Overview of the Distribution Test Grids With Distributed Generation and HVDC

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***Abstract*—Paper presents an overview of the electric distribution test grids, issued by IEEE, CIGRE and others technical institutions, which includes distributed generators. It shows their qualities, quantities, the main features as well as the purpose and the type of grids. The paper also demonstrates the well-known test grids (IEEE13, IEEE34, etc.) and the new test grids which are being developed in recent years to suit changes in distribution systems. These new test grids integrate distribution generation and HVDC technology. An example of application of the IEEE 13 for distribution generation testing is presented, also.**

***Index Terms*—IEEE test grids, CIGRE test grids, Distributed Generation testing.**

I. Introduction

In previous period many models, analysis, and simulation tools for electric distribution system computer analysis are developed [1-7]. These programs use a wide range of iterative technique. They are in the range from very simple, with a number of simplifications and assumptions which refers to the power lines and load, to the more sophisticated ones with little or no simplification. Due to existence of different programs, it was necessary to standardize the system in a form of distribution test grids for benchmark different algorithms and devices.

Distribution test grids are very useful and widely applied tools in power system research. Their use ensures that the research results can be easily checked and compared with the results of other studies. They are designed with the intention to allow testing of different algorithms on three-phase grids. Therefore, they have all necessary parameters clearly given, as well as the scheme and instructions for modeling of each part of the grid.

Monitoring the situation in some parts of the system, with the support of the processing of these data is based on monitoring changes in voltage, current and active and reactive power in characteristic nodes. For real grids not all parameters are known, dynamic and static data of the systems are not well documented, calculations of numerous scenarios are difficult due to large set of data, lack of software capabilities for handling large set of data, etc. On the other hand, all that is known and specified for the test grids.

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Modern distribution grids can assume high level of distributed generation (DG), such as solar photovoltaic (PV) and wind power plants. Distribution generators significantly alter distribution grid and classical test grids is necessary to adjust to that changes.

Furthermore, a high-voltage direct current (HVDC) electric power transmission system has been used mainly for point-to-point transmission. The integration of new renewable generation and electrification of wind generation, oil, gas, PV and other distributed generation, mainly onshore grids, as well as the integration of different electricity markets, resulted in a demand for new transmission and distribution solutions. A resolution for this demand may be medium voltage DC or hybrid AC and DC networks, while the full development and wider use of these technologies are expected in the future.

The aim of the paper is to present an overview of existing distribution test grids, mainly IEEE distribution test grids (4, 13, 34, 37, 123-bus feeders) and recently added cases, including European test grid (appeared in 2015) [8]. Also, distribution test grids with integration of DGs as an essential part in the concept of the future smart grids and the most recent DC test systems that include HVDC and distributed generation from renewable sources are included [9]. At the end an example of application of the IEEE test grid modified with distribution generators is presented.

II. IEEE Test grids

For distribution grids IEEE created test grids with 4, 13, 34, 37, 123, 324, 8500 nodes. Original document with descriptions of test grids with 13, 34, 37 and 123-buses and all parameters of their elements was created in 1992. It is approved for issue in 2000. There are also more recent test grids with 8500-buses (2010) and European low voltage test grid (2015). Test grids described in these documents are the real (physical) grids mainly from the North American continent, but since 2015 there is a European low voltage test grid.

A. IEEE 4-bus test grid

Test grid is designed for testing transformers models. Scheme of this model is presented on Fig 1.

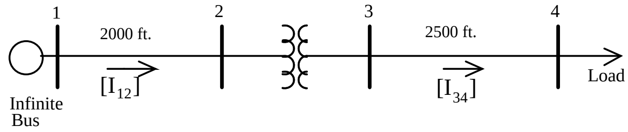

Fig. 1. IEEE 4-bus test grid.

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B. IEEE 13-bus test grid

This grid is quite small but it has very interesting characteristics. Grid voltage level is 4.16 kV and it is short and enough loaded. This system was designed to evaluate and benchmark algorithms in solving unbalanced three-phase radial systems. System consists of 13 buses which are interconnected with 10 overhead and underground lines, one generation unit, one voltage regulator unit, one transformer ΔY 115/4.16 kV, one in-line transformer YY 4.16/0.480 kV, two shunt capacitor banks, unbalanced spot and distributed loads. Single line diagram is shown in Fig. 2.

