Case Study of Enhancing the MATPOWER Polish Electric Grid

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***Abstract*—The MATPOWER Polish systems are several power system test cases that are created using the real power system of Poland circa 2000. However, dynamic model parameters and geographic coordinates were not provided with the initial cases in MATPOWER. To improve the Polish test systems, this paper describes the process of converting the Polish systems included with MATPOWER to the PowerWorld format, assigning geographic coordinates to the 400 kV and 220 kV high voltage networks and adding dynamic models. Additionally, several categories of power system metrics were analyzed for the MATPOWER Polish systems, and the results compared with the corresponding metrics from the United States power systems.**

***Index Terms*—Power System Network Models, Polish System, MATPOWER, Power System Dynamics**

I. Introduction

The Polish Systems consist of eight power system test cases made publicly available as part of the MATPOWER distribution [1]. The cases vary primarily in load levels and generation capacity based both on time of day and seasonal changes. These cases contain the required data for an AC Optimal Power Flow (ACOPF) study, namely bus numbers (without identifying names), network topology, branch parameters, generator cost functions, and necessary constraints: branch MVA, bus voltage, generator real and reactive power limits. The case chosen for updates, case2746wop, is representative of the Polish power system during the winter 2003-04 off-peak load level. Per [2], "Multiple centrally dispatchable generators at a bus have not been aggregated. Generators that are not centrally dispatchable in the Polish energy market are given a cost of zero." Before describing updates to one of the Polish test cases, a brief history is given that describes how these cases were originally created.

A. History of the MATPOWER Polish Systems

In approximately 1999, Dr. Roman Korab was working on his doctoral dissertation which involved performing analyses of locational marginal prices (LMPs) of the real Polish power system. At that time he needed access to an optimal power flow (OPF) solver and MATPOWER was the only one to which he had access. Subsequently, he created the Polish grid cases, which have subsequently shipped with MATPOWER distributions. The cases he created were of the entire transmission network of the Polish power grid at the time he created it. Initially he encountered trouble finding a good initial operating point for the Newton-Rhapson method for the AC power flow. Once convergence was achieved, he then proceeded to solve the OPF. He eventually got the OPF working after relaxing some constraints and finding and fixing all problems with the case; for example a line MVA limit in the given data was set to 10 MVA and should have been set to 100 MVA.

B. Motivations for the Modifications to the Polish Systems

A salient component of engineering is the modeling of real-world systems as sets of mathematical equations. Using those models, engineers can analyze the systems and devise solutions to problems within those systems. Typically, it is not acceptable to experiment on in-service, critical systems; and there are few systems more critical than the world's electric power grids. Hence, power systems engineers are constantly working to construct and validate models of power system networks and their components including transmission lines, electrical loads, generators, governors, and other equipment.

This paper details the modifications made to the mathematical model of the Polish electrical grid created by Dr. Korab for performing optimal power flow analysis of the Polish grid. The case2746wop case was used to perform the work for this paper, and will herein be referred to as "the case" or "the Polish grid case". The cases provided with MATPOWER only included an OPF-level model of the system. Power flow and optimal power flow simulations are valuable tools in the study of power systems; however, they only provide steady state information of the system and lack modeling information for transient or dynamics studies, and geographic coordinates.

In real-world systems the dynamic behavior cannot be ignored; the critical necessity of any power grid mandates its stability to potential disturbances [3]. Contingencies that

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perturb a power system from its steady state occur frequently and must be analyzed to ensure system stability. While line and generator outages are primarily considered, addition and removal of large loads may affect overall system stability. Necessary transient stability studies of a power system require the inclusion of dynamic models in the power system case.

Additionally, substation geographic information is required for analyses such as GIC studies [4], [5], the optimal placement of renewable resources [6], or examining the impact of severe weather or hazards such as wildfires on transmission networks [7]. By geo-locating the high voltage substations, the Polish grid case can be used to test improvements to algorithms such as these.

II. Review of Previous Improvements and Uses of the Polish Grids

Since its inception, the Polish grid has been used in a variety of different projects and studies, strengthening the case for its validity and further demonstrating the importance of the addition of dynamic models and approximate geographic coordinates. In [8], the Polish grid is used to test the design of an efficient wide-area measurement system and the observability of that system. Modifications were made to the grid in [9] where research was performed in devising a unit commitment algorithm; and there are many other references in the literature that cite the use of the other cases of the Polish grid included with MATPOWER.

