idTRAN, a transformer model for engineering studies with incomplete input data

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Abstract— **In this paper, a new transformer model is presented for low-frequency transient studies (transformer energization, faults, ferroresonance, GIC, etc.). The novelty of the modelling approach developed in the paper is its ability to provide a working and reliable model even when very little input data is available and even when the user is not a transformer specialist. The aim of this new model is to provide a practical solution for engineering studies where input data is incomplete and/or of poor quality. The model, whose name stands for "incomplete data transformer model", has been implemented as a ready-to-use EMTP-RV library device.**

Keywords: **transformer modelling, low-frequency transients, inrush current, transformer energization, ferroresonance, EMTP, idTRAN, PAMSUITE, parametric studies, parameter uncertainty.**

I. INTRODUCTION

Transformers are one of the main components of the electric power systems. As a consequence, good and relevant transformer models are essential when performing power system studies. This paper focuses on the modelling for low-frequency transients, as defined by CIGRE and IEC [1][2], which includes phenomena like transformer energization, load rejection, faults, ferroresonance and geomagnetic induced currents (GIC).

This paper deals with the fact that in real engineering studies a significant part of the input data required by the existing transformer models is usually not available. This forces the engineer to make more or less advised or arbitrary assumptions that have uncontrolled consequences and may end up in wrong or misleading results.

In the following sections, we will first discuss the problem of input data in existing transformer models; then we will present the new model, named idTRAN, aimed to cope with the situation; finally, we will show an example case that illustrates the particular features of the new model. The model has been implemented in EMTP-RV as a ready-to-use device with a front-end graphical user interface. It has been used in a previously published ferroresonance study [3], where its results are compared to field measurements.

II. THE PROBLEM OF THE INPUT DATA REQUIRED BY TRANSFORMER MODELS

In the low-frequency domain, two models have been traditionally used since the development of the EMTP in the 1970's: the single-phase Steinmetz model and the three-phase BCTRAN model [4]. In the 1990's and especially the 2000's, several research teams around the world have been working on better models, especially for three-phase transformers (see [5][6][7][8] and references there). These models aim to represent the internal structure of the transformer: mainly the structure of the core, but also the impact of the tank wall and, to different extents, the structure of the windings; whereas in traditional models the internal structure is neglected and the transformer is modelled much with a black-box approach. By doing so, these models (usually called *topologically correct* or simply *topological*) provide a better representation of the magnetic coupling between phases and allow to model the phase asymmetry of the transformer behavior, two phenomena that are especially important when the transformer saturates and thus becomes a non-linear device. Indeed, it has become increasingly clear that the non-linear behaviour of the transformer is the most important and also the most difficult and challenging phenomenon that needs to be modelled.

Quite naturally, the development of better models has come with increased requirements on the input data. In addition to the nameplate data (rated power, voltages and frequency, and vector group), traditional models required standard open and short-circuit test data; these data alone allowed to model the behaviour up to a slightly saturated state. If the highly saturated behaviour was also to be represented (which is in general the case), the air-core reactance of the winding of interest was also required, which is not a value required by standards nor usually provided by manufacturers. With topological models, many more data are required: relative dimensions of the core, and, depending on the particular model considered, the dimensions and relative spatial disposition of the windings and the tank, and the intrinsic magnetic characteristics of the core and tank material. Of course, these additional data are not standard and are not available in many cases.

Therefore, both in traditional and topological models some non-standard data is required, this requirement being much stronger with topological models. Very often, however, these data are not available. As a workaround, it is usually suggested to use typical data, these values being sometimes hard-coded in the model itself for the inexperienced user. This includes for example the air-core reactances, the core relative dimensions (lengths and sections) and the inner winding-to-core relative distance.

This requirement of non-standard data that are not usually available is one of the main problems that arises when trying to model a transformer. But it is not the only one. Sometimes, the required non-standard data are available, but they are not well known, they are rather known with a given degree of (un)certainty. This is typically the case of the air-core

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reactance, which is an essential input parameter for the modelling of highly saturated states. Indeed, the air-core reactance of a winding is usually calculated (by the manufacturer or, more rarely, the engineer in charge of the study) from the winding dimensions with formulas or abacus, and such formulas or abacus are associated to a 20-30% accuracy.

