Prospective power systems models development algorithms

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Abstract. This research aims to automate the creation of prospective models essential for long-term power system planning. Several algorithms and accompanying tools have been developed to transform an existing power system simulation model (SM) into a series of prospective simulation models (PSMs). This article outlines a general approach to SM conversion using a command system, enabling the binding of SM variants to specific planning periods and operating conditions (OC). Several tools to ensure PSM quality and adequacy, including forecasted power consumption balancing and security-constrained optimal power flow (SCOPF), are presented. Advanced techniques for assessing transient stability model quality and implementing hierarchical power system modeling are also integral parts of this development process.

1 Introduction

Accurate initial data and reliable simulation models (SMs) are essential for successful power system (PS) development planning. The accuracy of proposed technical solutions heavily relies on the correctness of this initial data and the SMs built upon it. Errors made during this stage can result in unreliable and inefficient PS operation. Traditionally, PS design authorities handled both the collection of initial data and the creation of SMs independently. The independent system operator (ISO) was tasked with verifying each project's prepared SM. However, a significant majority of issues arose from human error during this process of preparation and approval.

In 2022-2023, a number of regulation acts were adopted [1-5], aimed at creating a new effective planning system for long-term development in the electric power industry. A key innovation in this new system is the centralized initial data collection, verification, and PSM preparation for future planning periods. The responsibility for PSM development and ongoing updates has been granted to the Russian ISO, known as the "System Operator of the Unified Energy System".

2 The PSM generation task

The "Rules for the electric power industry long-term development documents creation and approval" [2] and "Methodological power systems development design guidelines" [4] establish key requirements for the PSM. These regulations cover long-term planning horizon, operational conditions, PSM components requirements and necessity of CIM notation for interoperability.

A software package (SP) has been developed to automate the creation of prospective simulation models (PSMs), addressing the requirements outlined above. This tool significantly reduces labor costs and minimizes the risk of errors during PSM development. The SP is capable of performing the following tasks:

1. Batch generation of 54 PSMs corresponding to the planning horizon of 6 years and 9 OCs on the basis of CIM.
2. Synchronized changes of PSMs set, selected by planning intervals and OCs.
3. Adoption of forecasted PS by regions consumption at bus level for the set of selected PSM.
4. Ensuring each PSM meets stability criteria, including convergent load flow (LF) with no constraints violations and transient stability simulation initial conditions consistency.

Tools have been developed to manage modifications to the existing SM, enabling the accomplishment of these tasks:

1. SM changes management using command system that provide binding to the planning intervals and OCs.
2. Forecasted consumption adoption at bus level, taking into account power losses.
3. Security constrained optimal power flow (SCOPF).
4. Transient-simulation model initial conditions validation.
5. Higher-level SM synthesis from lower-level SMs.

3 SM changes management using a command system

The command is a certain SM parameter change micro-algorithm. In the simplest case, the command is a replacement of the current value with the desired one. In more advanced cases, micro-algorithms may provide relative changes or parameter value calculation as a function of other SM parameters. The implemented command system is based on a standard data

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manipulation mechanism: CRUD: Create, Read, Update, and Delete.

The SM is stored in relational database form as a set of named tables linked by key fields. The fields of tables have fixed types. Delete and Update commands are trivial. The Create operation requires extra storage. For all SM tables supporting CRUD, there are extra companion command tables. These tables are identical in structure to the main SM tables but have additional fields, representing actions and their groups. Actions include the basic operations "Add", "Delete" and "Edit" and options for edit operations, such as: "Replace", "Increase" and "Multiply." Actions can be joined into the groups, allowing simultaneous application and binding to planning intervals and OCs.

The main SM table and the command table are linked by key fields. Commands are applied to records in the main SM table based on a matching of these key fields between the two tables. Key fields are complex in general. For instance, processing topological model branches requires the use of a triple key.

The relationship between the main SM table and the command table is shown on the left in Figure 1.

Main table fields can be selectively changed with actions from the command table, due to all fields of the command table having the attribute "Not set". Fields with such attributes are skipped by actions. In Figure 1 on the left, the operation of copying data fields is performed only for fields whose value differs from "Not specified" and thus does not have the "Not set" attribute.

