system operator (DSO) or both of them. Thus, a distinction of three new concepts of restoration strategies, i.e. Build-down, Build-together and Build-up, is introduced to clarify the actions that DSOs should take and the relationship between TSOs and DSOs. The three mentioned re-energization strategies are defined as following:

- Build-down means that no power source with black start capability is used in the distribution network. In this case, the assistance of the upstream TSO is required to re-energize the disturbed system of a DSO.
- Build-together indicates that there are power sources with black start capability in both the transmission and distribution network. The disturbed systems of a TSO and a DSO are self-re-energized separately.
- Build-up strategy means that no power source with black start capability is available in the transmission network, but only in the distribution network. The disturbed system of a DSO is self-re-energized and supports restoration of its upstream TSO.

5 Matrix of Network Restoration Strategies

The Build-down strategy can be applied together with either a Top-down or a Bottom-up re-energization strategy, or a combination of both. Build-together and Build-up cannot be applied with the Top-down strategy, but with the Bottom-up or a combination of Top-down and Bottom-up only. This is because Top-down defines that restoration of a disturbed system

15. Symposium Energieinnovation, 14. bis 16. Februar 2018, Technische Universität Graz, www.EnInnov.TUGraz.at
ISBN 978-3-85125-586-7 DOI 10.3217/978-3-85125-586-7

is only based on the assistance from neighboring secure TSOs, while both Build-together and Build-up indicate that network restoration is possible with the own black start power sources. Therefore, there are seven possible combinations of network restoration strategies as illustrated by the matrix in Figure 1. Build-down, Build-together and Build-up strategies can also be combined, as restoration of the disturbed systems of several DSOs connected to the same TSO may be conducted in different ways. This is not shown in Figure 1 to avoid a further expansion of the matrix.

The sequence of restoration actions, including voltage forwarding, black start and resynchronization, is represented by circled numbers in the matrix in Figure 1. For example, following the combination of Bottom-up and Build-down re-energization strategies, black start in the disturbed network of TSO 2 is carried out at the beginning of restoration state. After a complete re-energization, whether TSO 2 forwards its voltage to the disturbed system of its subordinated DSO 2 or synchronizes with the stable and secure neighboring TSO 1 first is not defined. This should be decided by involved TSOs and DSOs according to the actual situation.

