A Brief Overview of the Distribution Test Grids with a Distributed Generation Inclusion Case Study

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Abstract: The paper presents an overview of the electric distribution test grids issued by different technical institutions. They are used for testing different scenarios in operation of a grid for research, benchmarking, comparison and other purposes. Their types, main characteristics, features as well as application possibilities are shown. Recently, these grids are modified with inclusion of distributed generation. An example of modification and application of the IEEE 13-bus for testing effects of faults in cases without and with a distributed generator connection to the grid is presented.

Keywords: Distribution test grids, IEEE test grids, Distributed generation, Distributed energy resources (DERs).

1   Introduction

In previous period many models, analytical and simulation tools for electric distribution system computer analysis have been developed [1 − 8]. These tools use a wide range of iterative techniques to achieve desired goals. They can be very simple, with many assumptions in order to be less complex in modelling of the power lines and loads, up to the more sophisticated ones with few or no simplification. With more advanced computer technology and higher capacities of modern processors, these software tools became more realistic, with real time response. Now, they are backed with huge data bases, with numerous network parameters, characteristics, SCADA reports, etc., and therefore they are more suitable for practical engineering applications and decision making. On the other hand, as there are different techniques that test and examined a large number of scenarios, network states (faults, instability, etc.), control algorithms, compensation methods, renewable generation penetration effects and versatile loads demands characteristics and operational behaviour, which may be applied in simulation of electric distribution system operation, such tools became very complex, hardware demanding, not user friendly and expensive, so not suitable for everyday, wide spread academic research and testing. Furthermore,

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calculation of power system response requires monitoring of frequency variations, values of voltage, current, active and reactive power at characteristic nodes. However, for actual grids some parameters may not be known or may not be well documented, especially for parameters "deep" in the distribution network, so calculations of numerous operation scenarios are difficult and time consuming.

Therefore, it was necessary to establish one or more reference models of grids with standardized complexity, structure and known parameters, which may represent different transmissions or distributions grids [9 – 15]. These reference models or test grids are chosen and developed to be suitable for benchmarking and testing of different algorithms, operation scenarios and load behaviour. The test grids usually represent reduced models of actual grids (like IEEE[1] test grids or EPRI[2] test grids), but they may be synthetic test grids that are developed to be similar to actual electric grids in order to avoid confidential energy infrastructure information (like TAMU[3] test grids) or may be completely invented (like CIGRE[4] test grids) [16 – 20].

Generally, there are two types of test grids: transmission and distribution ones. This paper will focus on distribution test grids (DTG).

A test grid is a distribution network model that is able to replicate the behaviour of an actual distribution feeder [9]. In general, their aim is to reproduce the characteristics of an actual network, including specific particularities within a specific region. 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 (with possible sections with single-phase lines). Therefore, they have all necessary parameters clearly given, as well as the schematics and instructions for modelling of each part of the grid, which enable them much faster computation and more reliable simulation results.

Modern distribution grids may contain high level of renewable sources or distributed generation (DG), such as solar photo-voltaic (PV), wind power plants, small hydro, storage units and others. Existence of DGs significantly alters operation of the distribution grid and classical test grids need to adapt to these changes. However, the most applied test grids in many studies, reports, books or scientific papers, are classical test grids that do not include DGs. As stated in [9] there is a lack of realistic public test systems that includes DGs for modelling and testing of new algorithms for advanced controls, new distribution

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operation strategies, for minimization of total system costs, minimization of network losses, maximization of security of supply etc. In this case, a logical step is modification of classic test grids with DGs and appropriate new equipment (power electronics converters, storage units, etc.). This approach enables comparison of new grids, applied devices or algorithms with previous cases (old results). This is a common solution applied in many papers [10 – 15].

Furthermore, integration of new DGs with DC output or with off-shore locations may results in request for new distribution network solutions. Usual respond is application of the HVDC lines for transmission network. Implementation of mixed AC and DC networks or even pure medium/low voltage DC ones in a form of microgrids or parts of existing distribution networks may be considered, also. Still, full development and wider use of these technologies are expected in the future. In this paper, test grids with HVDC will be only briefly addressed.