The full set of commands describes SM changes necessary to convert it into PSM. But commands do not contain binding to planning intervals, OCs, order, and sequence of application to a particular PSM. The "Command Map" contains mapping and all extra rules between commands and PSM variants required. The "Object" field links commands to the map. All commands with matching "Object" will be applied in a single transaction. The relationship between command maps and commands is shown in Figure 1 on the right. The "Command Map" table also links to planning intervals and up to 9 OCs. There are switches to selectively exclude transactions from desired variants.

4 Forecasted consumption distribution

The only data available on power consumption forecasts is related to regions of SM. The stability studies required to ensure PSMs quality operate on bus-branch network model, where each bus must have individual load quantities regarding its region forecast. Moreover, the forecast includes power losses, and thus, they must be adopted into the overall PSM power balance. An algorithm allowing distribution of the forecasted region consumption between region's buses and is developed. All bus loads are associated with load models that have power constraints according to CIM model. These constraints are used by the algorithm to construct bus load sensitivity to region consumption.

Let the buses be combined into some sets corresponding to regions. Let's denote the bus belonging to the set A as $P \in A$. At the same time, ΣP, ΣQ can be calculated for A. The bus load (without an index, one bus is considered) is represented by the sum of the loads:

$$P = \sum P_i. \quad (1)$$

For each load P_i, there are set of parameters: P_{iref} (base state load or expected load value), constraints P_{imin} and P_{imax}, load tangent $tg\varphi_i$, an attribute linking the load to future-planned equipment B_i and attribute which allows to set load to be constant – C_i.

For loads with $B_i > 0$, the calculation of P_i is performed:

$$P_i = \begin{cases} P_{i_{ref}} & , C_i > 0 \\ k_{Ac} P_{i_{ref}} & , C_i \le 0' \end{cases} \quad (2)$$

where k_{Ac} is the multiplier given for the buses set of A in OC of type c. Loads with $B_i > 0$ do not change in further calculations.

