Power System Test Cases for EMT-type Simulation Studies

Aboutaleb Haddadi, Ming Cai, Ulas Karaagac, and Jean Mahseredjian

***Abstract*—This paper proposes a set of power system test cases that can be used by research community on electromagnetic transients to compare various solutions, numerical methods and results on the same basis. Power system test cases for such studies are rare. These test cases provide a more detailed representation of a power system compared to widely-available phasor-domain test cases and thereby enable a wider range of power system simulation studies including both fast (electromagnetic) and slow (electromechanical) transients. The challenge is often the required amount of model data. This paper presents the developed test cases and their main features. It further highlights the modeling guidelines used to develop them and model validation approach. By adding line distance protection to one of the proposed test cases, a case study is provided to show the application in large-scale power system protection studies, demonstrating the ability to accommodate a wide range of power system simulation research needs.**

***Keywords*: Electromagnetic transients, power system simulation, power system modeling, test case, transmission network.**

I. Introduction

The simulation of electromagnetic transients (EMT) has become indispensable to researchers in a vast range of power system studies [1]-[3]. An EMT-type study involves simulating a power system at a very high precision level in a wideband range of frequencies [3], which is enabled by EMT-type test cases incorporating a high level of modeling details and models adapted to the simulation type and frequency content of the studied phenomenon. Therefore, there is a growing need to develop standard EMT-type test cases allowing for a wider range of applications including both fast (electromagnetic) and slow (electromechanical) transient studies. The challenge is often the required amount of model data.

Despite the growing need for EMT-type simulation studies, standard EMT-type test cases for such studies are rare in the literature. A large number of widely-used phasor-domain benchmarks, traditionally used for studies such as load-flow and transient stability, have been presented in the literature [4], [5]. These existing benchmarks, albeit adequate for the aforementioned studies, do not contain sufficient modelling details required for an EMT-type study. Although a few EMT-type test cases do exist in the literature [6]-[19], reproducing these cases in different software environments and meeting the need of utility engineers in EMT-type studies are encumbered by the lack of adequate presentation of modelling details and parameters in these existing cases. Specifically, an EMT version of the IEEE 39-bus [20], IEEE 118-bus [4], and IEEE 14-bus [4] benchmarks were presented in [6]-[9], [11]-[13], and [16] respectively with no presentation of full model data. Other proposed EMT test cases include a voltage-sourced converter-based dc grid [14], a case for HVDC control studies [15], and an EMT model [17]-[19] of the IEEE 34-bus test feeder [21] including induction generators.

To address the above-mentioned gap in the literature, the authors have presented a number of EMT-type test cases in [22],[23], namely:

- three versions of a modified IEEE 39-bus test case [20] with supplementary modelling details (IEEE-39 base case), frequency-dependent (FD) transmission lines [24] (IEEE-39 FD line), and a generic wind generator model for renewable energy integration studies (IEEE-39 wind). Since the provided line data includes tower geometry and conductor type, it also allows developing a wide-band (WB) [25] version of the lines;
- two versions of a modified IEEE 118-bus test case [4] with detailed modelling data (IEEE-118 base case), and for Geomagnetic Disturbance (GMD) studies (GMD-118);
- three versions of a 40-bus 400-kV 50 Hz European transmission grid (T-grid) incorporating modelling details (T0 base case), a generic wind generator model (T0 wind), and a 459-bus version of T0 entitled T1 with sub-transmission, distribution, and generation voltage levels as well as wind generation; and
- an active distribution network (ADN) model which is a synthetic 50-Hz 79-bus unbalanced distribution system with representative characteristics of a typical ADN for smart grid control and protection studies.

Full model data have been provided in all versions of the presented cases to enable implementation within different software environments, overcoming the challenge of the lack thereof in the literature.

A key objective of [22] is to enable the users to expand the data base by adding new test cases. To achieve this objective, this paper provides the user with a set of modeling guidelines and validation measures to test the adequacy of future cases. Furthermore, the paper presents a summary of the developed test cases of [22] and the main features of each case.

All developed test cases are publicly available in an online

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repository [23], freely accessible to the research community for various types of studies including the testing of numerical methods, such as accelerated computations, unbalanced load-flow, initialization, and for testing modeling accuracy. The model data are agnostic to simulation platform; this paper presents the results of an implementation within EMTP [1].

II. Components Models

An EMT-type test case provides a more detailed representation of a power system compared to a phasor-domain case and hence, requires much more modeling data. The main challenge is to ensure the accuracy and consistency of the data. This section presents a summary of the guidelines followed in [22] to ensure data accuracy.

