An Enhanced IEEE 33 Bus Benchmark Test System for Distribution System Studies

Sarineh Hacopian Dolatabadi, Maedeh Ghorbanian, Pierluigi Siano, *Senior Member, IEEE*, and Nikos D. Hatziargyriou, *Life Fellow, IEEE*

***Abstract*—The transformation of passive distribution systems to more active ones thanks to the increased penetration of distributed energy resources, such as dispersed generators, flexible demand, distributed storage, and electric vehicles, creates the necessity of an enhanced test system for distribution systems planning and operation studies. The value of the proposed test system, is that it provides an appropriate and comprehensive benchmark for future researches concerning distribution systems. The proposed test system is developed by modifying and updating the well-known 33 bus distribution system from Baran & Wu. It comprises both forms of balanced and unbalanced three-phase power systems, including new details on the integration of distributed and renewable generation units, reactive power compensation assets, reconfiguration infrastructures and appropriate datasets of load and renewable generation profiles for different case studies.**

***Index Terms*—Balanced three-phase system, benchmarking, distribution system, IEEE 33 bus distribution test system, operation, planning, unbalanced three-phase system.**

I. Introduction

FOR several decades, the IEEE has provided various test systems to support research in power systems. In this context, the authors of this paper propose a multi-purpose test benchmark for distribution systems studies based on the well-known 33 bus distribution system. This system was developed in 1989 by Baran & Wu [1] to study the impact of reconfiguration in distribution systems on power losses reduction and load balancing. In the next years, the 33 bus distribution test system has gained popularity and has been widely used to study different problems in traditional distribution systems. Recent developments in smart power systems, associated with the integration of new technologies, such as distributed and renewable energy resources (RERs), demand side management (DSM) mechanisms and novel operational methods dictate the necessity of an extended test benchmark to address new challenges in research.

This paper presents an attempt to provide an enhanced benchmark for distribution systems suitable for studies addressing research needs in modern power distribution grids. The main features of the proposed benchmark is the introduction of distributed RERs and demand response (DR) mechanisms, together with appropriate reactive power compensation units. Finally, both balanced and unbalanced three-phase versions are provided, since the integration of single-phase production and storage units has increased the asymmetry among the network phases. Notably, [2] presents the motivation and preliminary planning studies for the provision of the IEEE 33 bus test system presented in this paper. The studies presented in [2] are based on the modification of Baran & Wu 33 bus distribution system using voltage sensitivity analyses to facilitate the integration of DR mechanisms, distributed generation (DG) units and reactive power compensators (RPCs).

The proposed test system tries to correct some of the shortcomings of Baran & Wu 33 bus distribution system and at the same time improves the test benchmark bringing it to near real operation limitations. By proposing two different configurations, the study of both radial and meshed distribution systems is made possible. Moreover, supplementary data to improve implementation of case studies have been added to the proposed test system. It is of course not possible to propose a test system that specifies all the parameters needed for every application. The goal is to develop a test system which can represent a typical distribution system close to real networks, considering operational and performance aspects, that can be used as a reference for testing the impact of different technologies. Notably, new features can be supplemented by the users in order to adapt the proposed test benchmark for particular applications. Results of a suite of analyses conducted on the proposed test benchmark are presented. The details of conducted study are shared via publicly available repository to enable and encourage online collaboration and continued evolution of the test benchmark by other users [3].

The remainder of this paper is organized as follows. In Section II, a brief history of the existing 33 bus distribution system and some of the features which are improved and enhanced in the modified IEEE 33 bus distribution test system are discussed. Section III, presents the details of the proposed test benchmark. Further details of the basic analyses conducted on the proposed

Manuscript received May 26, 2020; revised September 30, 2020; accepted November 9, 2020. Date of publication November 16, 2020; date of current version April 19, 2021. Paper no. TPWRS-00874-2020. *(Corresponding author: Sarineh Hacopian Dolatabadi.)*

Sarineh Hacopian Dolatabadi and Maedeh Ghorbanian are with the Department of Electrical and Computer Engineering, Isfahan University of Technology, Isfahan 84156-83111, Iran (e-mail: s.hacopian@ec.iut.ac.ir; m.ghorbanian@alumni.iut.ac.ir).

Pierluigi Siano is with the Department of Management and Innovation Systems, University of Salerno, Fisciano 84084, (Salerno), Italy (e-mail: psiano@unisa.it).

Nikos D. Hatziargyriou is with the School of Electrical and Computer Engineering, National Technical University of Athens, Athens 157 80, Greece (e-mail: nh@power.ece.ntua.gr).

Color versions of one or more of the figures in this article are available online at https://doi.org/10.1109/TPWRS.2020.3038030.

Digital Object Identifier 10.1109/TPWRS.2020.3038030

test system as a reference for future studies are presented in Section IV. Finally, Section V concludes this paper.

II. History of the Existing 33 Bus Distribution Test Systems

The original version of the 33 bus distribution system proposed by Baran & Wu [1] in 1989, consists of 33 buses, 32 fixed and 5 switchable lines, and no reactive power compensating units. The grid is supplied by a feeder connected to the first bus, and no other power generation units exist in the grid. The voltage limits of buses are 0.9 to 1.1 ($p.u.$). In the proposed test system, limits are changed to 0.95 to 1.05 ($p.u.$), which is an acceptable range for practical distribution systems. In order to relax these limits, addition of RPCs are necessary. Moreover, the possibility of voltage control at the feeder substation, using on-load tap-changing (OLTC) transformer and phase shifter at the branch number 1 is considered. These options facilitate voltage control in order to guarantee acceptable buses voltage limits and power losses [4]. The operation range of the OLTC and the phase shifter is 0.95 to 1.05 ($p.u.$) and, -5 to 5 ($degrees$), respectively.