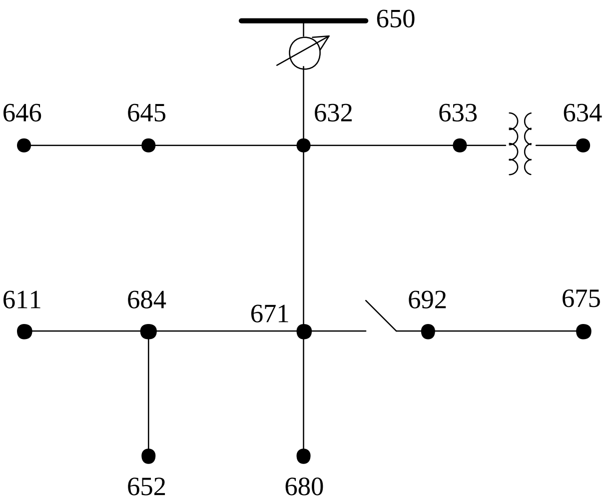

Fig. 2. Single line diagram of the IEEE 13-bus test grid.

C. IEEE 34-bus test grid

This grid is a customized version of the actual grid with nominal voltage of 24.9 kV, which is located in Arizona. Characteristics of this grid is that it is a very long grid, lightly loaded and has two in-line regulating transformers designed to provide good voltage profile, one in-line transformer that powers a short section of the grid, unbalanced load and shunt capacitor. Single line diagram is shown in Fig. 3.

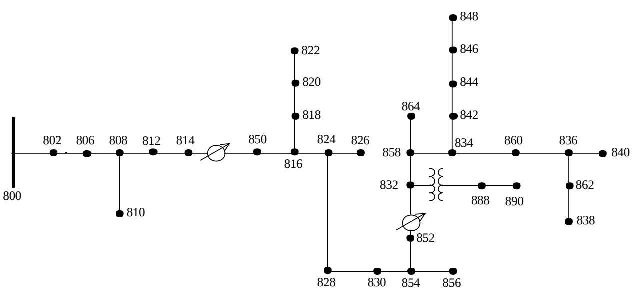

Fig. 3. Single line diagram of the IEEE 34-bus test grid.

D. IEEE 37-bus test grid

It is characterized by delta configured, all line segments are underground, and substation voltage regulation is two single-phase open-delta regulators with spot loads. Also this grid is characterized by a large unbalance and that all loads are spot loads, which represent consumers of constant power (constant PQ), constant current and constant impedance. All the above makes quite an unusual configuration. Single line diagram is shown in Fig. 4.

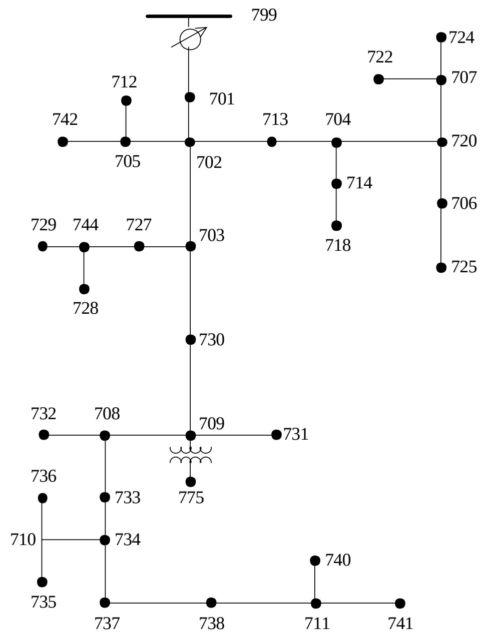

Fig. 4. Single line diagram of the IEEE 37-bus test grid.

E. IEEE 123-bus test grid

The IEEE 123 node test grid operates at a nominal voltage of 4.16 kV. This circuit is characterized by overhead and underground lines, unbalanced loading with constant current, impedance and power, four voltage regulators, shunt capacitor banks, and multiple switches. Single line diagram is shown in Fig. 5.