Furthermore, even standard data may not be available in many cases, at least for two different reasons. On the one hand, for old transformers the test reports may have been lost; also, even when the reports exist, the customer may have difficulties to provide them in time due to all kinds of company organizational problems and delays, and the engineer may need to start working long before they are finally made available. On the other hand, many studies are performed before the actual transformer is built or even designed, for example when evaluating the impact on the grid power quality of a future substation for a distributed generation plant. In this case, the engineer will not know much more of the transformer characteristics than the rated power, frequency and voltages, and possibly the short-circuit reactance.

It appears from these considerations that engineering powers system studies are very often performed with quite limited input data on the power transformers. However, without enough data, the transformer model will not work. The engineer does not have any other choice, then, than to use “fake” data based on more or less advised or arbitrary assumptions, depending on their degree of expertise. As not all powers system engineers can be transformer specialists, this usually ends up with unrealistic data being used. But even when the engineer is a transformer specialist, it is often very difficult (if not impossible) to guess the values of the lacking input parameters.

III. IDTRAN: A TRANSFORMER MODEL FOR INCOMPLETE INPUT DATA

For single- and three-phase core, two- and three-winding transformers and autotransformers, a new model is presented here that allows to cope with the situation described in the previous section, this is, the lack of transformer data in engineering studies. For this reason, the model has been called idTRAN, standing for *incomplete data transformer model*.

More specifically, the goal of idTRAN is to provide a model that

- does not require any special expertise on transformers nor transformer modelling;
- only requires input data that is always available, but also allows for other additional input data the engineer might have.

By doing this, idTRAN avoids uncontrolled user-assumptions and therefore guarantees the reliability of the results (within limits, of course; see especially III.A.2): see the example case in section IV.

The only input data required by idTRAN, which should be (almost) always available, are the following: nameplate data (rated power, voltages and frequency, and vector group) and positive-sequence standard test results (at least, for short-circuit). If the engineer has more data, the model will use it as well, the model will take advantage of the available data and manage with lacking ones.

For data known with uncertainty, the engineer will input a range of values covering the uncertainty (i. e., a central value and a half-interval V±I, or alternatively two bounds [V1,V2]). For the completely unknown data, idTRAN will automatically suggest a range that should include the real but unknown value. The suggested ranges are based on wide typical data, but the user can widen or narrow them as desired.

As some of the input parameters will not be defined by fixed values but by ranges, the model will become a parametric model. We will see later on how such a model is used in EMTP-like software programs.

A. Model structure

1) Single-phase transformer model

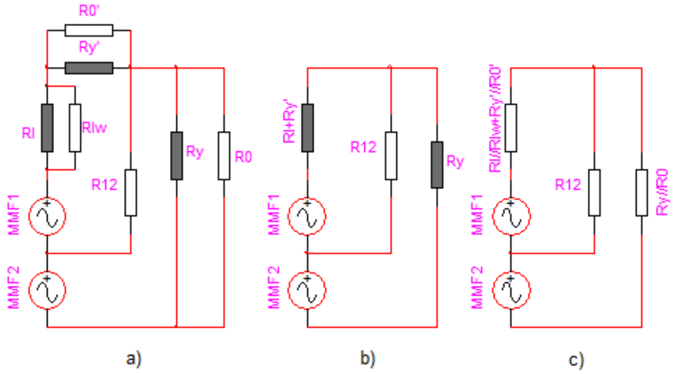
For single-phase transformers, the basic structure of the model is obtained by the magnetic circuits method, i. e. the Hopkinsons analogy [9], which provides topologically-correct models. Due to lack of space, and because this method is well known in the transformer modelling community, we won’t provide exhaustive details but rather we will focus on some significant aspects. Fig. 1 (a) shows the equivalent magnetic reluctance circuit of a single-phase two-winding transformer, either core or shell type (“l”=core leg; “y”=yoke; “12”=leakage volume; “0”=volume between core and tank). Black reluctances represent core volumes, thus they are nonlinear; white reluctances represent air volumes and are linear.