Moreover, in the proposed test system the number of switchable branches are reduced to three branches, in order to avoid unnecessary complexities and without losing the possibility of meshed grid operation. It is noticeable that this modification does not affect or restrict the reconfiguration possibility in the proposed test system. As the reconfiguration is an important function of modern smart grids, this modification simplifies the reconfiguration procedure by elimination of unnecessary complexities. To address the growing trend of distributed RERs integration, the proposed test system is enhanced with DG units. Additionally, an hourly and an subhourly load profile compatible with the proposed test system are provided. In the next section, detailed description of the proposed test system and its components discussing also the theoretical rationale used in the evolution of the proposed test benchmark are presented.

III. Proposed IEEE 33 Bus Distribution Test System

This research is aimed at providing a small scale and comprehensive benchmark for smart distribution systems analytic studies. According to the existing literature, there are several distribution test systems [5]–[14]. The current test benchmarks can be divided into two categories: small scale and large scale test cases. The most famous small scale test systems are IEEE 4, 13, 34 and 37-bus test grids [5], [7], [8], [14]. The well known large scale test benchmarks are IEEE 123-bus Test Grid, IEEE 342-Node Low Voltage Networked Test System (LVNTS), IEEE 8500 Node Test Feeder, IEEE Comprehensive Test Feeder (CFT) and IEEE European Low Voltage Test Feeders [6], [7], Electric Power Research Institute (EPRI) Test Grids including six test grids: K1, M1, J1, Ckt5, Ckt7 and Ckt24 [9], PNNL Taxonomy Feeders [10], and PG&E Prototypical Feeders comprising a set of 12 test feeders from approximately 100 nodes to 2000 nodes [11].

To the authors' knowledge, none of these has all features considered in the test benchmark presented in this paper. More specifically, the following features are considered important for future research.

1) Reconfigurable radial and meshed distribution systems with switchable lines.
2) Balanced and unbalanced three-phase distribution systems.
3) Different types of three, two and single-phase loads with Y and Δ connections.
4) Three and four-wire distribution systems.
5) Distribution systems equipped with RPCs, OLTC transformer and phase shifter.
6) Distribution systems with interconnected DG units, including RERs and energy storage systems (ESSs).

It is noticeable that each of the aforementioned existing benchmarks has some of the features provided by the proposed test benchmark but none of them has all the features fully. Moreover, the main goal of this test benchmark is the provision of a small scale and at the same time comprehensive test benchmark including nearly all features of real smart distribution systems even quite unusual configurations to facilitate a wide range of future researches and analyses. To provide a test benchmark for unbalanced distribution systems studies, the proposed test benchmark is provided in both balanced and unbalanced versions. The details of both models are presented in this paper.

A. System Topology

The topology of the proposed IEEE 33 bus distribution test system is shown in Fig. 1. The test system is a 12.66 (kV) system with one feeder substation, 4 DG units, 2 reactive power compensation systems, 33 buses, and 3 looping branches (switchable tie lines). It is noticeable that the test benchmark is prepared in two versions to simulate both balanced and unbalanced three-phase systems.

Bus Data: Except of the bus types and maximum and minimum voltage limitations, the bus data has not changed from the Baran & Wu 33 bus distribution system data. Table I lists the bus data for the proposed test benchmark. Buses 18, 22, 25, and 33 which contain DG units can be considered as PV buses, when they are voltage controlled, and the acceptable bus voltages during system operation should be limited in the range 0.95 to 1.05 ($p.u.$). Total active and reactive demand is equal to 3.715 (MW) and 2.3 ($MVAR$), respectively.

Generating Units Data: Table II presents the generating units data, including their production cost functions. These cost functions are derived based on the approaches used in [2], [15], [16]. It is noticeable that, due to the relatively low amount of DG power generation outputs compared to larger units (greater than 100 MW) in transmission systems, the quadratic terms of the cost functions are negligible and the typical quadratic function is approximately linear. It is noteworthy that the sizing of the DG units in the main test benchmark is determined so that the DGs penetration limits adopted in practice are respected, e.g. the total capacity of DG units is limited to less than 30% according to Ontario's standard [17]. The proposed DG units are considered dispatchable biomass-fueled units, while it is possible to replace them with RERs, such as wind and PV units. Considering the

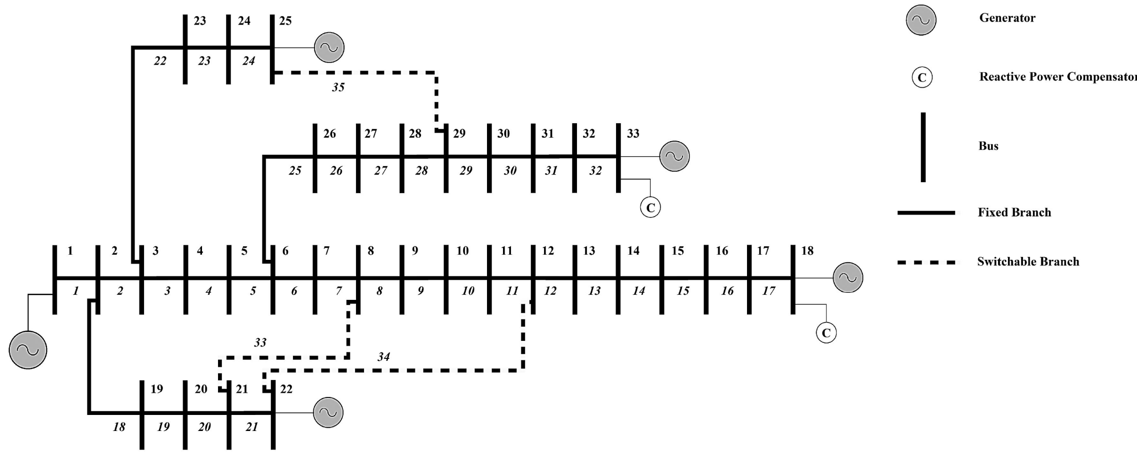

Fig. 1. The enhanced IEEE 33 bus distribution test system.