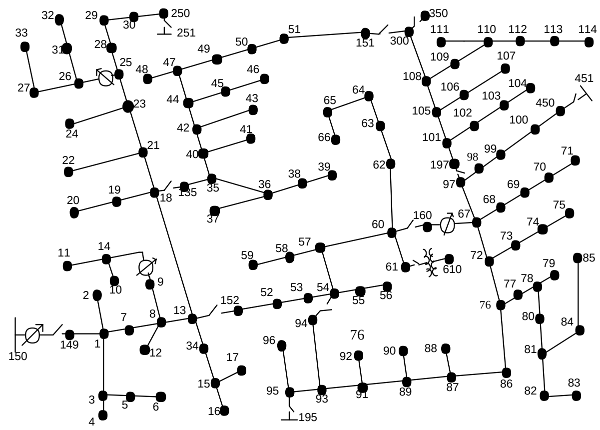

Fig. 5. Single line diagram of the IEEE 123-bus test grid.

F. IEEE European Low Voltage Test Feeder

Above mentioned test grids are based on actual grids that are physically located in North America. They operate on 60 Hz, and correspond to standards applicable in North America. For this reason there is a need to establish appropriate test grid, which would take into account European standards of electricity distribution. In 2015 a document on the establishment of European distribution test grid was adopted and approved [8]. This is a low-voltage radial test grid based on distribution system with fundamental frequency of 50 Hz, mainly 400 V, 4 wires, 3 phase grid. The feeder is connected to the medium voltage (MV) system through a transformer at substation. The transformer steps the voltage down from 11 kV to 416 V. Medium system is modeled as voltage source and appropriate impedance. Loads are modeled as constant PQ loads. Test grid consists of 55 loads, 905 lines and 906 buses. Simplified single line diagram is shown in Fig. 6.

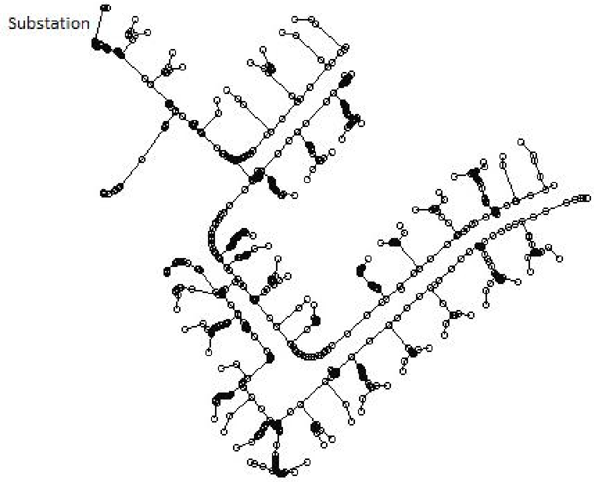

Fig. 6. Single line diagram of the IEEE European test grid.

III. OTHER TEST GRIDS AND TEST FEEDERS

There are many other distribution test grids and test feeders, which are applied at some universities or research institutes. All these network are used for specific purpose and differs in number of busses and nodes. Still, they mainly dedicated to test existing networks, with low penetration of DGs or without any of them in connection. Test grids for networks with HVDC or with only HVDC lines are developed separately.

IV. TEST GRIDS BASED ON IEEE TEST GRID, WITH ADDED DISTRIBUTED GENERATION

In recent years the fast development of electricity grids towards the idea of smart grids and the rapid increase in the number of distribution generators brought new conditions in distribution grids. This significantly changed the functioning of the distribution grids and imposed the need for examination of a large number new devices and algorithms for the new conditions in the grid. The easiest way to upgrade test grids to fit new conditions in the grid is that the existing test grid, which are well known and are in use for many years, add (connect) distribution generators. This is in fact the case that is most often in real grids, when in existing grid are added newly constructed distribution generators. This approach, which consists of changing the test grids, is implemented in the following papers, IEEE 13 test grid is adapted in [10], IEEE 34 test grid is adapted in [11, 12]. In [10] grid was changed by adding wind and PV generators with different types of control. Total input power when there is no DGs, at node 650 is 3.57 MW. Production of distribution generators is a 3.1 MW, so almost all load of the grid is covered by these DGs. This DG placement and size is proposed as optimal for IEEE 13 bus grid for minimizing the power system performance index (PI) (combines two terms to express both total active power loss and the average node voltage deviation) and power loss. PI and power loss are reduced for around 63%. A 2 MW wind farm and 1 MW solar power plant (PV1) are connected to a 4.16 kV distribution system through 15 km and 5 km, 4.16 kV feeders, respectively. An additional 100 kW PV power plant (PV2) is connected to the node 6 (node 675), which represents a smaller solar power plant, whose number is growing in modern power system, and which will largely take place in the smart grids of the future [10].