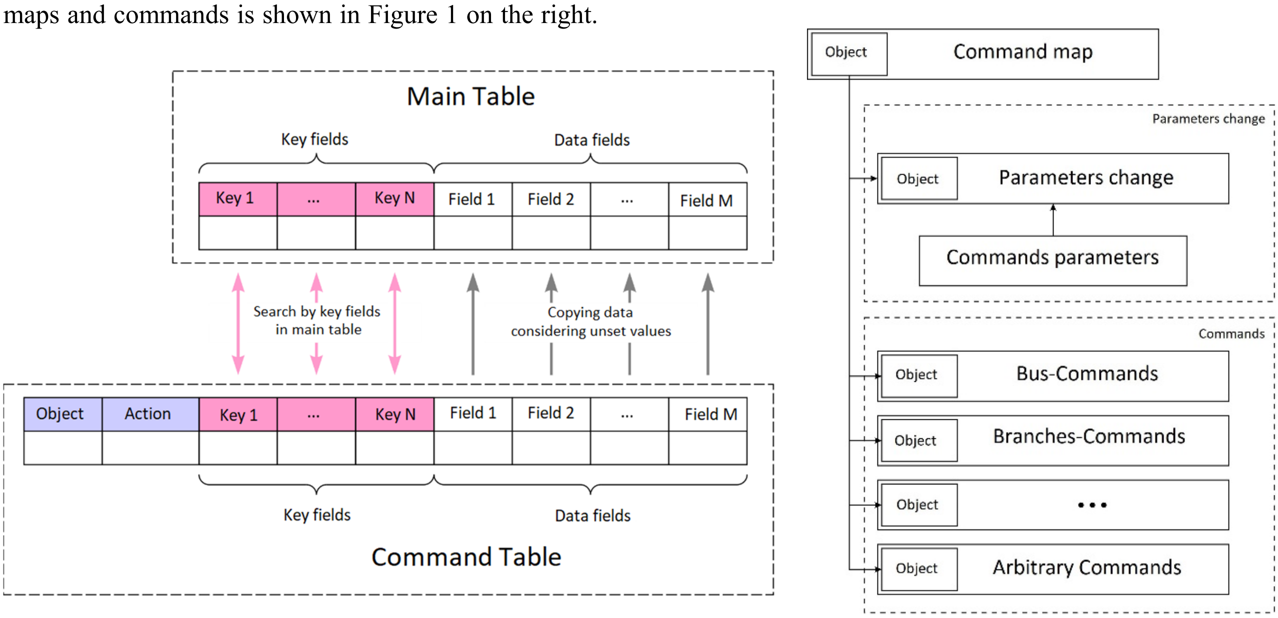

Fig. 1. Connection of main table and command table (left) and connection of "Command Map", "Parameter change" tables and tables commands (right)

For A, the constraints and the initial SM bus load point $\Sigma P_{i_{ref}}$ are calculated:

$$
\begin{aligned}
P_{A_{min}} &= \sum_{P_i \in A} P_{i_{min}}, B_i \leq 0 \\
P_{A_{max}} &= \sum_{P_i \in A} P_{i_{max}}, B_i \leq 0 \\
\Sigma P_{i_{ref}} &= \sum_{P_i \in A} P_{i_{ref}}, B_i \leq 0
\end{aligned} \tag{3}
$$

As a result, for each P_i, $B_i \leq 0$, a dependence on P_A can be obtained, shown in Fig. 2.

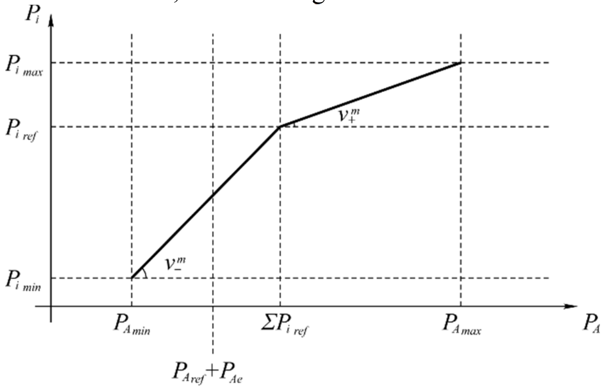

Fig. 2. Dependence of P_i on P_A

The goal is to achieve $|\Delta P_A^m| \leq \epsilon_A$, while:

$$\Delta P_A^m = P_{A_{ref}} - \Sigma P_{i_{ref}} + P_{A_e}^{m-1} \tag{4}$$

where $P_{A_{ref}}$ – given load of the set A; $P_{A_e}^{m-1}$– deviation of the load A from $P_{A_{ref}}$, while $P_{A_e}^{m-1} = P_{A_{ref}} - P_A^{m-1}$; m is iteration number; ϵ_A – tolerance. While $P_i^0 = P_{i_{ref}}$.

Since $P_{i_{min}}$, $P_{i_{max}}$ and $P_{i_{ref}}$ are set for P_i, the change of P_i can be performed at different rates depending on the sign of (4).

As the load increases $\Delta P_A^m > 0$, P_i changes with the rate:

$$
\begin{aligned}
v_{i_+} &= \frac{P_{i_{max}} - P_{i_{ref}}}{P_{A_{max}} - \Sigma P_{i_{ref}}} \\
P_i^{m+1} &= P_{i_{ref}} + v_{i_+} \Delta P_A^m
\end{aligned} \tag{5}
$$

When the load decreases $\Delta P_A^m < 0$, P_i changes with the rate:

$$
\begin{aligned}
v_{i_-} &= \frac{P_{i_{ref}} - P_{i_{min}}}{\Sigma P_{i_{ref}} - P_{A_{min}}} \\
P_i^{m+1} &= P_{i_{ref}} + v_{v_{i\_}} \Delta P_A^m
\end{aligned} \tag{6}
$$

The rates of load change v_{i_+} and $v_{i\_}$ do not depend on the variables involved in the iterative process, and can be calculated for each load once.