TABLE I
BUS DATA OF THE ENHANCED IEEE 33 BUS DISTRIBUTION TEST SYSTEM

Both Test Systems						Unbalanced Three-Phase Test System		
Bus Number	Type	Active Demand (MW)	Reactive Demand $(MVAR)$	Minimum Voltage $(p.u.)$	Maximum Voltage $(p.u.)$	Number of Phases	Connection Type	Number of Wires
1	Reference	0	0	1	1	3 (ABC)	Y	3
2	PQ	0.1	0.06	1.05	0.95	2 (AB)	Y	3
3	PQ	0.09	0.04	1.05	0.95	1 (A)	Y	3
4	PQ	0.12	0.08	1.05	0.95	2 (BC)	Y	3
5	PQ	0.06	0.03	1.05	0.95	1 (B)	Y	3
6	PQ	0.06	0.02	1.05	0.95	1 (C)	Y	3
7	PQ	0.2	0.1	1.05	0.95	3 (ABC)	Δ	3
8	PQ	0.2	0.1	1.05	0.95	3 (ABC)	Y	3
9	PQ	0.06	0.02	1.05	0.95	1 (A)	Y	3
10	PQ	0.06	0.02	1.05	0.95	1 (B)	Y	3
11	PQ	0.045	0.03	1.05	0.95	1 (C)	Y	3
12	PQ	0.06	0.035	1.05	0.95	1 (A)	Y	4
13	PQ	0.06	0.035	1.05	0.95	1 (B)	Y	4
14	PQ	0.12	0.08	1.05	0.95	2 (AC)	Y	4
15	PQ	0.06	0.01	1.05	0.95	1 (C)	Y	4
16	PQ	0.06	0.02	1.05	0.95	1 (A)	Y	4
17	PQ	0.06	0.02	1.05	0.95	1 (B)	Y	4
18	PQ/PV	0.09	0.04	1.05	0.95	1 (C)	Y	4
19	PQ	0.09	0.04	1.05	0.95	1 (A)	Y	3
20	PQ	0.09	0.04	1.05	0.95	1 (B)	Y	3
21	PQ	0.09	0.04	1.05	0.95	1 (C)	Y	3
22	PQ/PV	0.09	0.04	1.05	0.95	1 (A)	Y	3
23	PQ	0.09	0.05	1.05	0.95	1 (B)	Y	3
24	PQ	0.42	0.2	1.05	0.95	3 (ABC)	Y	3
25	PQ/PV	0.42	0.2	1.05	0.95	3 (ABC)	Δ	3
26	PQ	0.06	0.025	1.05	0.95	1 (C)	Y	3
27	PQ	0.06	0.025	1.05	0.95	1 (A)	Y	3
28	PQ	0.06	0.02	1.05	0.95	1 (B)	Y	3
29	PQ	0.12	0.07	1.05	0.95	2 (AB)	Y	4
30	PQ	0.2	0.6	1.05	0.95	1 (C)	Y	4
31	PQ	0.15	0.07	1.05	0.95	2 (BC)	Y	4
32	PQ	0.21	0.1	1.05	0.95	3 (ABC)	Y	4
33	PQ/PV	0.06	0.04	1.05	0.95	1 (A)	Y	4

TABLE II
GENERATORS DATA OF THE ENHANCED IEEE 33 BUS DISTRIBUTION TEST SYSTEM

Bus Number	Active Capacity (MW)	Reactive Capacity $(MVAR)$	Type	Cost Function $(\$/h)$
1	4	2.5	Feeder (Conventional Generation)	$0.003P^2 + 12P + 240$
18	0.2	0	DG	$0.0026P^2 + 10.26P + 210$
22	0.2	0	DG	$0.0026P^2 + 10.26P + 210$
25	0.2	0	DG	$0.0026P^2 + 10.26P + 210$
33	0.2	0	DG	$0.0026P^2 + 10.26P + 210$

TABLE III
REACTIVE POWER COMPENSATORS DATA OF THE ENHANCED IEEE 33 BUS DISTRIBUTION TEST SYSTEM (ONLY FOR RADIAL DISTRIBUTION SYSTEM)

Bus Number	Type	Reactive Capacity ($MVAR$)
18	Capacitive	0.4
33	Capacitive	0.6

geographical distribution of DGs, several wind and solar profiles can be used in studies related to RERs integration. Due to the importance of RERs integration in the modern distribution systems, a relatively comprehensive dataset for wind and solar power generation is presented in [3]. Moreover, the proposed DG units can be replaced or equipped with local ESSs to be able to study the effects of the growing trend of ESS integration in power systems planning and operation [18]. The ESS can be considered as generator or load with determined stored energy amount. The maximum and minimum power injections determine the charging and discharging power limits and the limitations on stored energy specifying the energy capacity. ESS units have losses during charging and discharging procedures, depending on their technologies [19], [20]. In the proposed test system two 100 (kW) and two 200 (kWh) ESSs located in buses 18, 22, 25, and 33, are considered.

Reactive Power Compensators Data: In order to address the required voltage restrictions in all cases, it is necessary to use reactive power compensation. In the case of radial distribution system compensators at buses 18 and 33 are considered. The details of RPCs are presented in Table III. It is noticed that for meshed distribution system structures, reactive compensation is not required. The approach used for siting and sizing of RPCs and DG units is based on the voltage and loss sensitivity analyses presented in [2], [21]. The voltage sensitivity method aims at voltage stability improvement according to the amount of locational power injection, while the loss sensitivity method determines the impact of power injection at each bus on grid losses [2], [21].

The location of the candidate buses for DGs and RPCs installation based on the voltage stability sensitivity to the amount of locational power injection can be expressed in the form of: [2].