Fig. 1 (b) and (c) show the same equivalent magnetic circuit in two extreme conditions: in unsaturated state, i. e. more or less for magnetic induction up to the rated value, which is typical of steady-state conditions; and in completely saturated state, i. e., for magnetic induction above 2 Tesla, which may occur in the transient conditions referred to in section I. In fact, Fig. 1 (c) models only the incremental behavior of the transformer departing from the unsaturated state of Fig. 1 (b). However, as the two circuits have the same structure, the parameters can be calculated in such a way as to represent this sequence of behaviors.

Most electrical circuit simulation software do not allow magnetic circuits to be easily represented [10]. This difficulty is overcome by applying a technique commonly used in the field, the construction of a dual electrical circuit [11]. Since the two circuits in Fig. 1 (b) and (c) have the same structure, the dual electrical circuit is the same. It is shown in Fig. 3, V1 and V2 being the nominal voltages of each winding. Also, in a classic approach, series (Rw) and parallel (Rmag) resistances have been added in order to model the load and core losses, respectively.

For the circuit in Fig. 2 to be a reasonable model of the transformer, the flux-current characteristics of Lmag1 and Lmag2 must be constructed in such a way that they have the appropriate value at each regime to properly represent these two extreme conditions, unsaturated and completely saturated.

For three-winding transformers, a similar analysis leads to the model shown in Fig. 3, where series and parallel resistances have been omitted for better readability. Moreover, in auto-transformer connection, nodes A and B are connected so windings 1 and 2 become series and common windings.



a) b) c)

Fig. 1: Equivalent magnetic circuit of a single-phase two-winding transformer: (a) general, (b) unsaturated, (c) completely saturated

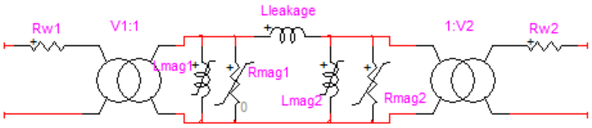


Fig. 2: Dual model of a single-phase two-winding transformer

A third condition must be accounted for, the so-called “knee” region between linear and complete saturation regimes. We will see below the solution we provide to this matter.

2) Three-phase transformer model

By using the same method used to develop the single-phase transformer model, the result would be a topologically correct model of a three-phase transformer [5][6][7][8], which depends on the type of magnetic core (3-leg, 5-leg, shell).

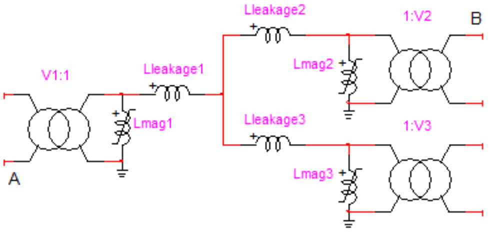


Fig. 3: Dual model of a single-phase three-winding transformer, with A and B connected in auto-transformer connection

However, in its current version, idTRAN does not use this method for the modelling of three-phase transformers. The reason for this is that the parameter determination procedures of three-phase topological models are much more complex and time-consuming, thus much more difficult to be efficiently parametrized: indeed, topological three-phase transformer models have many more parameters to determine and their determination procedure often involves a long optimization process (that, in addition, may not always converge).

In idTRAN, the three-phase transformer model is built as an extension of the single-phase model. For transformers with a 4/5-leg or shell core, the model consists of an assembly of three single-phase models. It is therefore assumed for these transformers that the behaviour in zero sequence is identical to the behaviour in positive sequence, which in general is a good approximation [12].

For 3-leg transformers, the idTRAN model introduces two other elements, in a similar way as BCTRAN: Firstly, a coupled RL branch representing the zero-sequence magnetization current and losses; this branch is connected to the high voltage side of the model because this is usually the topologically correct node (see for instance [13]). Secondly, a coupled L branch representing the positive and zero-sequence leakage inductance. The two branches are defined by positive and zero-sequence components. Such a sequence modelling implies that we neglect the phase asymmetry of the core.