In Fig. 7, a simplified single line diagram of the IEEE 34 test grid is shown, including adaptation with DGs at one location. Tests in this paper were done on IEEE 34-bus system with multiple inverter based DGs on multiple locations. Different cases were created in order to cover all possible scenarios for islanding and non-islanding [11].

From these examples it can be observed that by simply adding a distribution generators in existing test grid, and by connecting on the assigned nodes, via distribution transformers or in some cases directly to the grid, we can obtain an excellent basis for testing in the conditions of the grid that are similar to real modern distribution grids. If the research is carried out in Matlab environment, these link of the detail and easily adaptable models of distribution PV and wind generators, which are given by the MathWorks Company [7] can be very helpful. Models are easy to connect to the existing test grids. In case of adding a distribution generator in the existing model of the test grid it is important to note to expel the regulation transformer, and to set the main source as a swing generator. More details can be found in [10, 11, 12].

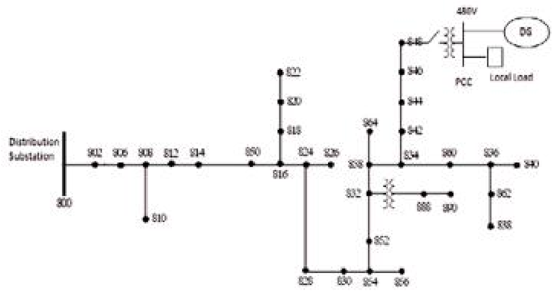

Fig. 7. Single line diagram of the IEEE 34 test grid modified with DGs [11].

V. TEST GRIDS WITH HVDC

With fast development and the increasing use of distribution sources that are using renewable energy sources appeared various problems in the transmission of electricity. As a possible solution to these problems HVDC technology established itself. HVDC grids are increasingly seen as a possible solution to manage the future power system with large amounts of renewable sources in a secure and cost-effective manner. Systems with significant amounts of DC transmission behave in a fundamentally different manner when compared to the traditional AC power system. The integration of HVDC systems introduces new fast dynamics and adds controllability to the combined system. As a result, the modeling and control of the entire interconnected system needs to be reevaluated in order to accurately compute the system behavior, both from the AC and DC system [13]. Also, High Voltage Direct Current (HVDC) grids are the most effective solutions for collection, integration and transmission of large scale remote renewable resources to load centers [14]. Because of all the foregoing, it is expected greater use of HVDC grid and thus bigger need for development of standardized test grids that include this technology in order to obtain a platform for testing new devices and algorithms.

In [9] is presented a test grid, called B4 DC Grid test system, developed by HVDC and Power Electronics committee of the Council on Large Electric Systems (CIGRE). This test grid pretends to become standard test grid for systems with HVDC. It consists of 2 onshore AC systems, 4 offshore AC systems, 2 DC nodes with no connection to AC and 3 voltage source converters (VSC)-DC systems. In Fig. 8 is shown simplified single line diagram of B4 DC Grid test grid.

Interesting paper, in which is shown in detail how to model each part of HVDC grid, as well as control of such grid is paper [13]. It gives an overview of the current research in the field of HVDC grids focusing on the interaction of the AC and DC system. Also, it gives a detail description of technology used in HVDC grids, with focus on converters, especially Modular Multilevel Converter (MMC). Also it discussed a DC breaker, as potentially most critical part of HVDC grids.

In [14] a five HVDC grid test models are presented, to provide a common reference and study platform for researchers to compare the performance and characteristics of a DC grid with different DC control functions and protection strategies. Test grids that are presented are: HVDC test system for integration of large scale onshore renewable power generation, for integration of offshore renewable power generation, DC grid for integration of small renewable power plants, LCC-HVDC grid for feasibility studies and one comprehensive test model. This paper presents two test grids shown in Figs. 9 and 10, other schemes, as well as detailed information about each grid can be found in [14].

Another paper that presents a HVDC test grid is [15]. This paper proposes a new HVDC grid test system for electromagnetic transient analysis. This test grid is also suitable for HVDC power system studies that investigate the protection of HVDC grids, dynamic studies of converter operation in HVDC environment and interactions between AC and DC part of grid. Simplified single line diagram is shown in Figure 11.