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix}J_{P\theta} & J_{PV}\\ J_{Q\theta} & J_{QV}\end{bmatrix}\begin{bmatrix}\Delta\theta\\ \Delta V\end{bmatrix} \tag{1}$$

$$S_Q^V = \text{diag}\left[\frac{\Delta V}{\Delta Q}\right] = \text{diag}[(J_{QV} - J_{Q\theta}J_{P\theta}^{-1}J_{PV})^{-1}] \tag{2}$$

$$S_P^V = \text{diag}\left[\frac{\Delta V}{\Delta P}\right] = \text{diag}[(J_{PV} - J_{P\theta}J_{Q\theta}^{-1}J_{QV})^{-1}] \tag{3}$$

Where, $J_{P\theta}$, J_{PV}, $J_{Q\theta}$ and J_{QV} are the submatrices of Jacobian matrix. ΔV and $\Delta\theta$ represent the changes of bus voltage magnitudes and angles, respectively. ΔP and ΔQ are the active and reactive power changes at each bus, respectively. The higher values of diagonal elements of S_Q^V and S_P^V, matrices indicate the most sensitive buses to reactive and active power changes and thus are the candidate buses for DG units and RPCs installation. In order to consider grid losses, their sensitivity to the injected active and reactive power at each bus can be calculated in a similar way and the buses with highest sensitivities are considered as suitable candidates for the installation of DGs and RPCs. Notably, due to the resistive nature of the test benchmark, it is necessary to consider the effects of both injected, active and reactive, power to determine the appropriate locations for the installation of DG units and reactive power compensation assets.

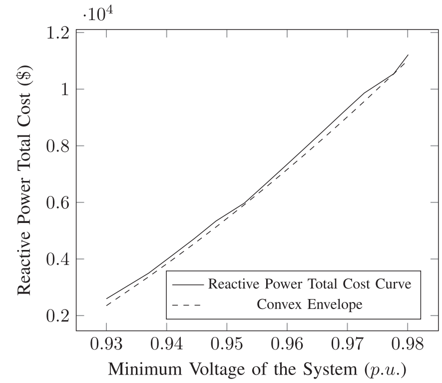

Fig. 2. Convexified reactive power total cost curve.

Finally, a novel method for evaluating the costs of providing reactive power support for the grid, in order to support the nodal voltage is presented. This simplified approach can help system operator in decision making with the integration of RPCs to achieve the desired operational conditions. The total cost of RPCs (TC^{RPC} (\$)) is defined as:

$$TC^{RPC} = \sum_r A_r^{RPC} q_r^{RPC} + B_r^{RPC} \tag{4}$$

Where, A_r^{RPC} and B_r^{RPC} are the variable and fixed costs of r-th reactive power compensator. A_r^{RPC} and B_r^{RPC} are considered equal to 1000 (\$) and 3000 (\$$/MVAR$), respectively, and q_r^{RPC} is the size of each RPC ($MVAR$) [22]. Alternatively, the total cost of reactive power compensation can be expressed in the form of the total cost of reactive power required for bringing the system minimum voltage in a certain level. Fig. 2 presents the relation of the total cost of reactive power and the system minimum voltage. These methods for power systems economic analysis are presented in several references, such as [23]–[26], showing that this cost function can be used appropriately for economic studies.

In the following, a suitable pricing method for reactive power compensation is proposed. This is the convex hull pricing model, which is a well-behaved convex approximation of the total cost function. The convex hull of a function (in some cases non-convex function) is the largest and closest convex function approximating the function from below that does not exceed the given function at any point in the domain (i. e. convex envelope). The convex hull $f_{CH}(x)$ of $f(x)$ is the greatest convex function that satisfies $\forall x,\ f_{CH}(x) \leq f(x)$ [23]–[25].

In other words, the convex hull pricing tries to convexify non-convex functions [23], [25], [26]. The convexification can be realized by replacing the actual total cost function with its convex envelope. Fig. 2 illustrates this approach. It is noticeable that, as

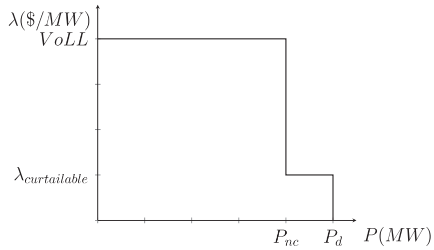

Fig. 3. Bid function or marginal benefit of dispatchable loads.

shown in Fig. 2, the convex envelope can be expressed as:

$$TC_{CH}^{RPC} = 643600V_{\min}^2 - 1056007V_{\min} + 427786 \quad (5)$$

Where, $V_{\min}$ is the system minimum voltage in $(p.u.)$. Notably, this representation of reactive power total cost can be used by system planners and operators for the enhancement of the distribution system aimed to satisfy certain operational conditions.

It should be noted that the RERs penetration level in the main test benchmark is about 21%, however it is extendable to studies of very high penetration of RERs. Although RERs penetration beyond 30% is studied in few papers [27], there is a growing trend in RERs utilization and a need for high RERs penetration studies arises. Therefore, an evaluation of the feasibility of this test benchmark to be used for studies of very high penetration of distributed renewable generation (e.g. 80%) is provided.

A very high penetration of RERs very highly leads to bidirectional or other uncontrolled power flows, therefore the application of flexible AC transmission systems (FACTS) in the distribution system, known as distributed FACTS (D-FACTS), might be needed [28]–[30]. Due to the proliferation of power electronic-based D-FACTS devices, integration of these devices in active distribution systems can improve electric power quality, and performs voltage regulation, unbalance compensation and power factor improvement, losses reduction and congestion management [28], [31]. In the proposed test benchmark several control (D-FACTS) devices, such as OLTCs, phase shifters, RPCs, including static capacitors, are considered [28], [29]. Their steady state modeling uses the node incidence matrix in order to avoid the difficulties of inverting the admittance matrix [32].

Branches Data: A significant change in the proposed benchmark is the reduction of the number of switchable branches to three in order to avoid unnecessary complexities. Notably, this modification does not affect the possibilities of general reconfigurations. Table IV presents the branches data for the proposed test benchmark. The ratio of the reactance to the resistance (X/R) of the branches is relatively low (i.e. 0.33 to 3.31), as met in practical distribution systems.