Though limited, the case has also been subjected to dynamics studies. In 2018, Dr. Cortilla-Sanchez gave a presentation, that summarized the work of adding to the case among other things, GENSAL generator, IEEE Type 1 exciter, Type 2 governor models [10]. Multiple protective relays are modeled in this update to the Polish grid case as well. This research was regarding mitigation of cascading failures in a power grid. This presentation was given to the cascading failure working group at the IEEE PES General Meeting held in Portland, OR during a panel session.

III. Metrics, Comparison and Analysis of the Polish Grid Case

In this section the important characteristic of Polish grid is compared to the US grid. A summary of important characteristics of Polish grid are mentioned in Tables I and II.

Several specific metrics based on important characteristics of the grids are extracted from US Eastern Interconnect (EI), Western Electricity Coordinating Council (WECC), and Electric Reliability Council of Texas (ERCOT) and introduced in [11], [12]. These metrics are originally created to validate synthetic grids. Texas A&M University (TAMU) synthetic grids are created over different footprints in the US with the incentive to create realistic publicly available grid data for research, teaching and training and are available in [13]. The strategy of creation of the TAMU synthetic grids is explained in [14]. Table III shows these metrics as the criteria from US grids and then show the statistics from Polish grid compared to these criteria.

TABLE I
Polish Grid Statistics

Number of buses	2746
Number of substations	1718
Number of areas	4
Number of zones	6
Number of transmission lines	3340
Number of transformers	174
Number of loads	1997
Number of generators	514
Number of LTC	171
Number of shunts	6
Number of phase shifters	1
Total design load (MW)	18962

TABLE II
Type and Number of Generators in Polish Grid

Fuel Type	Number of Units	MW Capacity
Natural Gas	2	215
Coal	144	25275
Hydro	19	1862
Unknown	341	3921
Other types such as biomass	8	471
Total	514	31744

From Table III, it is observed that the following sets of metrics are similar between the US grid and the Polish grid case: ratio of buses per substation, load per generator capacity, percentage of substations containing buses, and the percentage of load substations. The average load per bus is in the range of 6 to 8 MW and is 6.9 MW in the Polish grid. However, most generators' statistics are different in the Polish grid compared to the US grid. For example, based on the US grids, it is expected that more than 70% of the maximum reactive power per maximum real power ratio is in range 0.4 to 0.55 but only around 33% of generators from Polish grid are in this range.

Also, it is observed that US transmission grids usually use 69kV, 115kV, 138kV, 161kV, 230kV, 345kV, 500kV, and 765kV but the Polish grid uses 110kV, 220kV and 400kV voltage levels for the transmission grid. Therefore, the statistics from Polish grid are mostly different compared to the metrics extracted from US grids based on different voltage levels. In Table IV, a comparison of Polish grid statistics based on the

TABLE III
Polish Grid Statistics based on Criteria from US Grid Part 1

Validation Metrics	Criteria from US Grids	Polish Grid
Buses per substation	Mean 1.7-3.5	1.6
Percent of substations containing buses in kV range	<200 kV 85-100% >200 kV 7-25%	93.10% 6.90%
Substations with load	75-90%	90.90%
Load per bus	Mean 6-18 MW	6.9 MW
Generator capacity / load	1.2-1.6	1.3
Substations with generators	5-25%	1.68%
Generator capacities	25-200 MW 40+% 200+ MW 5-20%	36.70% 48.30%
Committed generators	60-80%	69.40%
Generators dispatched >80%	50+%	27%
Generator maxQ/maxP	0.4-0.55 for >70%	33.30%

TABLE IV
POLISH GRID STATISTICS BASED ON CRITERIA FROM US GRID PART 2

	US Criteria/ Voltage levels	400kV (US 500kV)	220kV (US 230kV)	110kV (US 115kV)
	Number of buses	59	157	2528
Transformer per-unit reactance on own base	80% within [0.05 0.2] pu	94.10%	99.20%	50%
Transformer X/R ratio and MVA limits by kV level	X/R 40% below median	90.20%	67.80%	0%
	MVA 40% below median	100%	100%	0%
	X/R 40% above median	9.80%	32.20%	100%
	MVA 40% above median	0%	0%	100%
	X/R 80% in 10-90 range	58.80%	99.20%	100%
	MVA 80% in 10-90 range	100%	100%	50%
Line per-unit per-distance reactance by kV level	70% within 10-90 range	4.40%	29%	20%
Line X/R ratio and MVA limit by kV level	X/R 70% in 10-90 range	77.80%	61.60%	69.60%
	MVA 70% in 10-90 range	0%	80.40%	72.70%
Lines/Substations by kV level	1.1-1.4	1.29	1.45	1.31

US metrics for the closest voltage level is given.

