ATTEST

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T4.4

Tool for Ancillary Services Procurement in Day-Ahead Operation Planning of Transmission Networks

D4.5

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AUTHOR(S)	Mohammad Iman Alizadeh, Florin Capitanescu
OFFICIAL REVIEWER(S)	Filipe Joel Soares

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Abbreviations and Acronyms

AC	Alternative Current
DC	Direct Current
DER	Distributed Energy Resources
DSO	Distribution System Operator
TSO	Transmission System Operator
ESS	Electical Energy Storage
FL	Flexible Loads
SCOPF	Security Constrained Optimal Power Flow
S-MP-L-AC-SCOPF	Stochastic Multi-Period Linear Security Constrained AC Optimal Power Flow
RES	Renewable Energy Sources

Executive Summary

This deliverable titled "Tool for ancillary services procurement in day-ahead operation planning of transmission networks" is the outcome of task T4.4 in WP4 of ATTEST project. The overarching objective of T4.4 is to develop a novel tractable tool for transmission system operators to enable them to procure ancillary services (for voltage control and congestion management) in the day-ahead operation planning of transmission systems. The tool develops a sequential linearization algorithm for solving the problem of ancillary services procurement, that is formulated as a stochastic multi-period security constrained AC optimal power flow in transmission systems. This deliverable describes in detail the functional and technical specifications of the developed tool, as well as its implementation in Julia programming language along with a user guide, which allows the potential users to successfully run the developed tool.

1. Tractable stochastic multi-period linear AC security constrained optimal power flow (S-MP-L-AC-SCOPF) tool for ancillary services procurement in day-ahead operational planning of the transmission network (Task 4.4)

To achieve a significant reduction of the Green House Gas (GHG) emissions, the European Union (EU) aims to produce most of the electricity through Renewable Energy Sources (RES). Under such a massive RES penetration, RES variability poses big technical and economic challenges to the operation and planning of future energy systems. One of the most important challenges from the operation point of view is that future energy systems will encounter different generation patterns compared to those observed in the past or to those foreseen when the system was first designed.

Power systems operate closer to their security limits and hence fulfilling N-1 security (i.e. the system is anytime capable to withstand the loss of any single equipment). This becomes a challenging task, particularly under stressed operation conditions, unexpected RES output, and/or unavailability of effective control actions. In this context, time-dependent emerging flexibility resources, such as flexible loads (FL) and energy storage systems (ESS), which are directly connected to the transmission network, and DER units present in distribution systems can play a major role in reserve procurement to support secure TSO operation planning. Possible DSO support to the TSO, and coordination between both operators at their interfaces to share the flexibility provided by distribution networks, is modeled through active/reactive power ranges of FLs.

The conventional tool to ensure cost-optimal procurement of ancillary services (e.g. for managing congestion and voltages) is the deterministic AC security-constrained optimal power flow (SCOPF). This state-of-the-art tool is mainly used in the day-ahead operation to enforce N-1 security at a given period.

Considering stochasticity of RES, ensuring N-1 security, and multi period decision making largely increase the computational burden of SCOPF, which is inherently a non-convex, non-linear problem.

Consequently, to achieve the optimal operation of transmission systems of future while considering the above-mentioned aspects, it becomes crucial to develop a tractable as well as scalable computationally efficient SCOPF tool. Task 4.4 proposes a tractable and scalable day-ahead SCOPF tool in order to procure ancillary services by taking-into-account all mentioned aspects of future transmission networks.

In the following, a high level functional and technical description, interaction with the other tools of ATTEST project, and implementation instructions of the developed tool in Julia programing language is provided along with its computational requirements.

1.1. Functional description of SLA-based S-MP-L-AC-SCOPF tool

The main objective of this tool is to enable TSOs to optimally procure ancillary services in day-ahead operation planning, specifically for voltage control and congestion management, to mitigate renewables uncertainty and ensure that the network N-1 security criterion is satisfied in day-ahead scheduling. To this aim, the developed SCOPF tool considers a set of postulated contingencies, the uncertainty of the renewables, 24-hours ahead temporal interlinks to benefit from additional flexibility provided by FL and ESS, directly connected to the transmission network, as well as flexibility from conventional generators.