Load Data: In modern active distribution grids DSM methods to treat dispatchable and curtailable loads are developed and need to be considered in power system studies. In the proposed benchmark a price-sensitive model for DSM of active demands is considered. In a simplified way, as illustrated in Fig. 3, the demand is non-curtailable (P_{nc}) for prices between $VoLL$ and $\lambda_{\text{curtailable}}$, and curtailable for prices below $\lambda_{\text{curtailable}}$

TABLE IV
BRANCHES DATA OF THE ENHANCED IEEE 33 BUS DISTRIBUTION TEST SYSTEM

Branch Number	From Bus	To Bus	Type	R (Ω)	X (Ω)
1	1	2	Fixed	0.0922	0.047
2	2	3	Fixed	0.493	0.2511
3	3	4	Fixed	0.366	0.1864
4	4	5	Fixed	0.3811	0.1941
5	5	6	Fixed	0.819	0.707
6	6	7	Fixed	0.1872	0.6188
7	7	8	Fixed	0.7114	0.2351
8	8	9	Fixed	1.03	0.74
9	9	10	Fixed	1.044	0.74
10	10	11	Fixed	0.1966	0.065
11	11	12	Fixed	0.3744	0.1238
12	12	13	Fixed	1.468	1.155
13	13	14	Fixed	0.5416	0.7129
14	14	15	Fixed	0.591	0.526
15	15	16	Fixed	0.7463	0.545
16	16	17	Fixed	1.289	1.721
17	17	18	Fixed	0.732	0.574
18	2	19	Fixed	0.164	0.1565
19	19	20	Fixed	1.5042	1.3554
20	20	21	Fixed	0.4095	0.4784
21	21	22	Fixed	0.7089	0.9373
22	3	23	Fixed	0.4512	0.3083
23	23	24	Fixed	0.898	0.7091
24	24	25	Fixed	0.896	0.7011
25	6	26	Fixed	0.203	0.1034
26	26	27	Fixed	0.2842	0.1447
27	27	28	Fixed	1.059	0.9337
28	28	29	Fixed	0.8042	0.7006
29	29	30	Fixed	0.5075	0.2585
30	30	31	Fixed	0.9744	0.963
31	31	32	Fixed	0.3105	0.3619
32	32	33	Fixed	0.341	0.5302
33	21	8	Switchable	2	2
34	12	22	Switchable	2	2
35	25	29	Switchable	0.5	0.5

TABLE V
HOURLY LOAD PROFILE OF THE ENHANCED IEEE 33 BUS DISTRIBUTION TEST SYSTEM

Time ($hour$)	Active Demand (MW)
12 - 1 AM	2.909
1 - 2 AM	2.741
2 - 3 AM	2.686
3 - 4 AM	2.63
4 - 5 AM	2.596
5 - 6 AM	2.518
6 - 7 AM	2.462
7 - 8 AM	2.63
8 - 9 AM	2.976
9 - 10 AM	2.976
10 - 11 AM	3.133
11 AM - Noon	3.245
Noon - 1 PM	3.301
1 - 2 PM	3.402
2 - 3 PM	3.301
3 - 4 PM	3.301
4 - 5 PM	3.267
5 - 6 PM	3.133
6 - 7 PM	3.211
7 - 8 PM	3.625
8 - 9 PM	3.715
9 - 10 PM	3.625
10 - 11 PM	3.581
11 - 12 PM	3.301

TABLE VI
THE POWER FLOW RESULTS

Configuration	$V_{min}(p.u.)$	$P_{gen}(MW)$	$Q_{gen}(MVAR)$	$P_{loss}(MW)$	$Q_{loss}(MVAR)$	Loadability Factor
Radial	0.95 (bus 30)	3.81	1.45	0.097	0.07	3.43
Meshed	0.96 (bus 32)	3.8	2.36	0.087	0.06	5.69

[19], [20], [33]. This model is able to split the load into an interruptible and non-interruptible block to be used for social welfare maximization. A possible split between the amount of non-curtailable and curtailable load is 80% and 20% of total load (P_d), respectively. This percentage can be of course changed based on the assumptions of different studies. It is also possible to consider voltage dependent loads specially located at buses equipped with voltage control systems (i.e. buses number 1, 18, and 33).

Table V gives an hourly load profile compatible with the proposed test benchmark without considering DR programs such as load shifting and load reduction mechanisms. It is noticeable that a dataset for load and RERs (i.e. wind and solar generation) with the time granularity of 15 minutes to simulate the effects of renewable intermittency are provided in [3]. The provided datasets come from [34].

B. Two Different Configurations of the Test Benchmark

The proposed benchmark can be used to study radial distribution systems or meshed ones. In the following, the radial and meshed configurations of the proposed benchmark are discussed.

Radial Distribution System Configuration: In the radial configuration branches 33, 34 and 35 are switched out (no loops). Buses 18 and 33 are equipped with reactive power compensation assets of 0.4 and 0.6 ($MVAR$) capacities, respectively.

Meshed Distribution System Configuration: In the meshed configuration branches 33, 34 and 35 are switched in, while reactive power compensation is not required. It is of course possible to study other configurations by switching in or out the branches of the proposed benchmark. It is noteworthy that the proposed test benchmark is well-compensated and presents an acceptable amount of power losses to model a near-real modern distribution system. Moreover, due to its power procurement capacity and operational limitations, it is able to integrate electric vehicles which is a growing trend in modern power systems [35]–[38]. The consideration of electric vehicles as energy storage devices which can improve the performance of the modern smart grids and at the same time bring several challenges to them is an active area of research nowadays.