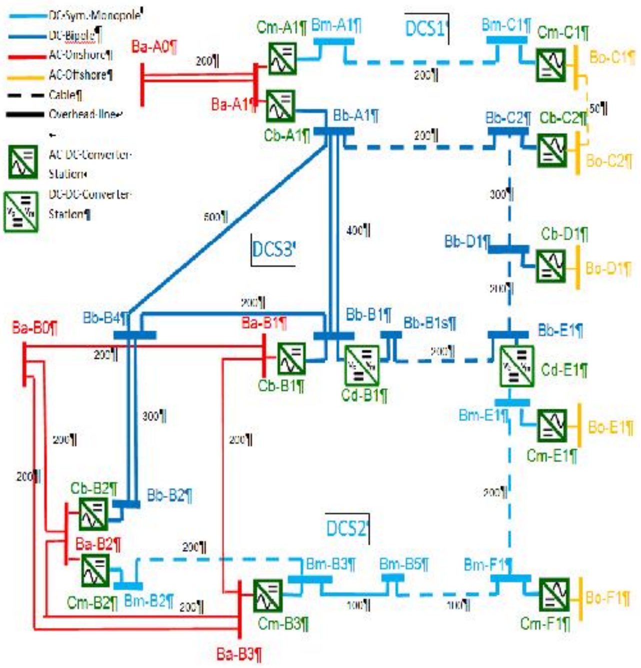

Fig. 8. CIGRE B4 DC test grid [9].

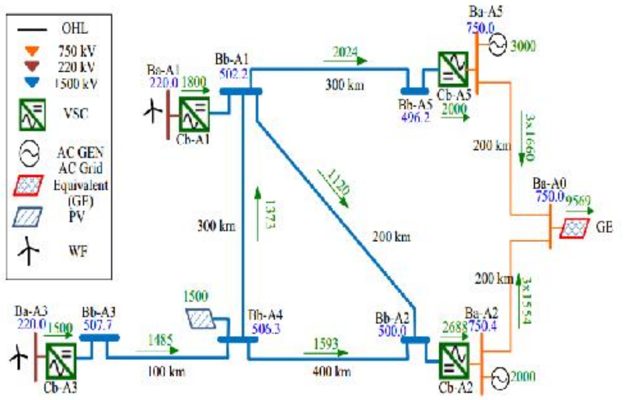

Fig. 9. Single line diagram of HVDC grid test system for integration of large scale onshore renewable power generation [14].

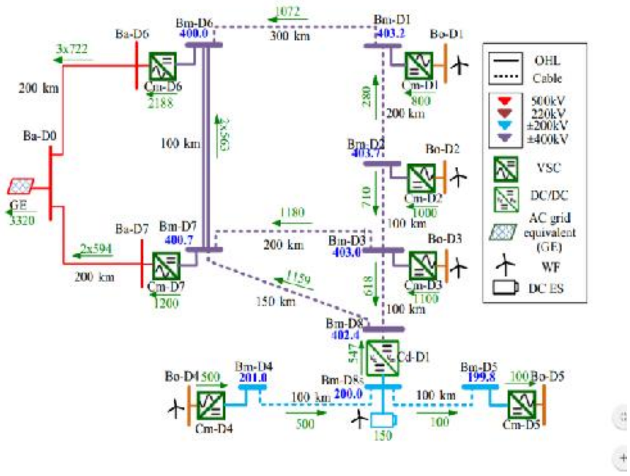

Fig. 10. Single line diagram of HVDC grid test system for integration of offshore renewable power generation [14].

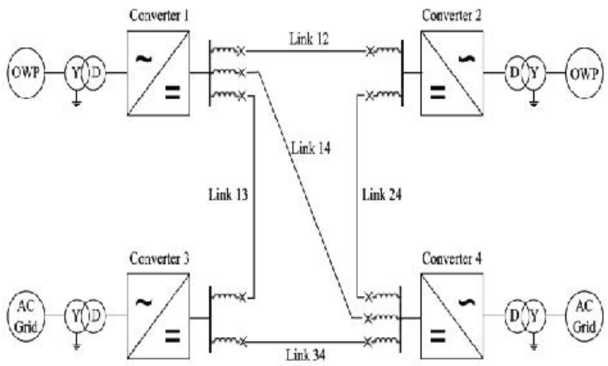

Fig. 11. Single line diagram of HVDC grid test system for HVDC grid dynamics and protection studies [15].