A number of the proposed test cases have been developed from phasor-domain versions by supplementing/modifying the original case data to enable time-domain simulations. In some cases, e.g., IEEE 118-bus model [4], the original case data contained inconsistencies and had to be modified. The following sections further present these modifications.

A. Transmission Line

An EMT-type simulation may require a line model which is accurate over a wideband range of frequencies. FD [24] and wide-band (WB) [25] models provide such accuracy, and require such data as conductor type, tower geometry, and line length. A challenge is to obtain these data since they are not provided by the existing phasor-domain cases in the literature [4],[5], and hence need to be estimated. An approach is to assume a typical wave propagation velocity of, e.g., 0.97×(the speed of light) and calculate the per-unit-length impedance and length of the line. However, applying this approach on the original line data of IEEE-118 [27] does not give reasonable line parameters. Hence, the original line data of IEEE-118 was replaced by typical north-American line data [28] of Table 1. All proposed test cases of this paper assume a continuously-transposed line, and hence, the FD line model is sufficient, and the WB model is not needed, but can be also selected and unbalanced lines can be created from given data. Based on the developed FD model, the parameters of more simplified constant-parameter (CP) and PI model of lines are calculated as presented in Table 2. Line lengths are calculated by dividing the per-unit-length inductance X'_1 of Table 2 by the original line inductance [27].

Table 1. Proposed line data of the modified IEEE-118 case.

138-kV line					
Phase Number	dc resistance (Ω/km)	Outside diameter (cm)	Horizontal distance (m)	Vertical height at tower (m)	Vertical height at midspan (m)
1	0.0574	2.392	-6	10.5	7
2	0.0574	2.392	0	10.5	7
3	0.0574	2.392	6	10.5	7
0	0.71	1.4	-3	16	13
0	0.71	1.4	3	16	13
Number of conductors			5		
Skin effect correction			solid conductor		
Relative permeability			1		
Line length (km)			57.6		
Ground return resistivity (Ω.m)			100		
345-kV line					
Phase Number	dc resistance (Ω/km)	Outside diameter (cm)	Horizontal distance (m)	Vertical height at tower (m)	Vertical height at midspan
1	0.0457	3.556	-10	19.4	15
2	0.0457	3.556	0	19.4	15
3	0.0457	3.556	10	19.4	15
0	0.71	1.4	-5	29	25
0	0.71	1.4	5	29	25
Number of conductors			5		
Skin effect correction			solid conductor		
Relative permeability			1		
Number of conductors in the bundle			2		
Spacing (cm)			40.6		
Angular position (degrees)			0		
Line length (km)			57.6		
Ground return resistivity (Ω.m)			100		

Table 2. Proposed pre-unit length line impedance of the modified IEEE-118.

Voltage (kV)	R'_0 (Ω/km)	X'_0 (Ω/km)	B'_0 (μS/km)	R'_1 (Ω/km)	X'_1 (Ω/km)	B'_1 (μS/km)
138	0.6010	1.080	2.537	0.0601	0.504	3.331
345	0.4080	1.022	2.583	0.0408	0.470	3.582

B. Transformer

The model of all three-phase transformers consists of three two-limb single-phase units as shown in Fig. 1 where R_H and R_X are the series resistances representing the conductor losses of each winding, L_H and L_X denote the leakage inductances of the windings, and R_m and L_m represent the core behavior including nonlinear saturation and core losses. The magnetization branch is placed on the high-voltage-side winding and is connected to a node which splits the leakage impedance. The nonlinear iron core has been modeled by a piece-wise linearly interpolated curve representing saturation; Table 3 presents the data (in pu) obtained from field test measurements of a single-phase shell-form 300MVA 765kV/120kV transformer [29].

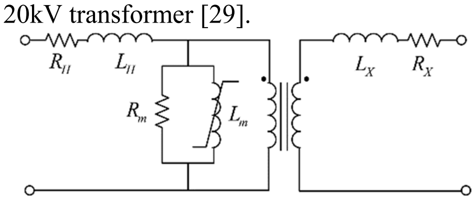

Fig. 1. Model of a single-phase two-winding transformer.

Table 3. Proposed saturation data of transformers [29].