C. Unbalanced Test Benchmark

Unequal connection of single and two-phase loads, load increase in one phase and unequal impedances of branches can cause unbalance in three-phase distribution systems having an impact on power quality, voltage profiles and power losses [39]. To overcome this challenge, phase balancing is commonly applied for the correction of unbalance. This can be realized by appropriate reconnection of single and two-phase loads. Rephasing is an effective approach to realize phase balancing in distribution systems, although like any other corrective procedure, it has its implementation difficulties and challenges [39], [40]. In this paper, a well-designed unbalanced three-phase distribution system with low unbalance is proposed. Several single and two-phase loads with various connection patterns have been considered, however by using phase balancing, the arrangement of the loads is determined in a relatively uniform distributed way to reduce the necessity of rephasing methods. The consequences of the adopted approach are discussed in the following Section.

TABLE VII
THE POWER FLOW RESULTS FOR VERY HIGH PENETRATION OF RENEWABLE GENERATION

Configuration	V_{min} $(p.u.)$	P_{gen} (MW)	Q_{gen} $(MVAR)$	P_{loss} (MW)	Q_{loss} $(MVAR)$
Radial	0.98 (bus 9)	3.76	1.34	0.043	0.04
Meshed	0.99 (bus 7)	3.76	2.34	0.045	0.04

IV. DISCUSSIONS AND FURTHER DETAILS

A key characteristic of the proposed benchmark is its capability to be used as a realistic radial or meshed distribution system. This can be used for different distribution system operation and planning studies that include the reconfiguration of the system. Additionally, the dataset of the proposed benchmark is compatible with power system analysis platforms, such as MATPOWER, MATLAB/Simulink, GAMS and DIgSILENT [19], [20], [41]–[44]. Note that the details of the proposed test benchmark are publicly available online in: https://github.com/PowerSystemsTestBenchmarks/IEEE33Bus [3]. In this section results from some basic power systems analyses are presented for the both the radial and the meshed configurations of the proposed benchmark. It is noticeable that the power flow and optimal power flow analyses are presented for 8-9 PM peak load hour, using MATPOWER [19], [20].

A. Power Flow Analyses

The results of power flow analysis for both the radial and the meshed configurations of balanced test benchmark are presented in Table VI. As seen, the results conform completely with the operational limitations of minimum voltage level and total grid losses (2.34 and 2.61% of total load in radial and meshed configurations, respectively). Moreover, the proposed benchmark presents a considerable loadability factor calculated based on the voltage stability limitations, as proposed in [2]. It is also possible to be used for simulating DSM applications, RERs and ESSs integration studies and power electronic-based custom power devices implementation. Notably, in the meshed configuration switchable lines 33, 34, 35 are considered active. The voltage profile of the test system at all buses for the power flow and optimal power flow are presented in Fig. 4. Table VII represents the results of power flow for the case with very high penetration of

TABLE VIII
THE OPTIMAL POWER FLOW RESULTS

Configuration	Objective function (total generation cost minimization) ($\$/h$)	Minimum marginal cost of nodes ($\$/MWh$)	Maximum marginal cost of nodes ($\$/MWh$)
Radial	1124.38	12.02 (bus 1)	13.17 (bus 16)
Meshed	1124.26	12.02 (bus 1)	12.62 (bus 32)

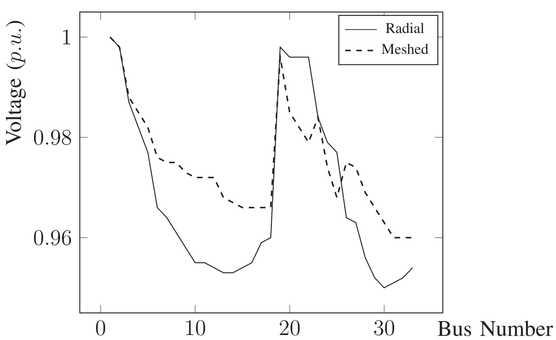

Fig. 4. Voltage profile of balanced test system in radial and meshed configurations.

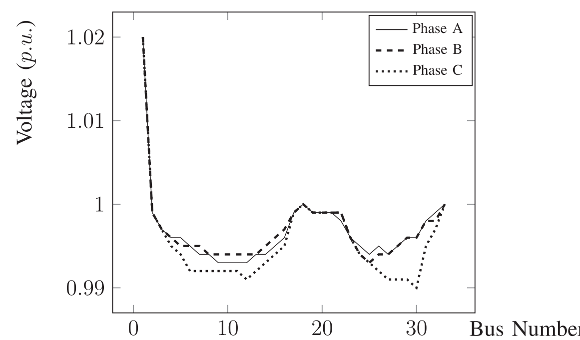

Fig. 5. Voltage profile of unbalanced three-phase test system in radial configuration.

RERs. The results demonstrate the applicability and adaptability of the proposed test benchmark for these studies. According to the results, the proposed distribution system, equipped with D-FACTS, is able to efficiently manage a high level of renewable generation causing bidirectional power flows and ensure low grid losses and a satisfactory voltage profile. It should be noted that bidirectional power flows can cause problems in the protection of radial networks, designed for unidirectional power flows [45]. In order to address these problems, the provision of a reconfigurable meshed grid equipped with switchable lines, as proposed in this test benchmark is important for relevant studies [45], [46]. Moreover, the study of OLTCs and phase shifters in order to facilitate power flow control can provide significant results [47].

B. Optimal Power Flow Analyses

The results presented in Table VIII, illustrate the economic results of the optimal power flow analysis of the proposed balanced test system. As seen, the proposed test system is able to perform economic power procurement in different ways aiming at minimizing total generation costs by the integration of DG units. This characteristic provides the potential for economic and market-based studies.

C. Unbalanced System Analyses

As a numerical case study, power flow analysis for the proposed unbalanced three-phase test benchmark as a three-wire distribution system comprising Y connected loads and equipped with OLTC is presented. The voltage profile of all buses of the test system is presented in Fig. 5. According to Fig. 5, it is obvious that the adopted procedure for designing the unbalanced test benchmark along with the consideration of OLTC for voltage control and regulation, similar to RPCs [4], provides a well-designed unbalanced three-phase distribution system with a relatively flat voltage profile, as shown in Figure 5. Moreover, the results demonstrate that the proposed unbalanced system has relatively low active and reactive power losses (0.055 (MW) and 0.04 ($MVAR$), respectively). In other words, relatively low power losses along with flat voltage profile verify the efficiency of the proposed unbalanced test benchmark.