The aim of this paper is to present an overview of existing distribution test grids, IEEE distribution test grids (with 4, 13, 34, 37, 123-bus feeders and Comprehensive test feeder) and recently added cases, including European test grid [16]. Also, the paper addresses distribution test grids with integration of DGs. Furthermore, some simple ways for making modifications on classical test grids to include DGs (both wind and solar), together with useful advices and links are presented, too. Connection to public available models that are easy to adapt for different research purposes, that authors consider applicable are given and used in presented example.

2   Distribution Test Grids

DTGs need to provide electrical model data (equipment or line data, protection, voltage control device, etc.), information about geographic distribution and connections (length of lines, routing and connectivity), load data corresponding to the node/feeder (customer number, sizes, classes, load profile, peak kW and power factor), one line diagram of the substation serving node/feeder and transformers information's (MVA, kV, impedance, winding connections, neutral impedance). They can be divided into two broad classes: the test grids that are based on real parameters and the synthetic test grids. Some research institutes provide test cases available in ready-made files of test grids, for simulations in software like Matlab/MPOWER (TAMU, EPRI) [17]. Simulation-tools companies, like Matlab, also offer ready-made fully modelled well-known test grids [8].

The first group has many representatives, but as some confidential data about the network are included, few of them are publicly available. In this paper this group is represented by the IEEE and EPRI distribution test grids. The

IEEE test grids are more common and popular in academic and research community.

The second, much larger group, the synthetic test grids, can be further divided into several subcategories, like test grids based on real grids but only statistically and functionally similar to real grids, test grids manually designed to suite for some theoretical or practical problem solving, or test grids that are mix of parts of several actual grids that are linked together. In this paper, the TAMU and the CIGRE test grids will represent this group.

Main parts of distribution test grid and thus main parts of interest for modelling are presented in Fig. 1 with bold squares (level 1, 4 and 5). It is classical vertical structure for standard North American electric grid with transmission voltage levels 230 – 765 kV and 69 – 169 kV and with distribution voltage levels 4 – 35 kV and 120 – 240 V (in Serbia, transmission voltages levels are 110 kV, 220 kV and 400 kV, while primary distribution voltage levels are 35 kV, 20 kV and 10 kV, and secondary distribution level is 400V/230V). The DTGs actually substitutes the power plant and transmission system and represent them as a high voltage power source and a substation with step-down transformer. The rest of a DTG is based on real distribution network divided in two segments – primary (medium voltage) and secondary (low voltage) distribution.
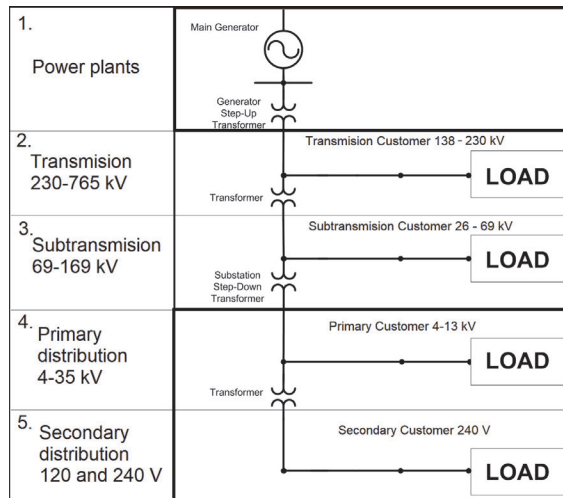

Fig. 1 – *DTGs general structure.*

3 IEEE Test Grids

The most commonly used DTGs are the IEEE test grids. The IEEE create test grids with 4, 13, 34, 37, 123, 324, 8500 buses (nodes) [16]. 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 publication in 2000. There are also more recent test grids with 8500-buses (from 2010) and European low voltage test grid (from 2015) [16]. Test grids described in these documents are simplified models of the real (physical) grids mainly from the North American continent, but since 2015 there has been the European low voltage test grid. Some important information, power level of DGs and specific task of test grid for what they are designed for are presented in **Table 1**. Single line diagrams of all presented DTGs are shown in Fig. 2.

3.1 IEEE 4-bus test grid

This test grid is primarily designed for testing transformers models (Fig. 2a). It consists of full three phase lines, and unbalanced loads.

3.2 IEEE 13-bus test grid

This grid is quite small but it has very interesting characteristics (Fig. 2b). 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.

3.3 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 (Fig. 2c). 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.