Current (pu)	0.001	0.01	0.025	0.05	0.1	0.5	1	2
Flux (pu)	1	1.075	1.15	1.2	1.23	1.37	1.55	1.86
Current (A)	0.96	9.6	24,0	48.0	96.1	480	961	1921
Flux (Wb)	1657	1781	1905	1988	2038	2270	2568	3082

Load-serving transformers are assumed to have a Yd1 winding connection; in practice, they may alternatively have a Dyn connection to provide a ground source to the distribution system. Under Yd connection, a zig-zag grounding transformer is installed on the delta side to provide the required ground source to the distribution system. The X/R ratio of load-serving transformers is between 30-40 depending on the nominal power of transformer. The winding reactance is set at 0.1pu which is within the typical range of 0.05-0.2pu.

Generator step-up transformers (GSUs) have a rated MVA consistent with the rated MVA of the corresponding power plant. Their winding reactance is set at 0.1pu.

C. Synchronous Machines (SMs)

SMs have been represented by a single-mass Wye-grounded configuration including saturation characteristics and a constant of inertia of 4 s. Their models incorporate machine controls including exciter ST1 [30], governor IEESGO [31], power system stabilizer PSS1A [30], and over-excitation limiter (OEL) MAXEX2 [32].

D. Loads

Two load models have been developed, namely, constant-impedance and PQ exponential whose real- and reactive-power consumption are described by [33]

$$P = P_0\left(\frac{V(t)}{V_0}\right)^{k_{pv}}\left(1+k_{pf}(f-f_0)\right)\frac{1+T_{p1}s}{1+T_{p2}s} \tag{1}$$

$$Q = Q_0\left(\frac{V(t)}{V_0}\right)^{k_{qv}}\left(1+k_{qf}(f-f_0)\right)\frac{1+T_{q1}s}{1+T_{q2}s}, \tag{2}$$

where subscript "0" denotes a nominal value, k_{pv}, k_{qv}, k_{pf}, and k_{qf} are coefficients defining dependence of real and reactive power on voltage and frequency, and T_{p1}, T_{p2}, T_{q1}, and T_{q2} are coefficients which define transient response.

E. Further Models for Specialized Studies

Further than the above modeling details, the test cases incorporate modeling details for specialized simulation studies. These additional models include on-load tap changer (OLTC) for voltage stability and GMD studies, ground model for GMD studies, GPS coordinates of substations, wind generator model including both type-III and type-IV, on-shore and off-shore, and protective relays. The repository [23] includes these additional models.

III. Model Verification

To ensure that the developed test cases meet representative characteristics of a typical power system, they have been put to the following performance requirement tests:

- Load-flow solution should converge and be feasible, and voltage amplitudes should be typically between 0.95-1.05pu. The proposed test cases of this paper meet this criterion.
- The test cases should be stable in time-domain. Under normal operating conditions, the frequency waveform should be flat. The transient response should be well-damped and stable under an N-1 contingency. Fig. 2 shows sample results of the proposed modified IEEE-118 case corresponding to a 100-ms three-phase fault on bus 37 followed by the isolation of buses 37 and 38 and the loss of a 60-MW generator at 4 s (the schematic of the case has been shown in [22] and is not repeated here due to page limitations.) In both scenarios, the model regains stability despite the severity of the disturbance. The same test has been performed on other test cases of this paper. All cases satisfy these criteria; their results have not been presented here.

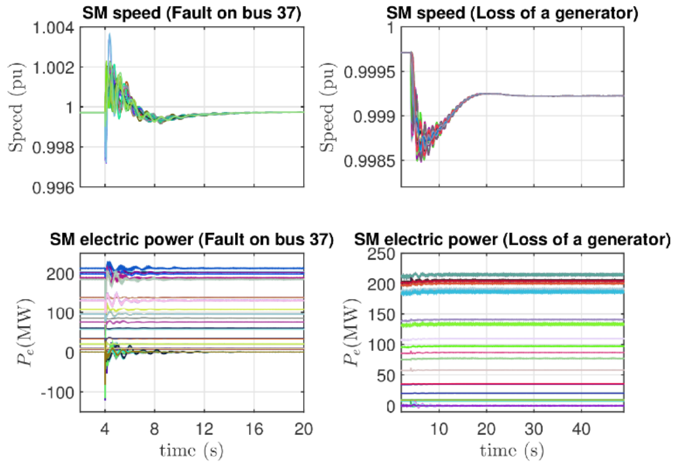

Fig. 2. Selected time-domain simulation results of the proposed modified IEEE-118 case (left: a 100-ms three-phase fault on bus 37 followed by the isolation of buses 37 and 38; right: loss of a 60- MW generator at 4s).

IV. Developed Test Cases

This section presents the developed test cases and their versions. All cases follow the modeling guidelines of Section II. The data of all cases are platform agnostic and can be implemented in an EMT software of user's choice. This paper shows an implementation within EMTP [1] for illustration purposes.