There is an algorithm for iterative bus loads refinement:

1. $m = 0$
2. Take $P_i^m = P_{i_{ref}}$.
3. Calculate P_A^m.
4. Calculate ΔP_A^m, if $|\Delta P_A^m| \leq \epsilon_A$ – cycle is completed.
5. Increase m by 1. If $m > m_{max}$ – cycle is complete with an error or iteration count exceeding.
6. Calculate P_i^{m+1} and repeat from step 3.

As the cycle ends, bus loads are calculated as (1) for $B_i \leq 0$. Next, the LF calculation or SCOPF is performed to refine power losses and update consumption based on the C_A to consumption of A. In order to achieve this, $P_{A_{ref}}$ is calculated.

$$
\begin{aligned}
P_{A_{ref}} &= C_A - L_A - LRC_A \\
LRC_A &= \sum_{n \in A} P_n(V_n) - P_n
\end{aligned} \tag{7}
$$

where L_A is the calculated losses of A; LRC_A is the consumption component, depending on the load response curves (LRC) associated with buses; $P_n(V_n)$ is bus load taking into account the LRC components.

Consumption balancing is performed in the outer loop of iterative process in m until a specified accuracy is achieved relative to C_A or a specified number of iterations. After consumption balancing, loads with $B_i > 0$ are added to the buses. The balance of A will be changed relative to targeted C_A, but this effect is considered appropriate for PSM.

5 Security constrained optimal power flow (SCOPF)

The following points must meet requirements for each of the PSMs, for all OPs in each planning interval:

- the voltage levels on the power facilities buses should be constrained;
- the current load of power lines and equipment should not be higher than the long-term permissible load current (LTPCL) in operational case and the active power flows through the system interfaces should not exceed the maximum load limit (MLL) in operational case.

To meet these requirements a security constrained optimal power flow (SCOPF) solution [6] is used. This algorithm provides is based on interior point method (IPM) optimization. The objective function is:

$$
\begin{aligned}
minF(x) &= \sum_i f_i(x_i) = \\
&= \sum_i a_i \left(x_i - x_i^{ref}\right)^2 + \sum_j b_j \left|x_j - x_j^{ref}\right|,
\end{aligned} \tag{8}
$$

with constraints, representing operational limits of equipment in the form of inequalities:

$$x_i^{min} \leq x_i \leq x_i^{max}, \tag{9}$$

as well as constraints in the form of equalities, basically – power balances at buses:

$$
\begin{cases}
-\sum_j V_i V_j y_{ij} \sin(\delta_{ij} - \alpha_{ij}) - P_i = 0, \\
\sum_j V_i V_j y_{ij} \cos(\delta_{ij} - \alpha_{ij}) - Q_i = 0.
\end{cases} \tag{10}
$$

where a_i and b_j are the weighting coefficients determined empirically.

The objective function consists of two components: the first least square of deviations, the second – absolute values of deviations.

The least squares of deviation are used to smoothly change the value of:

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- online generators power in order to maintain a power balance;
- the voltage references at generator buses within the constraints specified;
- the transformation ratios within the constraints specified (ratios are rounded to the closest tap).

Minimizing the deviation absolute values is used to account for the objective function:

- switching on the ready to run generators;
- switching on and off shunt compensators and other reactive power injectors.

6 Formation and initialization validation of the simulation model for the EMT

The current CIM representation of the SM is incomplete for transient simulation. To address this issue, it is necessary to conduct massive data collection, verification, and engineering to supply these data in CIM notation. The temporary solution is to achieve data for transient simulation from the native format of ISO software. To ensure data is transferred and converted appropriately, a short transient simulation with no disturbances for each PSM of 54 is performed. This way, the initial condition of the transient simulation can be verified on consistency. Due to rounding of data values, transient simulations can show low amplitude oscillations even for well-behaved cases. The goal is to ensure these oscillation decays, which indicates initial conditions acceptable.

The method of decay estimation is developed and applied in the Raiden SP. This method is now implemented into the RUSTab SP [7] to check transient decays.

