Simplified frequency stability tool for isolated systems: aDin

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Abstract—**The "aDin" tool has been designed to perform fast dynamic simulations in the frequency stability scope in isolated systems in ordinary office software. It is aimed to be used without any dedicated, technical and specialized software for dynamic simulation. Therefore it has been implemented as an Excel function. It is an easy-to-use tool which allows to obtain a huge number of results for several scenarios and hypothesis in a very short time.**

The computation speed allows "aDin" to be used as a simple Dynamic Stability Assessment (DSA) by the control center in real time, as an analyzer of the unit commitment outputs in order to validate them in the frequency stability scope, or as a system planning tool.

This article describes the tool functioning, the modelling capacities and the results which can be obtained. In addition, the article also describes the simplifications assumed by "aDin" (single node and governors modelled as first order linear systems) that are supported on the isolated systems characteristics, shows the proper physical formulation and justifies its accuracy by matching the simulations results of a power unbalance between "aDin" tool and a full model under "Siemens PTI PSS/E" tool.

All structural dynamic data set of the installed equipment in the system is easily integrated into a sheet of the Excel workbook. Besides, the tool provides a user-friendly interface to easily add new equipment data.

The "aDin" tool allows to model:

- **Complex contingencies of power unbalances, instantaneously or in ramp way.**

- **Generators based on renewable sources (power electronics) including, optionally, power-frequency regulation and inertia emulation.**

- **Synchronous compensators, motors and reversible power plants: either hydroelectric with pumping or energy storage systems (ESS) as batteries, ultracapacitors, fly-wheels, etc.**

- **Frequency and/or rate of change of frequency (RoCoF) protections of the modelled equipment including load shedding steps.**

- **Optionally, complex user written models.**

The tool makes it easy to control the simulation parameters and the dynamic admissibility criteria. It allows the execution in Excel macro mode providing full graphical reports and tables of the frequency and power evolution of every connected generator to the system.

The Excel flexibility allows to automate the massive preparation of different scenarios, which can be sequentially and quickly analyzed. Simulation rates up to 250 simulations per minute (Intel i5 processor) are achieved in an electrical system such as Gran Canaria (~ 600 MW peak demand) simulating up to the first extreme of the frequency excursion (it represents the most critical situation from the point of view of the frequency stability).

I. INTRODUCTION

The "aDin" tool was born due to a challenge received by the Electrical System Reliability Department of Red Eléctrica. It was requested to evaluate the frequency stability in the event of generation-demand unbalances of a huge amount of scenarios (8,760) in the Gran Canaria system, that is, the number of scenarios of a whole year.

It is practically unfeasible to try to approach the problem with conventional simulation tools of electric power systems. Consequently, the problem will be solved in a different way assuming the following reasonable simplifications:

- Reduction of the system to a single node.

- Considering simplified first order primary regulators, although this requires the determination of a simple equivalent time constant for the full power-frequency regulator of each generator.

Given that the generation scenarios are generated with the Excel application, the idea of integrating the unique bus simulation into the Excel application itself as a user-defined function written in the Visual Basic language was analyzed. The result has been a simple and quick tool to implement, since it has been programmed with the structure of an Excel

function. Moreover, the tool only needs to know the coupled generators in the scenarios where the function is going to be applied, their powers and their structural data, to determine the dynamic admissibility of those scenarios from the point of view of the frequency stability during generation-demand unbalances.

II. Tool Principles

The "aDin" tool is based on the possibility of assuming specific simplifications in the context of isolated and small systems. These simplifications are described and justified next. Besides, the theoretical formulation is shown.

A. Simplifying Assumptions

The tool takes advantage of the possibility of modelling in one bus the frequency stability issues of isolated and small systems, as is the case of the Spanish nonpeninsular electrical systems. This simplification is feasible in isolated and small systems since both the active power losses and the disturbances propagation delays in the grid can be neglected.