VI. EXAMPLE HOW TO UPGRADE CLASSIC TEST GRID WITH DGS

In this example will be shown how to upgrade IEEE 13 test grid with distributed generation, and how to connect models of DGs to existing test grid. The way of adding a simulation model of distributive generators in model of test grid is universal and the same can be applied to any test network. Creating a model is explained when Matlab/Simulink environment is used.

The first thing to start is the existence of models of classical test grid, which we will use as the basis of the power system, and in that grid model we add distribution generators. Suppose that the given model was already developed, and simplified model of that grid is already given in Fig. 2. If connect one 100 kW PV array on node 680, single line diagram will be changed, and it is shown on Fig. 12. For example, PV array can be modeled in Matlab as it is shown in [16]. This small solar power plant consists of 5-module string, 66 parallel strings (SunPower SPR305E-WHT-D). Model of PV array is connected to the 25 kV grid, via D_1Y_g distribution transformer. It is also possible to use this part of the PV array model, with the modification that the distribution transformer on the side towards the grid is set to a voltage of 4.16 kV, which is main voltage level of IEEE 13 test grid, as well as the voltage on node 680. As it can be seen in Fig. 12, voltage regulator is excluded from the model, because of earlier mentioned reasons, which concern to the added distribution generator. Also, the main source of this network is set to swing and with exclusion of voltage regulator, modeling is greatly facilitated. With these actions coupling the PV array to the network is accomplished and equality in line voltages levels. It is necessary to ensure that distribution generator and the network have the same phase voltage angles and frequency. Frequency settings are very easy to adjust. Desired frequency of PV array can be easily set in the inverter model. The aforementioned model already has the same frequency as the network. Voltage angle is recommended to align by setting the voltages angles in grid and voltages angles of distributed generator on the same value at the time of starting the simulation (t = 0 s).

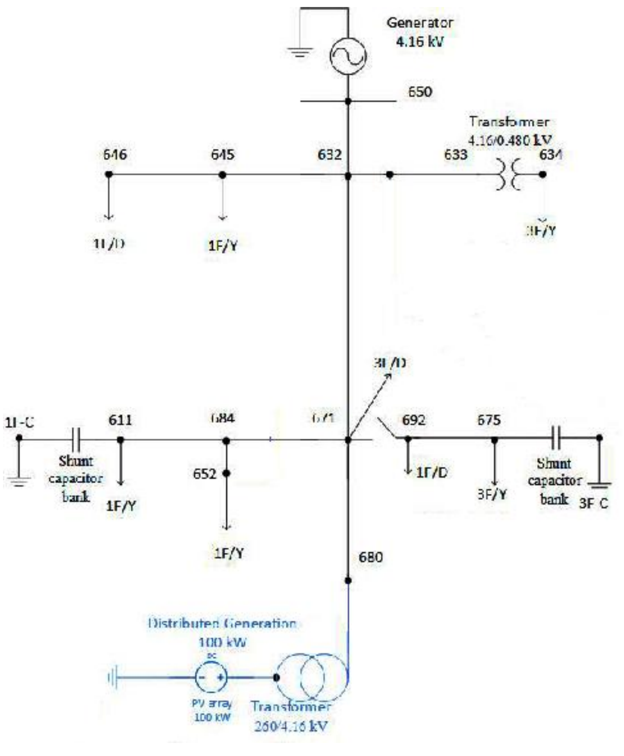

Fig. 12. Single line diagram of IEEE 13 test grid with 100 kV PV array added on node 680.

A. *Simulations on upgraded IEEE 13 test grid*

On Matlab model of IEEE 13 test grid upgraded with distributed generation, as explained bellow are performed simulations of the fault of phase A with ground, placed between node 632 and node 671. Implications of this fault are the voltage dips that occur on various parts of the grid, and that are observed and recorded. Result of these simulations is given on Fig. 13. Fault starts at 0.2 s and ends at 0.35 s. From 0 sec to 0.05 s, pulses to Boost and VSC converters are blocked. Voltage on busbar of DG corresponds to open-circuit voltage. At t=0.05 s, boost and VSC converters are de-blocked. DC link voltage is regulated at 500V. Steady state is reached at 0.15 sec.