In this paper, the case studies and numerical analyses are mainly directed on fundamental studies, such as power flow analysis. The studies are conducted on both balanced and unbalanced versions of the proposed benchmark. The proposed benchmark however can be used in future research for various aspects of distribution systems. Some of the most significant further research directions are:

1) The consideration of uncertainties. The proposed benchmark could be used for studies of distribution systems with a high amount of uncertainties in power demand and RERs.
2) The consideration of unbalanced distribution test systems. This is already provided in the proposed unbalanced version of the test benchmark introduced in this paper. Unbalance in nowadays distribution systems is increasing due to the higher penetration of interconnected single-phase DGs.

V. CONCLUSION

The established 33 bus benchmark distribution system has been extended by several enhancements, such as distributed generation units, reactive power compensation devices, switchable branches and the capability of integrating energy storage systems in both balanced and unbalanced configurations. It also provides load profiles at hourly and subhourly resolutions. Numerous system configurations have been considered for the development of this test benchmark system, in order to make it suitable for planning and operational studies. According to the considered data, the proposed model presents excessive generation capacity that facilitates economic studies taking into account participation in electricity markets. The consideration of reactive power compensation and branch switching provides further opportunities for balanced and unbalanced distribution system studies. The results of simulations verify the feasibility and adaptability of the proposed test benchmark under different operational conditions.

The authors have tried their best to create an appropriate dataset for modern distribution system studies, however they recognize that this is only the first step and further research is needed. The proposed test benchmark is available online, for further updates [3]. In addition to the data presented in this paper, the online repository includes formatted datasets for several common analysis software packages, including MATPOWER, MATLAB/Simulink, GAMS and DIgSILENT [19], [20], [41]–[44].

References

[1] M. E. Baran and F. F. Wu, "Network reconfiguration in distribution systems for loss reduction and load balancing," *IEEE Trans. Power Del.*, vol. 4, no. 2, pp. 1401–1407, Apr. 1989.

[2] M. Ghorbanian, S. H. Dolatabadi, and P. Siano, "Game theory-based energy-management method considering autonomous demand response and distributed generation interactions in smart distribution systems," in *Proc. IEEE Syst. J.*, vol. 15, no. 1, pp. 905–914, Mar. 2021.

[3] "Power systems test benchmarks," doi: 10.5281/zenodo.4030695. Accessed: Dec. 2019. [Online]. Available: https://github.com/PowerSystemsTestBenchmarks/IEEE33Bus

[4] T. Tewari, A. Mohapatra, and S. Anand, "Coordinated control of oltc and energy storage for voltage regulation in distribution network with high PV penetration," *IEEE Trans. Sustain. Energy*, vol. 12, no. 1, pp. 262–272, Jan. 2021.

[5] W. H. Kersting, "Radial distribution test feeders," *IEEE Trans. Power Syst.*, vol. 6, no. 3, pp. 975–985, Aug. 1991.

[6] R. F. Arritt and R. C. Dugan, "The IEEE 8500-node test feeder," in *IEEE PES T&D*, New Orleans, LA, USA, 2010, pp. 1–6, doi: 10.1109/TDC.2010.5484381.

[7] "Institute of electrical and electronics engineers (IEEE)," [Online]. Available: https://www.ieee.org/

[8] "IEEE PES AMPS DSAS test feeder working group," [Online]. Available: https://site.ieee.org/pes-testfeeders/

[9] "Electric power research institute (EPRI)," [Online]. Available: https://www.epri.com/

[10] "Pacific northwest national laboratory (PNNL)," [Online]. Available: https://www.pnnl.gov/

[11] "Pacific gas and electric company (PG&E)," [Online]. Available: www.pge.com

[12] A. M. Stanisavljevic, V. A. Katic, B. P. Dumnic, and B. P. Popadic, "A brief overview of the distribution test grids with a distributed generation inclusion case study," *SERBIAN J. ELECTR. ENG.*, vol. 15, no. 1, pp. 115–129, Feb. 2018.

[13] F. P. Marcos *et al.*, "A review of power distribution test feeders in the united states and the need for synthetic representative networks," *Energies*, vol. 10, no. 11, pp. 1896–1909, Nov. 2017.

[14] W. H. Kersting, "Radial distribution test feeders," in *Proc. IEEE Power Eng. Soc. Winter Meeting. Conf. Proc. (Cat. No. 01CH37194)*, vol. 2, Jan. 2001, pp. 908–912.

[15] D. Kirschen and G. Strbac, *Fundamentals of Power System Economics*. Hoboken, NJ, USA: Wiley, 2004.

[16] A. J. Wood, B. F. Wollenberg, and G. B. Shebl, *Power Generation, Operation, and Control*. Hoboken, NJ, USA: Wiley., 2014.

[17] "Ontario power authority," [Online]. Available: http://www.powerauthority.on.ca/

[18] M. R. Sheibani, G. R. Yousefi, M. A. Latify, and S. H. Dolatabadi, "Energy storage system expansion planning in power systems: A review," *IET Renew. Power Gener.*, vol. 12, pp. 1203–1221, Aug. 2018.

[19] R. D. Zimmerman, C. E. Murillo-Sanchez, and R. J. Thomas, "MATPOWER: Steady-state operations, planning, and analysis tools for power systems research and education," *IEEE Trans. Power Syst.*, vol. 26, no. 1, pp. 12–19, Feb. 2011.

[20] R. D. Zimmerman and C. E. Murillo-Sanchez, "Matpower [software]," 2018. [Online]. Available: https://matpower.org

[21] V. V. S. N. Murty and A. Kumar, "Reactive power compensation in ubrds based on loss sensitivity appraoch," in *Proc. 6th IEEE Power India Int. Conf.*, Dec. 2014, pp. 1–5.