Given that only the impact of generation-demand unbalances in the frequency stability are going to be studied, the dynamics associated to the voltage modules can be neglected, consequently considering that the voltage modules are constant.

Although the tool is not valid for short-circuit simulation, it can be useful if the short-circuits consist of correctly cleared faults, in the cases that it is known beforehand that there will not be other consequences for the system stability beyond the generation and demand that would disconnect because of the fault clearance, as well as the potential tripping of generation connected through power electronics without fault ride through capability. This potential generation and demand tripping can be integrated in the simulation modifying properly the system unbalance when it is needed. These modifications can be done because the tool allows to model the generation tripping in the instant indicated by the user and to add any load (positive or negative) to the total unbalance.

B. Theoretical Formulation

Once the single node is stablished, the inertial dynamic can be added in just one equivalent generator. This generator is equivalent to the set of synchronous generators which are connected to the system. The inertial dynamic responds to the oscillation equation of the synchronous generator, expressed in per unit of its base machine power:

$$2H_{eq}\frac{dn}{dt} = P_m - P_e \qquad (1)$$

In the equation (1):

- n is the unitary frequency deviation.

- H_{eq} is the equivalent inertia constant of the connected synchronous generators set, expressed in seconds.

- P_m is the aggregated mechanical power of all the synchronous generators (initial dispatch and the primary contribution with its corresponding delays).

- P_e is the electrical power resulting of the difference between:

  o The system demand d (active load, plus the system losses, plus the demand damping with the frequency, Dn, where D is the damping coefficient and n is the unitary frequency deviation).

  o And the power generated by the nonsynchronous generators (initial dispatch plus, when applicable, the primary contribution, plus, when applicable, the inertia emulation coming from the power-frequency regulation response of all the generators without real inertia).

The equivalent inertia constant H_{eq}, in seconds, is calculated according to the following equation:

$$H_{eq} = \frac{\sum_i H_i S_i}{\sum_i S_i} \qquad (2)$$

In the equation (2), H_i is the inertia constant, in seconds, of the connected synchronous generator i, and S_i is its corresponding apparent power in MVA.

If P_m and P_e are disaggregated by their previously described dynamic contributions, and the regulators limits and dead bands are included, the equation (1) can be represented using Laplace transform, as shown in Fig. 1.
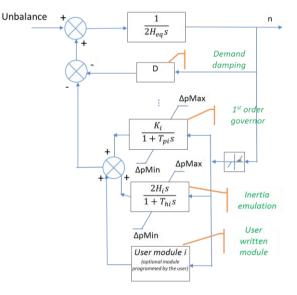

Figure 1. Blocks diagram of the differential equation which is solved by the "aDin" tool

In Fig. 1, for each i generator:

- K_i is the gain of the primary frequency regulation.

- H_i is the emulated inertia constant ($H_i = 0$ for synchronous generators).

- T_{pi} is the primary regulation time constant.

- T_{hi} is the low-pass filter time constant of the inertia emulation block ($T_{hi} = 0$ for synchronous generators).

- Optionally, the user can include a user block per generator as a Visual Basic subroutine. In this way, it is possible to consider special complex dynamics.

The primary regulation and inertia emulation blocks have been included in order to be able to model these controls for future power plants connected through power electronics, in planning horizons with very high renewable energy sources (RES) integration [1] & [2].

The base machine power to be considered in the oscillation equation will be the sum of the bases machine power of all the coupled synchronous generators ($\sum_i S_i$), without considering the generators connected through power electronics, as they hide their inertia behind the converters.

The differential equation is solved by means of numerical integration using Euler's method because the initial value of all the variables is known, as well as how to calculate the temporal derivatives of the state variables in each integration step.

III. TOOL DESCRIPTION

The tool is integrated in Excel as a mathematical function which is defined by the user and returns:

- If the simulation reaches the programmed final time: the minimum or maximum frequency value.