A. Modified IEEE-39 Test Case

1) IEEE-39 Base Case

IEEE-39 base case represents a portion of the 345-kV New England transmission grid [20], [26] consisting of 4 voltage levels, 39 buses, 10 synchronous generators (SGs), 34 transmission lines, 12 transformers, and 19 loads. It modifies the original data [20], [26] by representing transmission lines using the CP model and incorporating both static and dynamic load types, together with supplementary data in tower geometry, conductor types, transformers, and machine controls. The authors propose that this new version should become the new IEEE-39 bus reference for EMT simulations.

2) IEEE-39 FD Line

In this version, the transmission lines are modelled by their more detailed FD representation whose model is generated from the proposed line data.

3) IEEE-39 Wind

To enable wind integration simulation studies, this version adds two type-III and type-IV wind generators to the base case at buses B25 and B2, replacing the SGs at buses B37 and B30 respectively. Detailed model descriptions and parameters for all three versions can be found in [22]. It should be mentioned that [22] has only presented the high-level data of converter-interfaced devices such as wind generator models. These models have many parameters for the converter/control schemes whose detailed presentation is not practical. Users may refer to the repository [23] for the full details of the converter-interfaced devices.

B. Modified IEEE-118 Test Case

1) IEEE-118 Base Case

The IEEE-118 base case is a modified version of a portion of the American Electric Power (AEP) system in the US Midwest as of December 1962 [27], which contains 177 transmission lines, 91 loads, 9 transformers, 19 SGs and 35 synchronous condensers (SCs), by correcting inconsistencies in the original transmission data and the var limits of generators using typical data from a North American transmission system [28], and by adding complementary data on transmission lines (conductor, tower configuration, per-unit length positive sequence and zero-sequence line impedance, line length), transformers (rating, winding configuration, impedance, nonlinear saturation characteristics), and machines (machine control, electrical and mechanical data). These modifications enable EMT-type simulations which are not possible using the original load-flow-based case [27].

2) GMD-118

The simulation and analysis of the impacts of a GMD on bulk power system and the ability to mitigate its effects are important in improving resilience of electric power transmission grids [30]. In response to the inability of performing harmonic calculation and analysis of power system dynamics due to a GMD in existing GMD test cases [5], [34], a GMD version of IEEE-118 which incorporates supplementary modelling details for time-domain simulation of a GMD within an EMT-type package is developed in this work. The supplementary modelling details include: zero-sequence resistance of transmission lines for geomagnetically-induced current (GIC) calculations, GPS coordinates of substations, substation grounding resistance, nonlinear magnetization branch of transformers for simultaneous solution of dc GICs and ac var consumption, OLTC and machine controls. Furthermore, the Geoelectric Field (GEF) has been modelled as controllable dc voltage sources injected in series with each phrase of the transmission lines.

Full modelling details and parameters for both versions are given in [22].

C. T-Grid Test Case

1) T0

The model is based on the data of [35], which is a 400-kV, 50-Hz transmission and generation system comprised of 40 buses, and 35 SMs whose total generation capacity is 6855 MVA. The SM models include AVR/governor, exciter and PSS. Each SM has been interfaced to the transmission grid through a Dy+30° transformer with saturation data. The transmission lines are represented using equivalent CP models, and loads are calculated from the results of a 1989 load-flow test [35]. T0 Wind

In this version, the two SMs at buses CAYIR and SEYIT are replaced by onshore wind parks connected between buses ADANA and OSMAN with a total generation of 322.5 MW, and an offshore wind park whose total production is 1057.5 MW is added between buses IZMIR and ALIAG through a 350 MVA, 34.5 kV/150 kV, ΔYg+30° transformer and an HVDC link, as illustrated in Fig. 3 and Fig. 4.

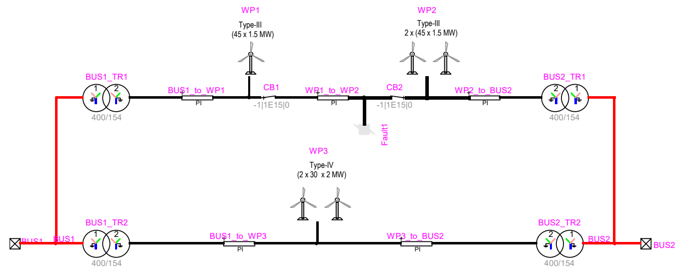

Fig. 3. Onshore wind parks connected between bus ADANA and bus OSMAN of T0.