3.4 IEEE 37-bus test grid

The IEEE 37-bus DTG is presented in Fig. 2d. 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.

3.5 IEEE 123-bus test grid

The IEEE 123 node test grid operates at a nominal voltage of 4.16 kV (Fig. 2f). 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.

Table 1
IEEE test grids features.

Name	Primary Voltage Level [kV]	Peak Load [MVA] / No. of loads	Level of DGs [MVA]	Length [km]	Designed for:
4-bus	12.47	6.3/1	0	1.3	For testing transformer models.
13-bus	4.16	3.6/9	0	2.5	Provided a good test of the convergence of a program for a very unbalanced system
34-bus	24.9	1.6/24	0	94	A very long feeder requiring the application of voltage regulators to satisfy ANSI voltage standards
37-bus	4.8	2.73/25	0	5.5	A three wire delta underground system
123-bus	4.16	3.8/114	0	12	A large system consisting of overhead and underground single phase, two phase and three phase laterals along with step voltage regulators and shunt capacitors
European LVTF	0.4 (416 V)	3.7/55	0	10.4	Focus is to provide a benchmark for researchers who want to study low voltage feeders, which are common in Europe, and their mid- to long-term dynamic behaviours
CTF	24.9	4.17/36	0.15	81.7	This DTG tests the capability of a program to represent a wide variety of components in one system.

3.6 IEEE Comprehensive test feeder

Test grid added in 2010, and updated with new model and solutions in 2014 (Fig. 2e). This test feeder tests the capability of a simulation-tool to represent a wide variety of components in one system, test the models of all distribution components and to test the convergence qualities of a verity of switching schemes. Grid includes switching devices, and this allows wide range of different grid configurations. Also there is different equipment like overhead and underground lines, single lines, parallel lines, substation transformers, step voltage regulators, detail motor models, detail generator models, capacitor banks, and the mixture of distributed and spot unbalanced loads. In node 751 is installed induction generator which can represent wind or small hydro power

plant with 150 kVA, and all power is produced as 150 kW. Rated voltage of generator is 480 V.
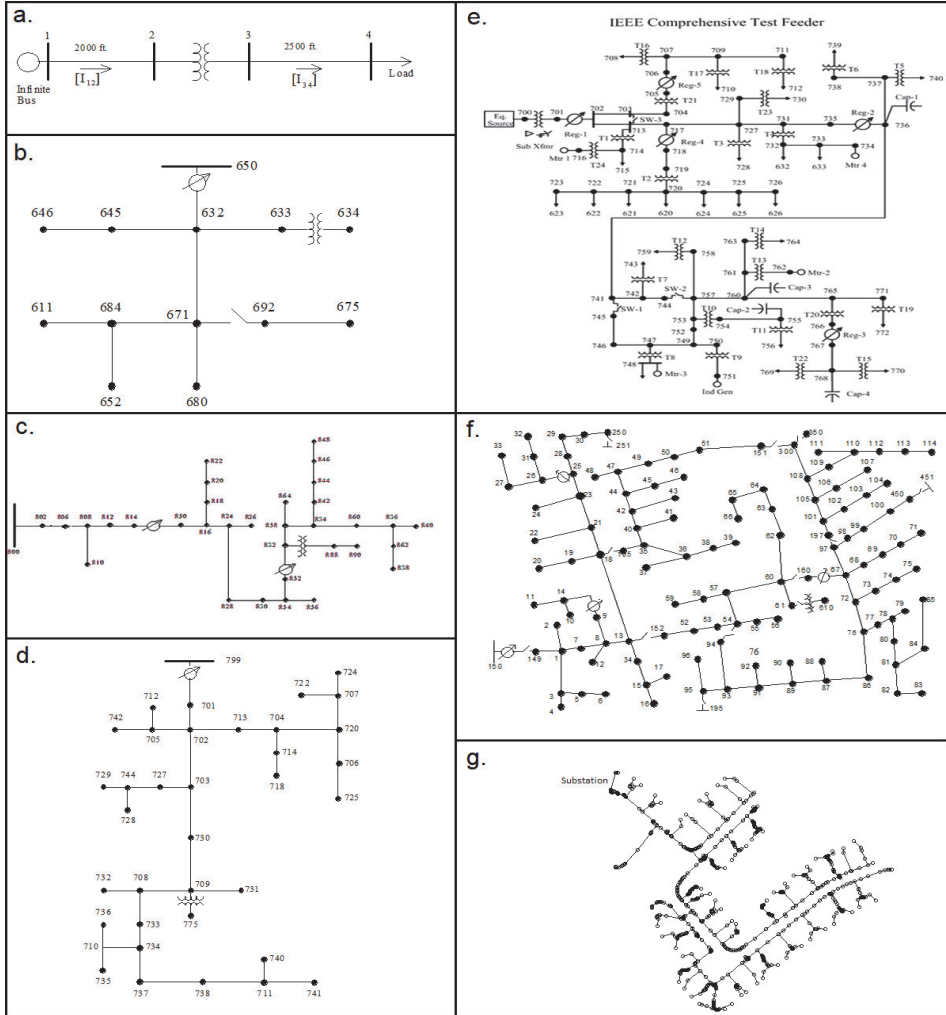