IV. IMPROVEMENTS TO THE POLISH GRID CASES

As discussed earlier in Section I, the Polish systems included with MATPOWER do not include substations with geographic coordinates, or dynamic models for the generators. This section describes how the substations were created, geographic coordinates were assigned, and how the generators were updated to include dynamic model parameters.

A. Adding Geographic Coordinates

The first step towards assigning geographic coordinates to the Polish grid case was to create substations and assign buses to those substations. The algorithm for creating the substations is as follows: the first substation is created, and the lowest numbered bus in the case is assigned to the substation. Next, all buses connected to this bus via transformer(s), or bus tie(s) (non-transformer branches with X+B per unit impedances below a specified threshold, usually 0.005 per unit) are added to this first substation. This process is repeated with the newly added buses, until all buses connected only by transformer(s) or bus tie(s) are added to the first substation. Next, a new substation is created, the lowest numbered bus not assigned to a substation is assigned to this new substation, and the process above is repeated. This algorithm is repeated until all buses in the network are assigned to substations.

After the substations were created, all of the 400 kV and 220 kV substations were assigned approximate geographic coordinates using two publicly available one-line diagrams and a list of generator substations. The first one-line diagram used, shown in Fig. 1, contains the present-day high voltage (HV) substations and transmission line right-of-way paths in Poland superimposed over a geographic map of Poland [16]. The second one-line diagram shows the high voltage (HV) substations and transmission lines, but with approximate transmission routings [15]. The list of generating substations included the generators centrally dispatched by the transmission system operator (TSO) and connected to the 400 an 220 kV transmission networks. These generators also had their corresponding bus number from the case2746wop MATPOWER file, as well as the three letter substation code displayed in Figs. 1 and 2. Some of these three letter abbreviations are the names of the major cities where the substations are located, some are the abbreviations of the generating stations, and the source of other abbreviations is unclear.

Since the original MATPOWER Polish system cases contained no geographic coordinates and no bus names that could be used to identify their corresponding locations, the list of generators was first used to determine the geographic coordinates of their associated substations. The general process adopted for identifying the locations of the remaining substation is to start from one substation on the outskirts of Poland (called the base substation for this discussion) and gradually move inwards. Once a starting point is decided, all the substations connected to the base substation are examined. Information such as number of parallel transmission lines connecting substations, approximate length calculated from X and B values, and number of connected substations at each voltage level can be used to determine which substation names on the geographic one-lines correspond to which substation numbers in the case.

For example, consider the generating substation GBL as the base substation. Using the information from both Fig. 1 and Fig. 2, it is observed that GBL is connected to three other substations: ZRC, OLM and GRU. In the case, these three substation are numbered 110, 105, and 103. The transmission network map shows that GBL is connected to ZRC using two transmission lines; thus, substation number 110, which is connected to GBL via two transmission lines, must be ZRC. Next, it is observed that substation number 103 is connected to four other HV substations, whereas substation numbered 105 is only connected to two other HV substations. Thus using Fig. 1 it is inferred that 103 is GRU and 105 is OLM.

In cases where the substations are connected to the same number of substations, the distance and approximate calculated line lengths are used to differentiate and correctly identify the substations. For example, in southwest Poland, substations ABR and MKR both have 3 connections. However, MKR and ZAM are close together, and this information can be used to differentiate these two substations in the case when examining the calculated line lengths.

The complete transmission network, substation by substation, from North to South, was traced with this approach. Then, the approximate GPS coordinates of the substations were determined using the underlying geographic map in Fig. 1 and Google maps. For example, substation GBL is just north of the city Pruszcz Gdański. In cases where the cities were not readable on the map, other geographic features such as roads or country borders were used to identify approximate substation locations. Finally, the resulting geographic one-line diagram was created as shown in Fig. 3, with orange representing 400 kV and light blue 220 kV. In this figure, the green arrows show the direction of power flow and the size of arrows are proportional to the MW power flow in transmission lines.

Fig. 1. High voltage transmission one-line diagram from 2021 from Polskie Sieci Elektroenergetyczne (PSE), the Polish transmission grid operator

1) Challenges in Adding Geographic Coordinates: While the method described above in Section IV-A is fairly straightforward, there were multiple factors that complicated the analysis and addition of geographic coordinates. First, there were the discrepancies between the two geographic one-line diagrams in Figs. 1 and 2. For example, substations or transmission lines would appear on one map but not the other, e.g. OLT and KRM in Fig. 1, or WRZ to HCZ in Fig. 2. Also, there were several substation connections shown in one or both one-lines that were not present in the Polish grid case, e.g. ROK to LAG in Fig. 1 or BGC to PEL in 2. The converse was also true, as there were multiple connections present in the case that weren't listed in either of the one-line diagrams, e.g. KLA to SIE in Fig. 1 or BGC to CHM in Fig. 2. There were also some discrepancies in the number of parallel circuits shown in the one-line diagrams compared to the Polish grid case, e.g. PAS to DBN in Fig. 1. Finally, the close geographic proximity of the substations in South Central Poland made it difficult to read the maps and identify the associated cities. While not insurmountable, all of these discrepancies made implementing the process described above more difficult and arduous.