- If the simulation stops before the programmed final time: the frequency or the derivative of the frequency with respect to time infringement value.

- The value *zero* in the case of finalization with error conditions.

The integration as an Excel function provides simplicity and ease of use. The tool can be run also as an Excel macro. In this case:

- It is possible to obtain additional information of the simulation of one scenario, or a selected set of scenarios, to be handled later with Excel.

- Choosing the right options, the tool generates automatically graphic information of the frequency and the power produced by all the coupled generators.

A. *Tool features*

These are the tool meaningful features:

- The tool allows to incorporate easily the dead bands of all the power-frequency governors, as well as the inertia emulation. The dead bands modelling is a very important matter to be taken into account in isolated systems with high frequency variations, due to its great impact and effect in the primary regulation delay.

- It allows to control all the simulation parameters and the criteria to stop the simulation based on both the frequency and the derivative of the frequency respect to time.

- When the tool is run as an Excel macro, it allows to choose between three levels of information:

  o At a first level, the tool generates a comprehensive report with the parameters of the simulation for all the selected scenarios (frequencies, maximum and minimum frequency gradient, occurrence times, etc.).

  o At a second level, a graphic with the frequency evolution of the selected scenario is generated, as shown is Fig. 2. Additionally, the tool generates a table with all the information, for each integration step, regarding the value and gradient of the frequency, the unbalance, the total primary power and the emulated inertial response injected to the system, the demand damping, etc. If more than one scenario had been chosen, this information is only generated for the last scenario.
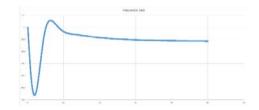

Figure 2. Temporal evolution of the system frequency

  o At a third level, the tool generates a graphic with the active power evolution of each coupled generator, as shown is Fig. 3. Additionally, for each coupled generator, the tool generates a table with all the information, for each integration step, regarding the mechanical power, the primary power and the emulated inertial response injected to the system. If more than one scenario had been chosen, this information is only generated for the last scenario.
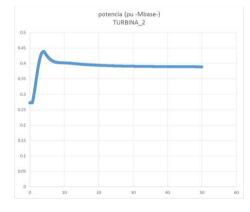

Figure 3. Temporal evolution of the mechanical power of one generator

- The Excel flexibility allows to automate the massive preparation of different scenarios, which can be sequentially and quickly analyzed. Simulation rates

up to 250 simulations per minute (Processor Intel Core i5-4300U, 1.90 – 2.50 GHz, 8.00 GB RAM) are achieved in an electrical system such as Gran Canaria (~ 600 MW peak demand), simulating up to the first extreme of the frequency excursion (which represents the most critical situation from the point of view of the frequency stability).

- The following types of contingencies can be defined:

  o Generation tripping, instantly or as a ramp (ramps are useful for wind or photovoltaic power variations).

  o Pumps tripping.

  o Demand variations, instantly or as a ramp.

- For the same simulation, any combination of the defined contingencies, in different times defined by the user, can be applied.

- It is able to model:

  o Generators based on renewable sources (power electronics) including, optionally, power-frequency regulation and inertia emulation.

  o Synchronous compensators, motors and reversible power plants: either hydroelectric with pumping or energy storage systems (ESS) as batteries, ultracapacitors, fly-wheels, etc.

  o Frequency and/or rate of change of frequency (RoCoF) protections of the modelled equipment including load shedding steps.

- It is able to model, for generators and pumps, the frequency and the derivative of the frequency protections, with their logic relation between them.

- It is able to model under frequency and derivative of the frequency load shedding.

- Taking advantage of the possibility of incorporating user models to the tool, a governor-turbine model (TurbineGov) for a hydroelectric power plant has been developed (Fig. 4).
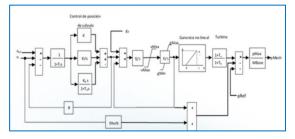

Figure 4.   Block diagram of "TurbineGov" model

- The user models parameters are incorporated in the Excel sheet instead of in the source code. This way, is easier for the user to change the parameters if it is needed.