B. *Model parameter determination*

Due to lack of space, we will focus here on the aspects that depart from known methods in the transformer modelling community (see for instance [5]). The leakage inductances and load losses resistances are computed with usual techniques from the standard short-circuit test results. For 2-winding transformers, if the DC winding resistances are known, they are used to divide the total measured resistance, otherwise a 0.5 ratio in pu is assumed. For three-phase transformers, the zero-sequence magnetization parameters are computed from the standard zero-sequence no-load test results (if available).

The most challenging item is the determination of the nonlinear element characteristic curves, especially the magnetization inductances Lmag. A first part of their flux-current curve, the part corresponding to a core that is not or is only slightly saturated, is computed from the standard no-load test results. The curve seen from the terminals is computed with the algorithm presented in [14]. This curve is divided equally among the 2 (two-winding model) or 3 (three-winding model) Lmag (an acceptable assumption because this part only models the slightly saturated condition). Magnetization resistances, Rmag, are computed in the same manner.

Beyond saturation, the circuit in Fig. 1 (a) becomes (incrementally) the one in Fig. 1 (c), which consists in two windings in an air medium. The Lmag inductances in Fig. 2 and Fig. 3 must account for this. From the saturation point, the inductance of the model seen from each winding terminals must be equal to the inductance of the winding in the air, i. e. the air-core inductance of the winding. This provides the last value of the incremental inductance of the Lmag, i. e., the slope of the last segment of the curve, Lsat (see Fig. 4). For the 2 winding transformer model, the system of equations is given by (1), where the sought unknowns are Lsat1 and Lsat2. For the three winding model, the system of equations is given by (2).

$$L_{air-core,HV} = \frac{1}{\frac{1}{L_{sat1}}+\frac{1}{L_{leakage}+L_{sat2}}} \tag{1a}$$

$$L_{air-core,LV} = \frac{1}{\frac{1}{L_{sat2}}+\frac{1}{L_{leakage}+L_{sat1}}} \tag{1b}$$

$$\frac{1}{L_{air-core,i}} = \frac{1}{L_{sat,i}} + \frac{1}{L_{leak,i}+\frac{1}{\frac{1}{L_{leak,j}+L_{sat,j}}+\frac{1}{L_{leak,k}+L_{sat,k}}}} \tag{2}$$

with {i,j,k} = {1,2,3}, {2,3,1}, {3,1,2}.

The procedures just described allow to compute the two extreme parts of the flux-current characteristics (see Fig. 4). The intermediate part, the saturation knee, in the middle, is yet to be defined, which we will do in the following section.

C. Uncertainty handling

The idTRAN model aims to provide the engineer the ability to model a transformer even with very little data. The model will take advantage of the available data and manage with lacking ones. For the data that is partly or completely unknown, idTRAN will consider a range of possible values. These ranges can be set by the user, according to his limited knowledge of the data (given with some uncertainty); or, if the user does not have any clue, the ranges can be suggested by idTRAN in order to cover all the possible values (according to the field literature) given the known characteristics of the transformer. The lack of data involves especially two areas: the zero-sequence test and the transformer saturated behavior.

1) Zero-sequence behavior

This part is related to three-phase transformers only. For the zero-sequence test results, if the user does not have the no-load and/or the short-circuit test data, idTRAN allows to define a central value and an associated uncertainty. If the user does not have any information, idTRAN suggests a range based on the other (known) characteristics of the transformer. In the final (parametric) model, the admittance matrices of the branches that model the zero-sequence behavior are then computed according to this range of values.

2) Saturation behavior

The transformer behavior in the saturation condition is always difficult to model due to incomplete data. This involves unequally the three parts of the flux-current characteristic considered in Fig. 4: the slightly saturated no-load test part, the knee part, and the fully saturated air-core part. The first part is derived from the standard no-load test (as described in the previous section), which provides as many points as the number of excitation levels in the test. In this part there are usually no uncertainties, except when the transformer is not built yet. In this case, the no-load test results will be associated to an uncertainty and so will be the derived points of the flux-current curve. This is shown in the left-hand side (in blue color) of the curve in Fig. 4, where the real (but unknown) curve stands somewhere in between the two curves shown, which we will call frontier curves.