Fig. 2 – *Single line diagram of: (a) IEEE 4-bus; (b) IEEE 13-bus; (c) IEEE 34-bus; (d) IEEE 37-bus; (e) IEEE Comprehensive test feeder; (f) IEEE 123-bus and g) European test grid [16].*

3.7 IEEE European low voltage test feeders

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 [9]. 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 (Fig. 2g). 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 modelled as voltage source and appropriate impedance. Loads are modelled as constant PQ loads. Test grid consists of 55 loads, 905 lines and 906 buses.

4   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. These networks are used for specific purpose and differ in number of busses and nodes. Still, they mainly dedicated to test grids with low penetration of DGs or without having connected any of them.

There are also, test grids for networks that include HVDC connections, AC and DC busses and necessary power electronics conversion systems that are developed separately. As they are usually part of transmission system, they will be described only briefly.

4.1 Texas A&M engineering test grids

Texas A&M engineering test grids are available at [17] and algorithm used to develop these grids is described in [18]. These models are in the opposite to most of IEEE test grids, synthetically designed and modelled. But, they are functionally and statistically similar to actual power grids but without modelling any actual lines. Big advantage of this TG is that they do not contain confidential critical energy infrastructure information. They offer test models in several formats, and besides they own test grids like ACTIVSg200, ACTIVSg500, ACTIVSg2000, ACTIVSg10k, UIUC150, ILLINI 42 Tornado ILLINIGMD 42 HEMP, they offer literature based power flow test cases, like IEEE test grids (IEEE 14, 24, 30, etc). These test grids cover wider range of power systems and not only distribution grids. Looking at the structure represented in Fig. 1, it can be observed that A&M test grids cover all 5 parts of a network. Therefore, in this paper they are only mentioned, as they offer various (different) grids and cases for testing. They are mainly designed for computer assignments for calculation of small and medium power systems, power flow analysis, economic dispatch and contingency analysis, optimal power flow and transient stability analysis, etc.

4.2 Electric Power Research Institute test grids

These test grids were designed as a part of EPRI's Green Circuit project database. The descriptions and models are available for public use in [16, 19]. The models are representative of actual small, medium, and large grids from various utilities. Six test grids: K1, M1, J1, Ckt5, Ckt7 and Ckt24 are briefly describer and main features are presented in **Table 2**. Models are designed mainly to enable testing of new concept of Smart grids. Three test grids K1, J1 and M1 are designed for evaluation of the impact of photovoltaic generation to the system, while the Ckt5, Ckt7 and Ckt24 are design for testing of power flows in Smart grids.

Table 2
EPRI's test grids features [19]

Name	Primary Voltage [kV]	Peak Load [MVA] / No. of loads	Level of DG [MW]	Length [km]
K1	13.2	6/321	1	45.1
J1	12.47	6/1384	1.7	93.3
M1	12.47	5.5/1470	/ *	20.9
Ckt5	12.47	1.950/1379	/ *	77.2
Ckt7	12.5	2.4/5694	/ *	12.9
Ckt24	34.5	3.3/119.1	/ *	119.1

*/ information is not public available

4.3 Test grids with HVDC

As HVDC is often consider to be the best solution for solving connection and transmission problems that appeared with large remote (off-shore) renewable resources (wind farms), the CIGRE test grid with HVDC will be described briefly. Purpose of this grid is to give a common reference for studies of DC grids. Besides, properly described and modelled DTGs that can be recommended for use are presented in [20 – 22].