B. Dynamics Modeling of the Polish Grid

In this subsection, various dynamic models are assigned to generators in the Polish grid case, according to generator fuel

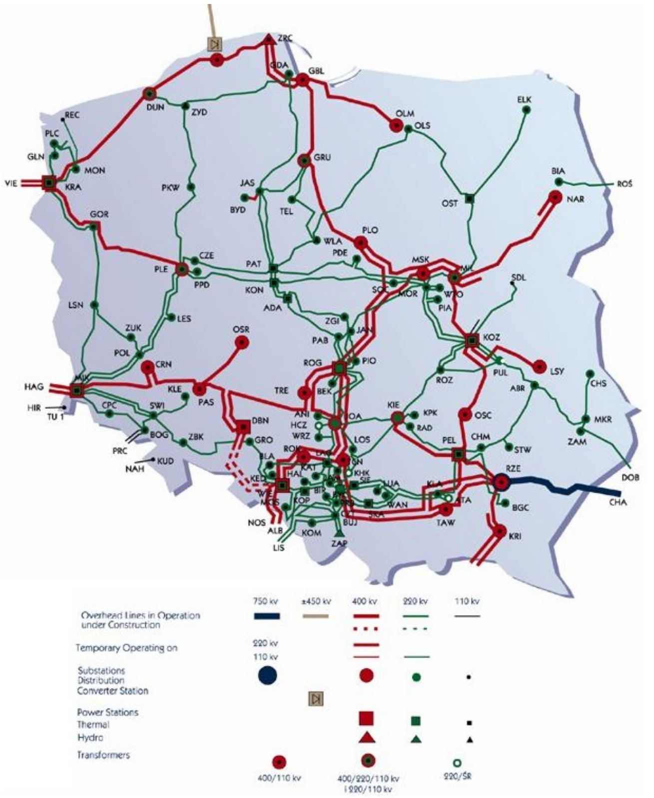

Fig. 2. High voltage transmission one-line diagram of Poland circa 2011 [15]

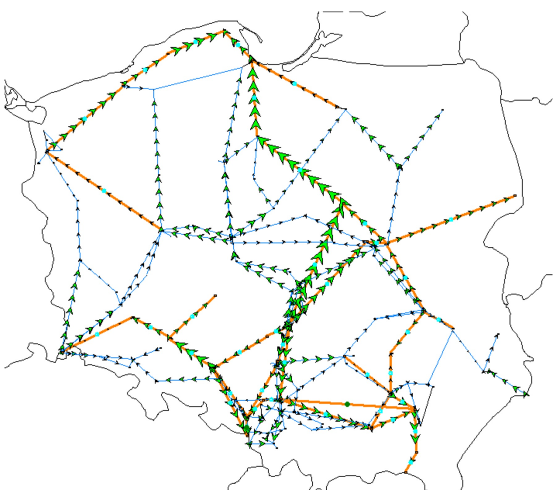

Fig. 3. High Voltage Network One-Line for the Polish System Case

types. Reference [17] proposed a method to produce dynamics data for synthetic generators for multiple fuel types, including natural gas, coal, nuclear and hydro. Work [18] further extend the dynamic cases with integration of renewable generators.

In this work, the methodology proposed in [17], [18] are utilized to model system dynamics of the Polish grid case. Dynamic models and parameter templates are identified and extracted from WECC cases and then assigned to generators in the Polish grid case. The generators in the Polish grid case are mainly coal-fueled power plants. Multiple machine (GENROU), governor (IEEEG1) and exciter (ESAC1A, ESAC6A, ESST4B, EXAC1, IEEET1) models are utilized in the case. Details of all dynamic models are listed in Table. V.