The last part of the curve represents the complete saturated state of the corresponding core leg. This part is defined by the saturation inductance, L_{sat}, computed from the air-core inductance as explained in the previous section. However, the air-core inductance is usually known with a given uncertainty due to the simplifying assumptions used in its calculation, or not known at all. In this case, a range of possible values will be suggested by idTRAN. This range of values of the air-core inductance defines a range for L_{sat}. This is shown in the right-hand side (in red color) of Fig. 4, where two curves are defined by the two extreme values [$L_{sat,lower}$, $L_{sat,upper}$]. Again, the real curve stands somewhere in between the two frontier curves.

Finally, the knee part of the curve is the most challenging. This is due to the fact that no data is ever available between the last no-load test point and the fully saturated state defined by L_{sat}. Even if the core dimensions and the B(H) characteristic of the core steel sheets are known, it is very difficult to model this part because it depends heavily on the air-gaps at the core joints. Thus, modelling the saturation knee is a problem for all the transformer models, even when all the desired data is available. The parametrized approach presented here offers a solution to this problem.

We will consider two frontier bounds that frame the real (but unknown) knee curve. If the knee is modelled by a single linear segment, its slope must be in between two extreme values: lower than the last slope of the no-load test part of the curve and higher than the slope at full saturation, L_{sat}. Moreover, the full saturation state where the slope becomes L_{sat} is reached when the magnetic induction equals the saturation induction of the core steel sheets, B_{sat}. This saturation point corresponds to a linkage-flux λ_{sat} that can be computed from the rated induction B_r:

$$\lambda_{sat} = \lambda_r \cdot \frac{B_{sat}}{B_r} \tag{3}$$

where $\lambda_r=V_r/\omega$ is the rated flux.

If we put together all these facts, it follows that the real knee part of the curve is somewhere in between the two curve frontiers shown in dotted lines in Fig. 4.

For transformer core steel, B_{sat} is about 2 Tesla. This is the value that idTRAN will use unless the user sets another value. The rated induction B_r depends on the transformer design. If this data is not known, a range can be set; idTRAN will suggest B_r=[1.5,1.8] Tesla. If B_{sat} and/or B_r are defined by ranges, then λ_{sat} is as well and two values $\lambda_{sat,lower}$ and $\lambda_{sat,upper}$ are considered, as shown in Fig. 4.

Finally, Fig. 4 shows two magnetization curves, upper and lower. The real magnetization curve is not known but is surely located between these two frontiers.

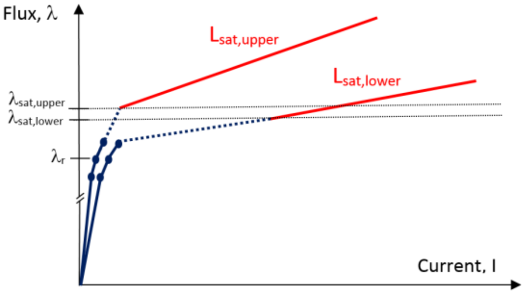


Fig. 4: L_{mag} flux-current curve building parts in idTRAN
(scales are distorted for better readability)

D. Model parametrization

As a consequence of the input data uncertainty ranges, the final model parameters are not single values but ranges of possible values or frontier curves framing the possible curves. For this reason, idTRAN allows to build two kinds of final EMTP models: single-deterministic or parametric-stochastic.

If the single-deterministic option is selected, the user must choose among several options that will “pick” the meaningful values and curves among all the possible ones. For example, the option “maximize magnetization and zero-sequence currents” will choose the lowest zero-sequence impedance values and the lower magnetization curve. The option “minimize magnetization and zero-sequence currents” does the opposite. The choice of one or another option depends on the phenomena under study. For example, if the user is interested in RMS voltage drop at transformer energization, the “maximize magnetization and zero-sequence currents” could be a good option in order to simulate the worst case.