[22] F. Ugranli, E. Karatepe, and A. H. Nielsen, "MILP approach for bilevel transmission and reactive power planning considering wind curtailment," *IEEE Trans. Power Syst.*, vol. 32, no. 1, pp. 652–661, Jan. 2017.

[23] P. R. Gribik, W. W. Hogan, and S. L. Pope, "Market-clearing electricity prices and energy uplift," 2007. [Online]. Available: http://www.hks.harvard.edu/fs/whogan/Gribik_Hogan_Pope_Price_Uplift_123 107.pdf

[24] R. Rockafellar, *Convex Analysis* (Princeton Landmarks in Mathematics). Princeton, NJ, USA: Princeton Univ. Press, 1997.

[25] D. A. Schiro, T. Zheng, F. Zhao, and E. Litvinov, "Convex hull pricing in electricity markets: Formulation, analysis, and implementation challenges," *IEEE Trans. Power Syst.*, vol. 31, no. 5, pp. 4068–4075, Sep. 2016.

[26] B. Hua and R. Baldick, "A convex primal formulation for convex Hull pricing," *IEEE Trans. Power Syst.*, vol. 32, no. 5, pp. 3814–3823, Sep. 2017.

[27] P. Denholm and M. Hand, "Grid flexibility and storage required to achieve very high penetration of variable renewable electricity," *Energy Policy*, vol. 39, no. 3, pp. 1817–1830, 2011.

[28] W. N. Chang, C. M. Chang, and S. K. Yen, "Improvements in bidirectional power-flow balancing and electric power quality of a microgrid with unbalanced distributed generators and loads by using shunt compensators," *Energies*, vol. 11, no. 12, 2018, Art. no. 3305.

[29] J. Dai *et al.*, "Optimal configuration of distributed power flow controller to enhance system loadability via mixed integer linear programming," *J. Modern Power Syst. Clean Energy*, vol. 7, no. 6, pp. 1484–1494, Nov. 2019.

[30] D. M. Divan *et al.*, "A distributed static series compensator system for realizing active power flow control on existing power lines," *IEEE Trans. Power Del.*, vol. 22, no. 1, pp. 642–649, 2007.

[31] K. M. Rogers and T. J. Overbye, "Some applications of distributed flexible AC transmission system (D-FACTS) devices in power systems," in *Proc. 40th North Amer. Power Symp.*, Calgary, AB, 2008, pp. 1–8.

[32] P. Arboleya, C. Gonzalez-Moran, and M. Coto, "Modeling FACTS for power flow purposes: A common framework," *Int. J. Elect. Power Energy Syst.*, vol. 63, pp. 293–301, Dec. 2014.

[33] P. Siano and D. Sarno, "Assessing the benefits of residential demand response in a real time distribution energy market," *Applied Energy*, vol. 161, pp. 533–551, Jan. 2016.

[34] "Data platform time series," [Online]. Available: https://data.open-power-system-data.org/time_series/

[35] E. L. Karfopoulos, K. A. Panourgias, and N. D. Hatziargyriou, "Distributed coordination of electric vehicles providing V2G regulation services," *IEEE Trans. Power Syst.*, vol. 31, no. 4, pp. 2834–2846, Jul. 2016.

[36] E. L. Karfopoulos and N. D. Hatziargyriou, "Distributed coordination of electric vehicles providing V2G services," *IEEE Trans. Power Syst.*, vol. 31, no. 1, pp. 329–338, Jan. 2016.

[37] N. Hatziargyriou, "Guest editorial special section on microgrids for sustainable energy systems," *IEEE Trans. Sustain. Energy*, vol. 5, no. 4, pp. 1309–1309, Oct. 2014.

[38] E. L. Karfopoulos and N. D. Hatziargyriou, "A multi-agent system for controlled charging of a large population of electric vehicles," *IEEE Trans. Power Syst.*, vol. 28, no. 2, pp. 1196–1204, May. 2013.

[39] M. Dilek, R. P. Broadwater, J. C. Thompson, and R. Seqiun, "Simultaneous phase balancing at substations and switches with time-varying load patterns," *IEEE Trans. Power Syst.*, vol. 16, no. 4, pp. 922–928, Nov. 2001.

[40] C. Lin, C. Chen, H. Chuang, M. Huang, and C. Huang, "An expert system for three-phase balancing of distribution feeders," *IEEE Trans. Power Syst.*, vol. 23, no. 3, pp. 1488–1496, Aug. 2008.

[41] MathWorks, "Matlab/simulink 9.3," 2019. [Online]. Available: https://www.mathworks.com

[42] J. Y. Wong, "IEEE 33 Bus System," 2020, MATLAB Central File Exchange. Accessed: Sep. 15, 2020. [Online]. Available: https://www.mathworks.com/matlabcentral/fileexchange/73127-ieee-33-bus-system.

[43] G. D. Corporation, "General algebraic modeling system (GAMS) release 27.1.0," Fairfax, VA, USA, 2019. [Online]. Available: https://www.gams.com/

[44] "Digsilent powerfactory," 2019. [Online]. Available: https://www.digsilent.de/

[45] J. Kim, S. Cho, and H. Shin, "Advanced power distribution system configuration for smart grid," *IEEE Trans. Smart Grid*, vol. 4, no. 1, pp. 353–358, Mar. 2013.

[46] R. Rajaram, K. Sathish Kumar, and N. Rajasekar, "Power system reconfiguration in a radial distribution network for reducing losses and to improve voltage profile using modified plant growth simulation algorithm with distributed generation," *Energy Rep.*, vol. 1, pp. 116–122, Nov. 2015.

[47] V. Levi, M. Kay, and I. Povey, "Reverse power flow capability of tap-changers," in *Proc. CIRED 2005-18th Int. Conf. Exhib. Elect. Distrib.*, 2005, pp. 1–5.