The method is based on a sequential search for the state variables extremums. The search is performed at each integration step. After detecting the min to max transition, the max to min transition is expected. The resulting extremums are checked each component of state vector. When the next extremum is located, it is compared with the previous one of the same type. If there are conditions for decreasing the maximum or increasing the minimum, the counter of successive extremes of the component increases. If there are not such conditions, the counter is reset. Transient decay is reported when the counters of all components reach the set value D_{dc} (Decay detector cycles).

Fig. 3 shows the transient simulation result curve for the rotor angle δ of a synchronous machine with AVR and turbine governor. The arrows mark the extremums. The minimum increase is noted for all minima (each subsequent minimum exceeds the previous one). The decreasing maximum also noted for extremums with numbers 3, ..., 15. Therefore, the counter of the oscillation decrement of the δ component begins with an extremum of 3. For $D_{dc} = 3$, the decay of δ will be detected at the extremum with number 8 (three decreasing maxima and three increasing minima).

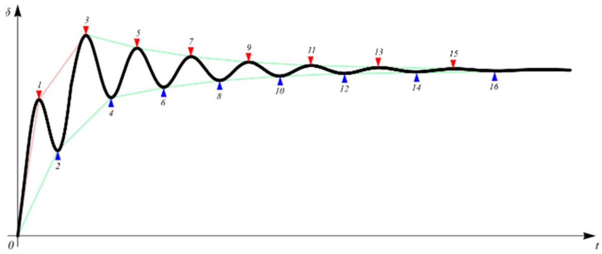

Fig. 3. EMT attenuation estimation method

This algorithm works also in the case of monotonous changes of state variables and is not prone to false-positive decays.

7 Hierarchical PSM synthesis

Due to the hierarchical structure of authorities the hierarchical approach in power system modeling is also adopted. An arbitrary number of lower-level PSM must be combined into one large, higher-level PSM. This process is called “synthesis”. This process includes the removal of equivalent parts of lower-level PSMs. The parts to be removed identified as power system regions, neighboring with another lower-level PSMs.

Before synthesis, a list of lower-level PSMs is created. All buses from one of the matched neighboring regions are to be removed, and links between neighboring PSM is established by branches.

SM synthesis is carried out according to the following rules:

1. A list of branches linking PSMs is established. For each branch two buses in neighboring PSM are identified.
2. According to the branch attribute in the list, each bus is either included into higher-level PSM, or removed. The branch itself is also incorporated into the higher-level PSM with parameters from selected lower-level PSM.
3. All buses not in neighboring regions are included into the higher-level PSM as is.

8 Practical experience

Since January 2023, the practical application of the developed technology for generating and monthly updating PSMs has commenced.

In 2023, the System Operator of the United Power System received over 700 requests from engineering providers seeking PSMs for long-term development of the electric power industry. Each PSM provided relevant information for the month of the request concerning the existing and prospective state of the United Power System. To fulfil these requirements, over 72 000 PSMs were created in 2023 including lower-level PSM of local power systems.

The developed algorithms automate the processes of creating and updating PSMs, enabling the provision of engineering providers with PSMs that adhere to strict technical requirements concerning parameters of the power system, grid, and equipment within the timeframes stipulated by a Decree of the Government of the Russian Federation.

9 Conclusion

This article outlines approaches for constructing prospective power system simulation models and describes algorithms implemented within a software prototype capable of generating and updating these models. This prototype allows users to specify a desired planning horizon and the number of operational cases, facilitating PSM creation.

A developed command system enabling the generation of sets of changes for existing simulation models minimizes the risk of errors stemming from manually entered data. For the resulting simulation models, the application of a Security Constrained Optimal Power Flow ensures compliance with constrained voltage levels and current loads in existing and projected equipment. Additionally, it guarantees that operation conditions variables, including permissible active power flows in the interfaces remain within constraints.

The prospective simulation models generated using this developed software package and provided by the System Operator offer a versatile toolset for addressing diverse tasks: including long-term development planning of the electric power industry, investment planning, assessment of interconnection possibilities to electrical networks, and scientific research approaches.

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