TABLE V
DYNAMIC MODELS USED IN THE POLISH GRID CASE

Model	Description	Number
GENROU	Solid rotor generator represented by equal mutual inductance rotor modeling	487
IEEEG1	IEEE Type 1 speed-governor model	487
ESAC1A	IEEE Type AC1A excitation system model	71
ESAC6A	IEEE Type AC6A excitation system model	90
ESST4B	IEEE Type ST4B potential- or compound-source controlled-rectifier exciter model	134
EXAC1	IEEE Type AC1 excitation system model	45
IEEET1	IEEE Type 1 excitation system model	147

For each dynamic model, appropriate parameter templates need to be determined and assigned. Some parameters depend on the generator capacity (i.e., machine inertia and X_d), and all parameters are related as well. Once one parameter is determined, all other parameters can be determined or estimated by their relationships. These dynamic models and parameter templates are then validated and tuned to match dynamic responses of actual cases. The small signal performance criteria described in [19] are used to assess the dynamic performance of generator excitation control systems. Commonly accepted dynamic performance features of the excitation control system are listed in Table VI. Further tuning and adjustments are made if one generator is unstable or does not meet any of the aforementioned performance features.

TABLE VI
COMMONLY ACCEPTED DYNAMIC PERFORMANCE FEATURES

Gain margin	$\geq$ 6dB
Phase margin	$\geq 40°$
Overshoot	0% to 15%
M_P	1.1 to 1.6
Damping ratio	$\geq$ 0.6

After modeling and tuning the dynamic models, N - 1 contingencies are applied to the Polish grid case to demonstrate the system dynamic responses. A python package, ESA, is used to interact with PowerWorld Simulator and obtain simulation results [20]. We run a 100-second no-disturbance simulation to ensure that the case is not affected by numerical issues and provides valid simulation results. The first example is a generator trip event. Generator at bus 82, which is the largest generator in the Polish grid case, is disconnected from the rest of the system at 1.00s. All simulated bus frequencies are plotted in Fig. 4. The frequency oscillations are damped out shortly after the contingency event. The second example is a balanced three-phase fault event. Bus 54 (400 kV) is faulted at 1.00s and its cleared in 0.05s. As shown in the figure, frequency variations are observed due to an imbalance between load and generation. These fast dynamics are eliminated within 10 seconds and the system settled down to a new steady-state.

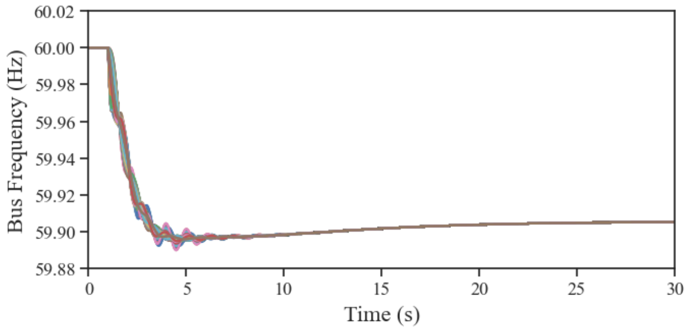

Fig. 4. Simulation results using the Polish grid after generator drop event

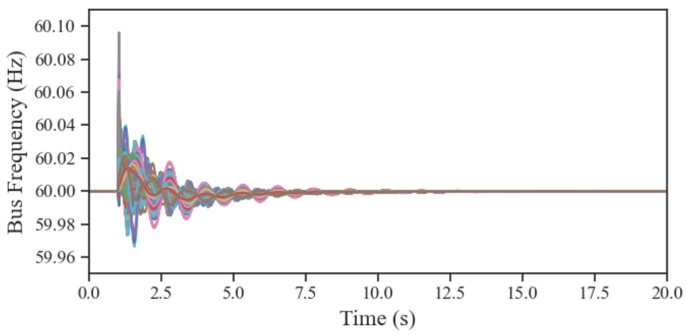

Fig. 5. Simulation results using the Polish grid after bus fault event

Hence, simulation results show that the developed Polish grid case with integrated dynamic models has satisfactory dynamic response and can be used in dynamic studies.

V. Conclusion and Future Work

The Polish system test cases were created using the real Polish network from 2000-2005. First, network statistics from the Polish system were compared against the same metrics gathered from the United States power system network models. While many of the statistics were similar, there were some differences, indicating differing design and modeling choices between the grid creators and operators in the two countries.

As is typical of most publicly available power system test cases, the Polish grid test cases include only steady-state generator parameters, and the cases do not include substations with geographic coordinates. To improve the quality of the Polish system networks, this paper described the process by which the geographic coordinates were added to the network, and the generator models were expanded to include parameters such as field voltage impedance, inertial and frictional constants and other parameters. By expanding the Polish systems to include these models and geographic coordinates, the Polish network models can be used for analyses such transient stability, GIC studies, transmission expansion, and other simulations involving geographically-based phenomena such as weather or extreme events.

Future work will include utilizing or creating algorithms to calculate the geographic coordinates of the remaining 110 kV substations.

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