- It is possible to consider the synchronous generators performing as synchronous compensators:

  o Without power-frequency regulation

  o With power-frequency regulation from an under frequency threshold with a certain timing:

    • This option is only available by means of an user model.

    • The TurbineGov model has been modified to incorporate this option.

B. Structural data integration

Structural and dynamic generators data are easily included in a sorted way within an Excel sheet using a predefined format for "aDin". This sheet includes also the under frequency and derivative of the frequency relays, both instant and timing.

Likewise, the load shedding data is given in another Excel sheet, being able to include as many under frequency and derivative of the frequency steps as the user requires.

C. Simulation parameters setting

The simulation parameters are easily included in a sorted way within an Excel sheet using a predefined format for "aDin" (Fig. 5).

	A	B
1	Damping demand coefficient (pu system demand)	1
2	Minimum frequency (pu 50 Hz)	47.5
3	Maximum frequency (pu 50 Hz)	52
4	Minimum frequency derivative (Hz/s)	-10
5	Maximum frequency derivative (Hz/s)	4
6	Integration step (s) (less than 1/4 the smaller constant time)	0.01
7	Level of information to generate (only from macro)	3
8	Stop with the first change of sign of df/dt	0
9	Apply load shedding	1
10	Apply generators relays performance	1
11	Maximum simulation time (s)	30
12	Time constant of the filter of the synthetic inertia (s)	0.1
13	Breakers opening time (s)	0.05

Figure 5.   Excel sheet with the simulation parameters setting

IV.   THE EXPERIENCE WITH "ADIN": THE ISOLATED SYSTEMS USE CASE

As stated throughout this paper, one of "aDin" main features is the capability to speed up dynamic simulations in the systems stability scope, simulations that have been traditionally slow, due to heavy computation requirements and the use of conventional software.

This capability allows to open transient stability analysis to a broader set of studies, specifically to those who intend to evaluate system stability over a wide range of possible scenarios. Is in this scope where "aDin" has been revealed as an extremely valuable tool.

This section highlights some of the use cases where Red Eléctrica has used "aDin" as a fast-track transient analysis tool.

A. Determination of stability requirements at Gran Canaria system in a future scenario with pumped hydro storage

The Gran Canaria Island, together with the rest of the Canary archipelago, is experiencing an important momentum

regarding RES development. In this context, a pumped storage hydro plant (PSHP) is being projected [3], in order to enable large renewable penetration expected in the coming years.

The generation mix will therefore change substantially, not only in terms of an increase in nonsynchronous generators, but having new synchronous hydro power units from the new pumped storage hydro plant.

In order to come up with an operation strategy for the overall Gran Canaria system in general, and for the PSHP facility in particular, a wide set of possible generation scenarios has been assessed. This assessment, from the transient stability point of view, has been performed using "aDin", as it allows to perform analysis over a large set of scenarios within a reasonable timeframe.

To use "aDin" for the intended purpose, several steps must be faced, namely: the modelling of system units, the definition of critical contingencies and the determination of the set of scenarios to put under test.

The generation modelling process, which comprised the characterization of both, the current units in operation and the future PSHP units, concluded with a validation process against similar simulations carried out with PSS/E. Fig. 6 shows sample results.

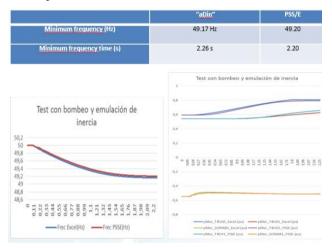|	"aDin"	PSS/E
Minimum frequency (Hz)	49.17 Hz	49.20
Minimum frequency time (s)	2.26 s	2.20

Figure 6.   Validation of "aDin" results vs PSS/E

Regarding the contingencies to be evaluated, the worst case scenario was considered to be the loss of the biggest connected unit, thermal or hydraulic, in terms of actual power generation. This severe contingency has been simulated for each of the defined test scenarios.