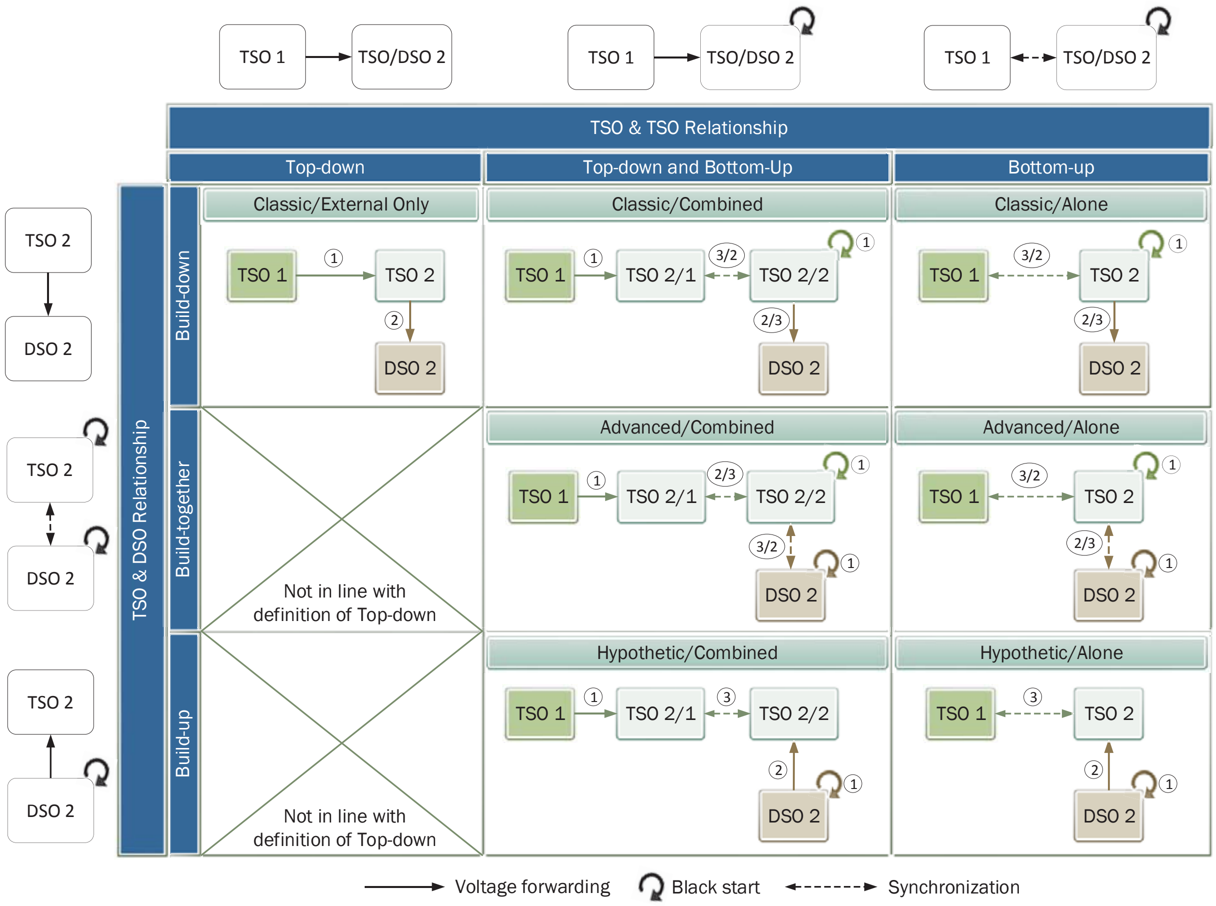

Figure 1. Matrix of network restoration strategies

A more intuitive way to name the network restoration strategies shown in Figure 1 is introduced as well. Each designation of those strategies consists of two parts, which represent the TSO-DSO relationship and the TSO-TSO relationship, respectively. The Build-down strategy is referred to as "Classic," as this strategy is so far designated to carry out network restoration from the transmission network to the distribution network. The build-together strategy is referred to as "Advanced", as high penetration of renewable energy

ISBN 978-3-85125-586-7 DOI 10.3217/978-3-85125-586-7

sources increases generation capacity in distribution networks significantly and DSOs can use this to re-supply their customers independently from the TSO. Furthermore, it offers the potential to re-supply customers faster by a parallel network re-energization from the distribution and transmission network. The Build-up strategy is called "Hypothetic", because in this strategy, the TSO does not have its own power sources with black start capabilities or cannot deploy them. This does not consider the legal requirement that TSOs are responsible for system security in their control areas. Regarding the TSO-TSO relationship, Top-down strategy is referred to as “External Only", as the network restoration is done exclusively with the assistance of other TSOs. Bottom-up is referred to as “Alone”, since network restoration does not require the assistance of a neighboring TSO. As for the combination of Top-down and Bottom-up, it is called ”Combined”.

6 Conclusion and Outlook

This paper reviews the existing network restoration strategies in Central Europe. As no responsibility of DSOs for network restoration is given according to current legal requirements, three new concepts are introduced. In case of a blackout, Top-down or Bottom-up strategy, or a combination of both can be applied with the Build-down and Build-together strategies, which is currently the basis for grid restoration plans. Since only TSOs are responsible for system security in their control areas according to current legal requirements, the proposed Build-up strategy allowing DSOs to re-energize its own area and support the upstream TSO’s restoration in some European countries, e.g. Germany, is so far unlikely to be carried out. Regarding Build-together strategy, both TSOs and DSOs can use their own power sources with black start capability to re-energize and stabilize the disturbed networks as well as re-supply their customers in parallel. Besides the advantage of multiple possible starting points in case of a blackout, this approach guarantees an acceleration of the whole restoration process. After synchronizing these islands, a more stable grid area will be obtained.

As discussed in this paper, RES brings great challenges to the network operation. In every restoration strategy, the threat from automatic reconnection of distributed generation is a major problem, which all network operators face, because of some RES being always involved, within islands. Besides, it should be noted that the majority of distributed generators are directly connected to the distribution networks and TSOs and DSOs have no control over them. In order to apply the new restoration strategies, new recommendations on network codes for emergency and restoration, addressing whether and how distributed generation should contribute as well as which technical requirements must be met during the restoration process, should be further considered. Moreover, an innovative restoration tool shall be developed at a later stage of the Restore4RES project to guide the operators during the network restoration process. It will be able to provide network operators with information about possible further steps and their consequences.

7 Acknowledgement

RestoreGrid4RES is a joint project of TU Kaiserslautern, TU Wien, KNG-Kärnten Netz GmbH, and Netz Oberösterreich GmbH. This project has received funding in the framework of the joint programming initiative ERA-Net Smart Grids Plus. The initiative has received

ISBN 978-3-85125-586-7 DOI 10.3217/978-3-85125-586-7

funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 646039.

8 References

[1] A. E. M. Operator, "Update report-Black system event in South Australia on 28 September 2016.," Adelaide, South Australia, 2016.

[2] V. FNN, "Erzeugungsanlagen am Niederspannungsnetz, technische Mindestanforderungen für Anschluss und Parallelbetrieb von Erzeugungsanlagen am Niederspannungsnetz," Technical report, VDE-Verlag, 2, VDE-AR-N 4105, 2011.

[3] R. Schmaranz, J. Polster, S. Brandl, H. Renner, M. Weixelbraun, K. Köck and M. Marketz, "Blackout: key aspects for grid restoration," in *CIRED 2013*, paper 0002, Stockholm, Sweden, June 2013.

[4] ENTSO-E, "Establishing a network code on electricity emergency and restoration," ENTSO-E: Operation Handbook, Brussels, 24 November 2017.

[5] Bundesrecht, "Gesamte Rechtsvorschrift für Elektrizitätswirtschafts- und -organisationsgesetz 2010," Fassung October 2017. [Online]. Available: https://www.ris.bka.gv.at/GeltendeFassung.wxe?Abfrage=Bundesnormen&Gesetzesnummer=20007045. [Accessed 18 January 2018].

[6] ENTSO-E, "P5–policy 5: Emergency operations," Continental Europe Operation Handbook, 2017.