CIGRE test grid with HVDC, the B4 DC Grid test system [20] is presented in Fig. 3. It consists of 2 DC nodes with no connection to AC, 3 voltage source inverters connected to DC systems, 4 offshore AC systems of rated voltage 14 kV, 2 onshore AC systems of 380 kV (only overhead lines) both AC and DC, DC-DC converter stations, AC-DC converters and HVDC links 200 kV and 400 kV. In grid is 5.5 MW of distributed generation, mainly offshore. Grid frequency is 50 Hz.
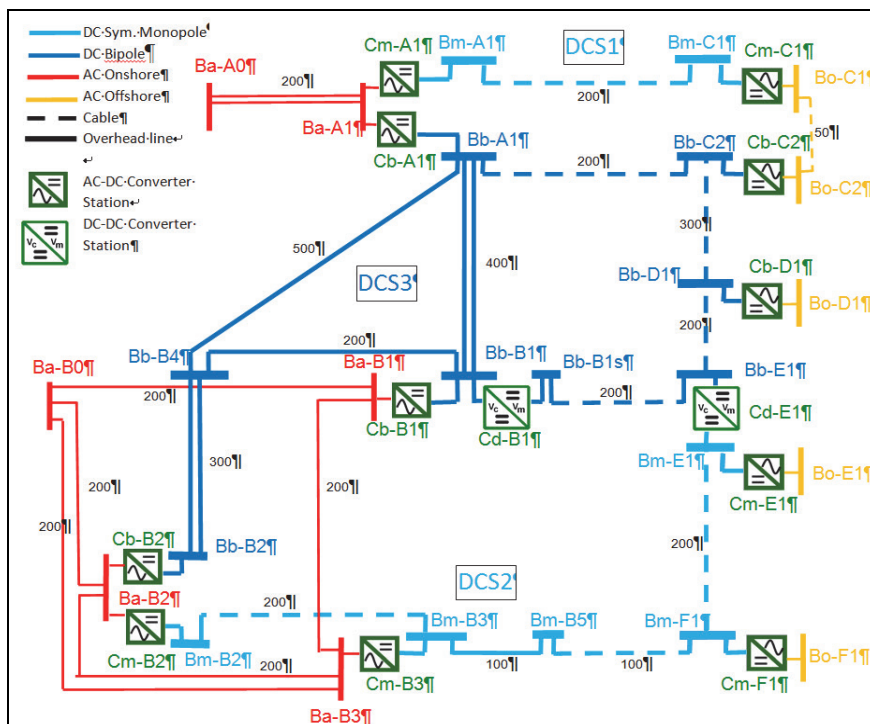
Fig. 3 – *CIGRE B4 DC test grid [20].*

5 Case Study: Classical Test Grid with DGs Inclusion

Application of a classical DTG with inclusion of DGs (wind and PV) and useful links with models that are publicly available will be presented in this section as a case study. Modelling is based on Matlab/Simulink environment, but the procedure is general and can be applied to any test system and program.

The IEEE 13-bus test grid is used as basic of the model. In this grid three DGs are added: one 1 MW PV power plant at the node 652, one two 1 MW wind power plants at the node 633. Fig. 4 presents a single line diagram of modified IEEE 13-bus DTG. Detail descriptions of models that are adjusted and used are available in [24 – 26]. Similar test grid the authors used for testing algorithms in distribution grid with high level of distributed generation [15]. Information about impact of DGs on losses, exact parameters for every generator, control of power plants, the influence of wind changes on the production of generators and how it change conditions in grid are voltage conditions during the fault are described in [15]. DGs placement and size that is used is optimal for power loss reduction and PI losses reduction.

When modelling distribution grids it is very useful to exclude voltage regulator, and replace the generator with predefined parameters with swing generator. In this way model is simplified without losing accuracy. Voltage regulator must be excluded because DGs may change voltage levels in the grid. With swing generator there is no need for recalculation of power flow and change of generator settings, because it will adapt to new configuration. Also, generator can be set to 4.16 kV, and connected directly to distribution lines.