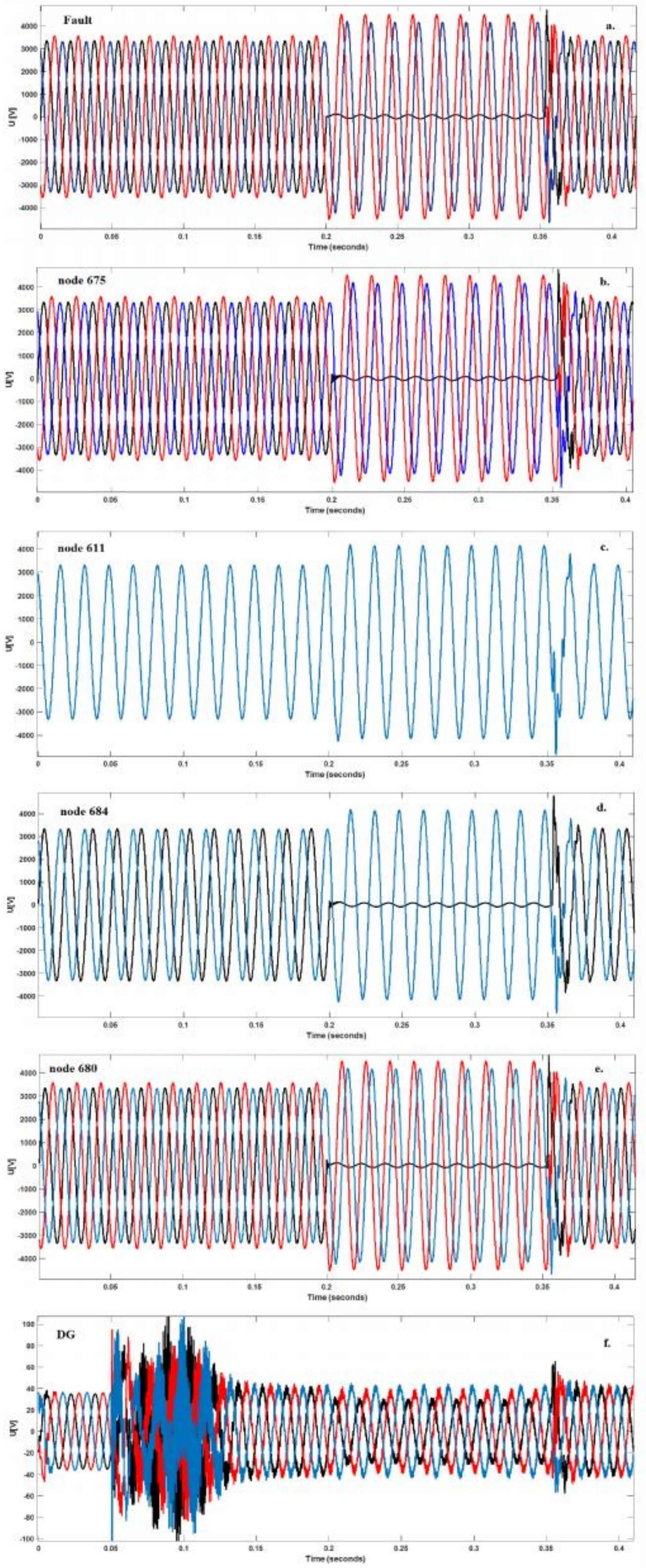

Fig. 13. a. Voltage signals on the place of the fault, b. Voltage signals on the place of node 675, c. Voltage signals on the place of the node 611 (this part of the grid consists of only 1 phase, phase C), d. Voltage signals on the place of the node 684 (this part of the grid consists of only 2 phases, phase A and C), e. Voltage signals on the place of the node 680, f. Voltage signals on the place of the busbars of distributed generator, after distribution transformer.

VII. CONCLUSION

The changes that take place in the electricity grids are increasing fast. Distribution generators, which are now common phenomenon throughout the world, and a new way of connection of remote renewable energy sources to the grid, HVDC, which is in recent years more and more actual, are main tasks of most studies.

The paper gives an overview of the distribution test grids from basic IEEE, which represents classical test grids, over the test grids that include the distribution generators, and that are in the current situation mostly often actual state of the grid, to the grids that contain HVDC technology and that are expected to become widespread in the future. Also are presented interesting links and papers with detail models and advices for modeling of these types of grids, and detail guide for suiting classical test grid to real conditions by adding distribution generator in test grid.

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