The set of scenarios itself comprises 8760 individual test cases, obtained by a combination of a unit commitment/economic dispatch algorithm, a tentative hydro plant operation strategy, and an estimation on wind and solar power production derived from historical data.

The fast analysis capabilities of "aDin" allowed to cover simulations on such a large data set in a relative short period of time, if we compare it with the cost of performing a similar analysis using conventional software.

As a result, several conclusions were found, being the most important ones those related to the minimum synchronous must-run units needed to keep security of supply in future large RES penetration scenarios.

B. Analysis of minimum inertial requirements in El Hierro system

The island of El Hierro supplies part of its demand out of a unique power plant - a wind park linked to a pumped hydro storage system. The wind power is fed in when available. In times of oversupply water is moved to an upper reservoir used for storage in order to be used to generate electricity on demand [4].

In order to maximize renewable integration in El Hierro while keeping security of supply, it is critical to find out the minimum synchronous inertial response needed to overcome the most severe wind power ramps. Once those ramps where identified, "aDin" tool was used to simulate those contingencies against a specific set of scenarios. The scenarios, created by an ad hoc Excel tool, cover a wide range of synchronous generation schedules (comprising both diesel units and hydro turbines), wind power production and demand levels. The complete set adds up to over 2000 test cases ready to be evaluated.

Fig. 7 shows a visual representation of the total set of evaluated scenarios, classified by different criteria.
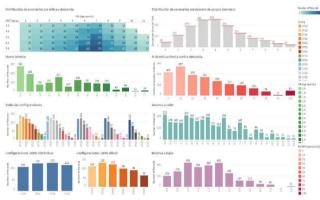

Figure 7.   Set of test scenarios classified by different criteria

As a previous step to perform the transient stability analysis, it is mandatory to model the generation units in "aDin", together with the frequency and RoCoF protections and the defined load shedding plan. A preliminary modelling task was therefore faced, were both thermal and hydro units were modelled and validated, through the comparison between simulated results and real events recorded at the system.

The use of "aDin" as the stability simulation tool for this study allowed to perform the transient stability analysis of the whole test set within a few hours. As a result, a better knowledge on minimum inertial requirements for several common scenarios was gathered.

Furthermore, the speed of the overall process allowed to repeat the analysis several times, putting under test additional sets of scenarios, which lead to results that add to the preliminary conclusions.

Results obtained were used as a valuable input to the redefinition of the operation strategy at El Hierro Island, allowing to increase RES penetration while keeping system parameters within security margins.

V.   CONCLUSIONS

The "aDin" tool has been designed to perform fast dynamic simulations in the frequency stability scope in isolated systems in ordinary office software. It is aimed to be used without any dedicated, technical and specialized software for dynamic simulation. Therefore it has been implemented as an Excel function. It is an easy-to-use tool which allows to obtain a huge number of results for several scenarios and hypothesis in a very short time.

The computation speed allows "aDin" to be used as:

- A simple Dynamic Stability Assessment (DSA) by the control center in real time.

- As an analyzer of the unit commitment outputs in order to validate them in the frequency stability scope.

- As a system planning tool: massive analysis of planning scenarios.

- Synchronous must-run identification.

- Disturbance analysis with large frequency excursion and load shedding.

The tool makes it easy to control the simulation parameters and the dynamic admissibility criteria. It allows the execution in Excel macro mode providing full graphical reports and tables of the frequency and power evolution of every connected generator to the system.

If programmable user modules are not used, the tool is able to simulate 250 scenarios per minute (Processor Intel Core i5-4300U, 1.90 – 2.50 GHz, 8.00 GB RAM). In addition, the tool achieves valid results from the point of view of system security.

ACKNOWLEDGMENT

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