With these actions in order to prepare grid for DGs connection, coupling the DGs to the grid can be accomplished in few simple steps and equality in line voltage levels and stability in grid will be accomplished. It is necessary to ensure that distribution generator and the grid have the same voltage magnitudes, phase voltage angles and frequency, e.g. to be synchronized. Frequency settings can be simply adjusted. Desired frequency of DGs can be set in the model of control of power converters, which connect DGs to the grid. The aforementioned models and grid have already the same frequency. Voltage angle is recommended to align by setting the voltages angles in grid and voltages angles of distributed generators to the same value at the time of starting the simulation, in the control model at $t = 0\,\text{s}$. Voltage magnitudes can be adapted with distribution transformers added between DGs and the grid. When these steps are finished, simulations with model of IEEE 13-bus grid with 3 MW of distributed energy may be started.
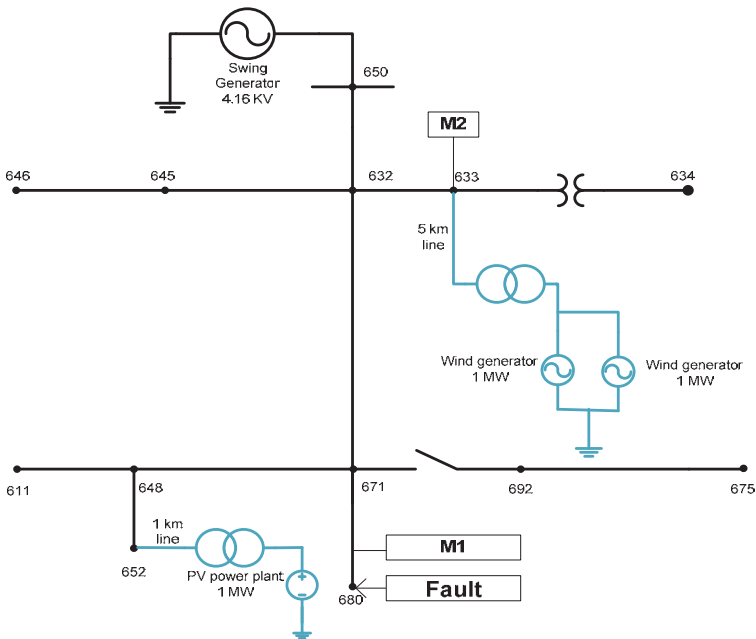

Fig. 4 – *Single line diagram of modified IEEE 13-bus DTG.*

It is assumed that at the node 680 a three-phase fouls occurs. Location of a fault is shown in Fig. 4, as well as the site where the voltages are measured (M1 and M2). This is the case which will be simulated.

Fig. 5 represents the Simulink model of modified IEEE 13-bus test grid, which has been used in simulations.

In Fig. 6 simulation results for a fault line-to-ground at the node 680 at 0.05 s, of the IEEE 13-bus test grid without DGs and with DGs inclusions are shown. The results for the first case are given in Figs. 6a and 6b, at measuring points M1 and M2, respectively. Very low voltage at the M2 can be observed. The second case is presented in Figs. 6c and 6d, i.e. the voltage waveforms at the measuring points M1 and M2 are shown. Differences and better voltage conditions in the grid during the fault can be observed. It proved ability of the connected PV system to stay connected during a fault in the network, as demanded with low voltage ride-though (LVRT) strategy in the latest distribution grid-code requirements [27].
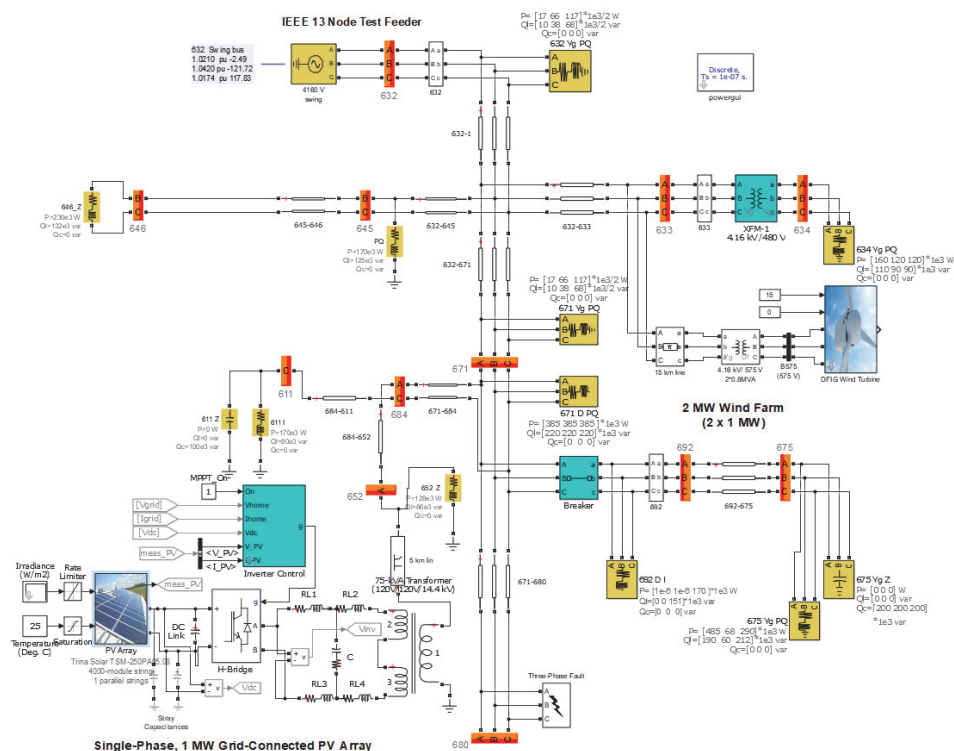