However, the single-deterministic approach has several drawbacks (see [15] for an exhaustive discussion): On the one hand, it requires an expert engineer capable of identifying the worst-case option for their particular study case. Moreover, in many cases it is impossible, even for the expert engineer, to guess which is this worst-case option. On the other hand, dealing only with worst-case scenarios may lead to cost-ineffective solutions, as very unlikely events may be given excessive importance.

The most efficient use of idTRAN is as a parametric-stochastic model, which allows to avoid uncontrolled assumptions and to adopt a risk-based approach to compute event/fault probabilities (see the example case in the next section). In this mode, all the possible values and curves are considered: the zero-sequence short-circuit and no-load impedances vary freely in their uncertainty range, and the magnetization curves vary freely in between the two frontiers shown in Fig. 4. For this, EMTP needs to be used in conjunction with a parametric simulation tool that varies the values of the uncertain data in their uncertainty range. In the example below, we use PAMSUITE [15].

IV. EXAMPLE CASE

In this section we illustrate the features of the idTRAN model. The system under study is represented in Fig. 5. It consists in the energization of a 20 MVA YNy0n 63/20 kV three-phase 3-leg transformer connected to a 500 MVA short-circuit power grid through a 40 km line.

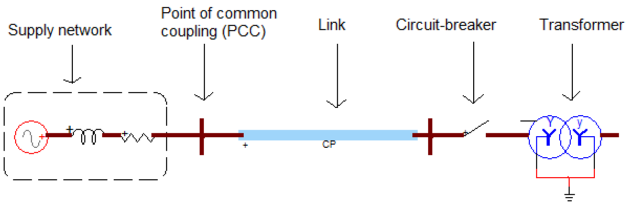


Fig. 5: Study System

The events under scrutiny are the RMS voltage drop at the point of common coupling (PCC) and the resonant temporary overvoltages (TOV) at the transformer terminals [16].

The circuit-breaker (CB) closing times and the transformer residual flux are random parameters. They are modelled as follows (see §VIII of [15] for full details): on the one hand, the CB poles may close any time over the 50 Hz power-frequency period and there is a small pole span among the three closing times; on the other hand, the transformer residual fluxes may vary between zero and 80% of the rated flux, with a phase pattern depending on the de-energization angle.

The known transformer input data are the nameplate data and the positive-sequence short-circuit test results. As the rest of the transformer characteristics are unknown, the following uncertainty ranges are set in the idTRAN form:

- zero-sequence short-circuit reactance equal to positive-sequence with a 10% possible difference;
- zero-sequence open-circuit reactance (open delta) in the range [0.3,1.0] pu (suggested by idTRAN, based on the known transformer characteristics);
- positive-sequence no load-test results equal to those of a similar transformer with a 20% possible difference;
- rated magnetic induction in the range [1.52,1.78] T (suggested by idTRAN);
- winding air-core reactance in the range [0.2,0.4] pu (known values for other transformers).

The energization has been simulated with four idTRAN models: the parametrized-stochastic model that takes into account all the range of variation of the unknown characteristics and three single-deterministic models: “maximize magnetization and zero-sequence currents”, “minimize magnetization and zero-sequence currents”, “mean magnetization and zero-sequence currents”. The “mean” model uses the central (or mean) values of all the data ranges and the mean magnetization curve between the two frontier curves. This mean model has two meanings: it is a) the model that the user will get if they disregarded all the uncertainties and unknowns, whether by lack of awareness or by lack of time; b) a model that one could expect to provide the mean value of the simulation results (we will see that this is a mistaken assumption).

Given the uncertainties on the CB closing times and the transformer residual flux, and given that a parametrized-stochastic idTRAN model is used, a parametric simulation tool is needed in addition to EMTP. Here, PAMSUITE [15] has been used to perform 3000 Monte Carlo simulations. Each simulation includes four independent circuits like the one in Fig. 5, each circuit using one of the aforementioned idTRAN transformer models. The four circuits share the same set of CB closing times and transformer residual fluxes, which are randomly generated by PAMSUITE (which also generates the parameters of the parametrized-stochastic transformer model).