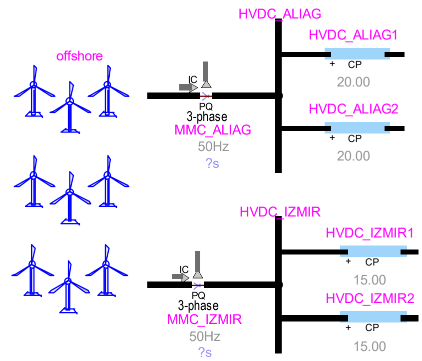

Fig. 4. Off-shore wind park connection.

A three-phase bolted fault event is simulated after performing a multiphase unbalanced low-flow solution. The fault, whose duration is 0.1 s, occurs at bus ADAPA at $t = 1s$. Fig. 5 presents the total active and reactive power outputs from the offshore wind park before, during and after the fault. It is noted that the initial perturbation is due to low-flow and initialization inside the MMC stations after HVDC transmission. Fig. 5 shows both active and reactive power outputs stabilize after fault elimination, further validating the feasibility of the developed test case.

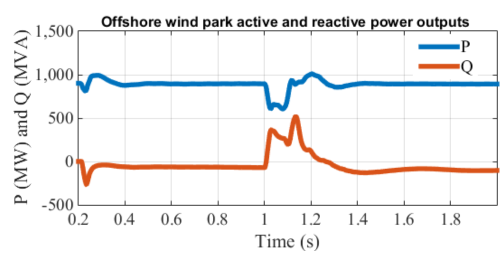

Fig. 5. Offshore wind park total active and reactive power outputs.

2) T1

T1 is a 459-bus version of T0 that consists of 7 voltage levels (transmission, sub-transmission, distribution and generation), 637 transmission lines represented by both CP models and PI sections, and 10 type-III onshore wind generators connected at sub-transmission level.

Once again, parameters and modelling details [22] can be used by researchers for wind integration studies, numerical methods and models, and simulation performance studies for EMT-type simulation tools.

A test of relay applications is performed by adding two distance relays [36] at the terminals of every line of this test case. The test shows a scenario where the breakers at the terminals of the faulted line (between buses IZMIR and SEYIT) do not open (e.g., due to a mechanical failure) after the occurrence of a phase-A-to-phase-B fault. Consequently, two relays, namely Relays 1 and 2, at buses ALIAG and YENNIK trip in backup Zone 4 and Zone 2 with a time delay of 1.5 s and 0.5 s, respectively. The phase AB locus of both relays are presented in Fig. 6, and their tripping signals are shown in Fig. 7.

This test illustrates the application of the developed test case in large-scale power system protection studies, demonstrating the ability to accommodate a wide range of power system simulation research needs.

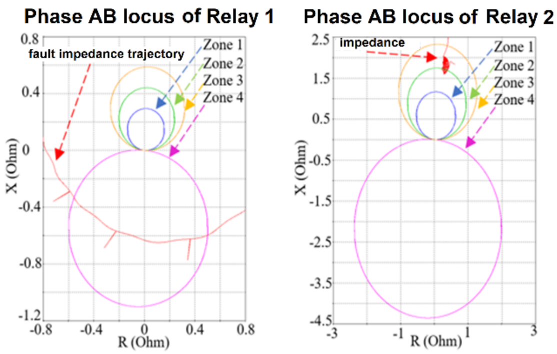

Fig. 6. The phase-AB locus of Relay 1 and Relay 2 during the fault scenario of Section IV.C.2 (left: phase-AB locus of Relay 1; right: phase-AB locus of Relay 2).

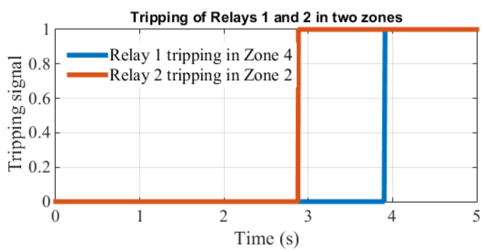

Fig. 7. Relays 1 and 2 trip signals.

V. Conclusions

This paper proposed four EMT test cases, namely, IEEE-39, IEEE-118, T-grid, and an ADN model to address the need for such in the research community for EMT-type simulation studies. Overcoming the difficulty of inadequate data in the existing EMT-type test cases, full modelling details and parameters have been provided for various versions of each test case presented in this paper to enable different types of power system EMT studies at a high precision level. These developed test cases have been further validated in terms of feasibility of load-flow solution and ability of regaining stability after being subjected to physical disturbances. All test cases are publicly available to researchers to compare various solutions, numerical methods and results on the same basis.

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