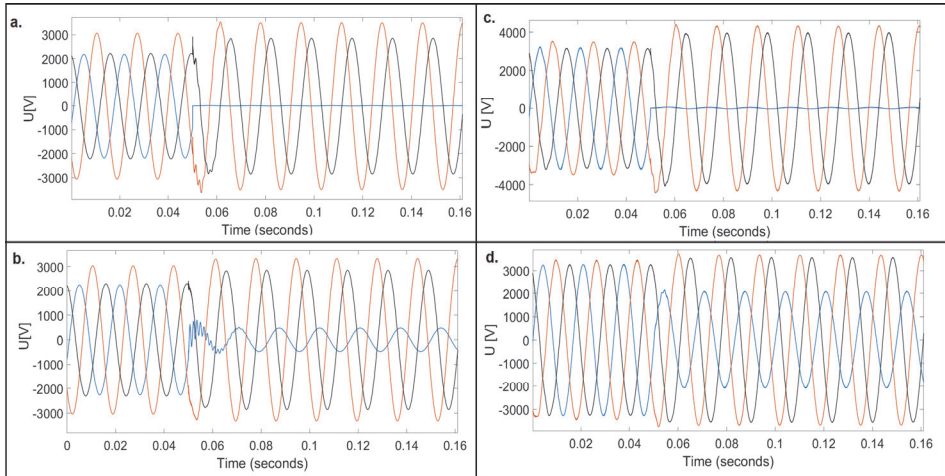**Fig. 5 –** *Matlab/Simulink model of modified IEEE 13-bus test grid.*

Fig. 6 – *Matlab/Simulink simulations – IEEE 13-bus test grid for fault in line 1 with ground at 0.05 s, in node 680. Left: Original IEEE 13.-bus test grid: (a) Voltage waveforms at the M1 and (b) Voltage waveforms at the M2; Right: Modified IEEE 13-bus test grid: (c) Voltage waveforms at the M1 and (d) Voltage waveforms at the M2.*

6   Conclusion

Distribution power grids are constantly changing and evolving. Appearance of DGs in last decade and their significant penetration in the distribution network, new smart grid technologies and a new way of connection of remote renewable energy sources to the grid through HVDC, add new challenges and problems in task to enable reliable operation and high quality of electric energy. In order to overcome appeared problems and test new devices and changes in grid to ensure power quality and reliability, many studies, projects and tests were conducted. However, there is shortage of realistic test systems that are publically available and thus classic test grid are often changed to suit new conditions in the grid.

The paper gave an overview of the distribution test grids from basic IEEE ones, which represents classical test grids, over the test grids that include the distribution generators, to the grids that contain HVDC link together with offshore and onshore renewable resources. Some interesting links and papers with detail models and advices for modelling of these types of grids have been presented. Also, at the end, a case study of for adapting classical test grid (IEEE 13-bus) to real conditions by adding different types of DGs was shown. A capability for the LVRT operation is demonstrated.

7 Acknowledgement

8 References

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