Fig. 6 shows the cumulative distribution function (CDF) of the RMS voltage drop obtained with each of the models. Considering the single-deterministic models, the model that mimimizes the currents provides the lower voltage drops, the model that maximizes them provides the higher voltage drops. The difference between these two CDF show the importance of choosing the right single-deterministic model, which depends on what the user is interested in. In fact, a better option is to use the parametrized-stochastic model, which makes no assumptions and considers all the possibilities.

However, the mean model provides intermediate results that are very similar to those provided by the parametrized-stochastic model. This means that, for the study of the RMS voltage drop, a mean single-deterministic model should be good enough, the parametrized-stochastic model is not really necessary.

However, this is not a general truth: in general, using a mean model offers no guarantee of reliable results. This can be observed by considering the results for the other event under scrutiny, the resonant temporary overvoltages (TOV) at the transformer terminals. The CDF obtained with each of the models are shown in Fig. 7. Again, the single-deterministic models that mimimize/maximize the currents provide the lower/higher TOV. However, it is no longer true that the mean single-deterministic model provides the same results as the parametrized-stochastic model. Indeed, the mean model provides much higher TOV than the parametrized-stochastic model.

Thus, using a single-deterministic model is not always safe and may lead to wrong conclusions. For example, in our example case, if the grid operator is concerned by TOV exceeding 1.3 pu because they can damage the transformer insulation, Fig. 7 shows that the probability of this event computed with the mean single-deterministic model is 14%, whereas the results with the parametrized-stochastic model show that it is only 4%.

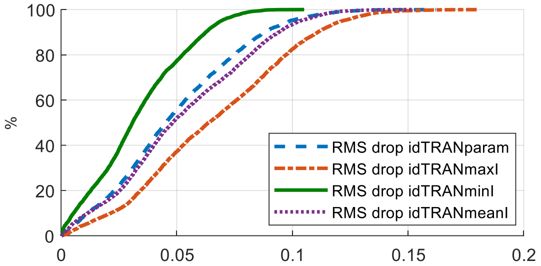


Fig. 6: RMS voltage drop CDF

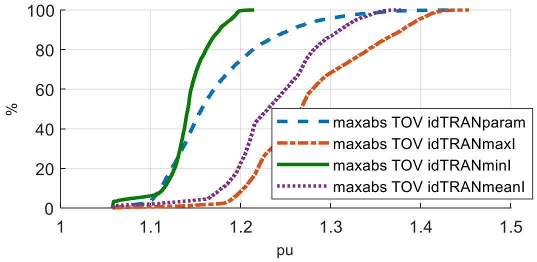


Fig. 7: Temporary overvoltage CDF

The reason why the evaluation of the RMS voltage drop with a single-deterministic model is correct is that the voltage drop is a fairly linear function of the peak inrush current; thus, a mean model and a parametrized-stochastic model provide similar results. On the contrary, the generation of TOV is a much more complex non-linear phenomenon that depends on the interaction between the inrush current harmonic content (which is not directly related to the peak value) and the supply grid parallel resonances [16].

V. CONCLUSIONS

In this paper we have dealt with the problem of the usual lack of input data for transformer modelling in engineering studies. Indeed, we have shown that the existing models require an important amount of transformer characteristics that are often not available. To cope with this situation, we have developed a new transformer model for low-frequency transient studies, called idTRAN, which has been implemented in EMTP-RV. The novelty of the presented modelling technique is that it allows to build a working model even with very little input data on the transformer and even when the user is not a transformer specialist.

Among other possibilities, idTRAN provides a parametrized-stochastic model that accounts for all the data uncertainties. With an example case, we have shown that this type of model is particularly useful when the goal of the study is to determine the probability of an event/fault, or when it is difficult or impossible to guess the transformer parameter values (in their range of uncertainty) leading to the worst case. Indeed, the presented simulation results show that using a traditional single-deterministic approach may lead to wrong conclusions.

VI. ACKNOWLEDGMENT

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