The resulting SCOPF problem which involves all the above-mentioned features is a stochastic multi-period AC security constrained optimal power flow (S-MP-AC-SCOPF), the most complete and challenging uncertainty-aware and flexibility-driven SCOPF problem to date, tackled for the first time in [1]. Consequently, to break-down the high computational complexity of the resulting problem, a novel tractable methodology, based on sequential linear algorithm (SLA) model is developed which ensures the tractability as well as scalability of the resultant tool, as disseminated in [2]. The methodology combines in the best possible way (i.e. by adapting and leveraging) of the most advanced knowledge and techniques in the area of SCOPF, combining them in a unique way. The methodology achieves tractability by solving sequentially a limited number of different linear approximations of the S-MP-AC-SCOPF problem. These linear approximations differ in terms of losses approximation, carefully reduced sets of constraints or tightening of critical constraints.

The proposed tool is tested against several test cases which are developed in T2.3 as mentioned in Table 1. Further information about these test cases can be found in D2.3 (Test cases) of WP2 (Toolbox specification, support tools and test cases).

TABLE 1: TRANSMISSION NETWORK TEST CASES DEVELOPED IN T2.3

Network Type	Country	No. of networks
Transmission	*Portugal*	*7*
	UK	*2*
	Croatia	*3*

A high-level functional diagram of the developed tool is shown in Fig. 1.

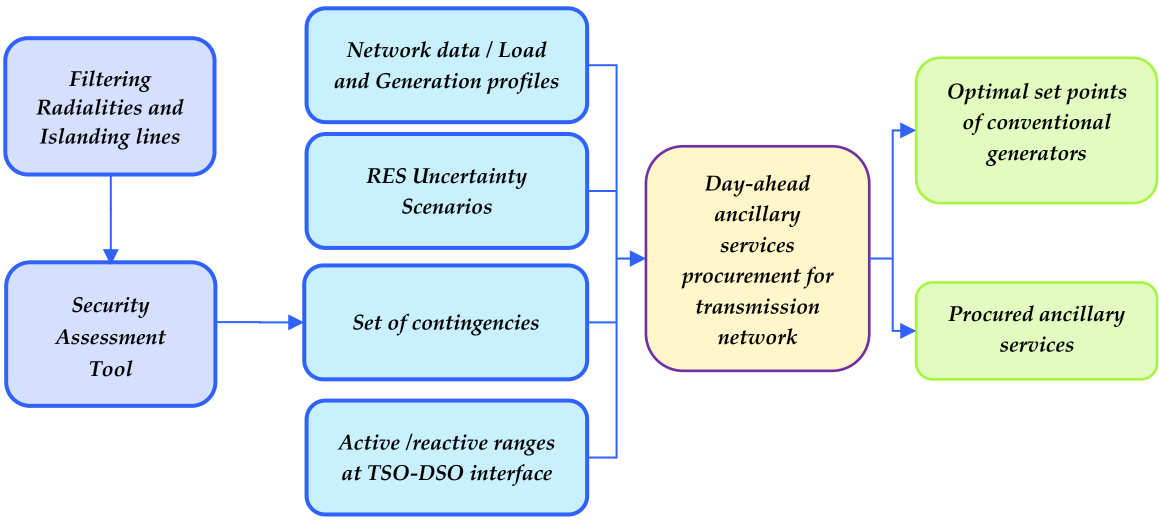

FIG. 1: HIGH LEVEL FUNCTIONAL DESCRIPTION OF TOOL 4.4

1.2. Technical description of S-MP-L-AC-SCOPF tool

The proposed tractable tool is based on two main computation modules: the S-MP-L-AC-SCOPF, which is used with three different versions to solve various instances of linear programming (LP) problems, as explained below, and an AC power flow module.

1.2.1. S-MP-L-AC-SCOPF

Eq. (1)-(28) represent the S-MP-L-AC-SCOPF formulation for procuring optimally, in day-ahead operation planning, flexibility for congestion management and voltage control such that to meet N-1 security. The problem seeks optimal set-points of all sources of flexibility, both conventional control means (generators) and flexible resources (FLs, ESSs), in every time period *t*, uncertainty scenario *s* and system state *k*.

$$\min \sum_{t\in T}\Bigg\{\pi_0\Bigg[\sum_{g\in G}\left(P^0_{G_{g,t}}-P^*_{G_{g,t}}\right)c_g+\sum_{e\in E}\left(P^{ch,0}_{e,t}+P^{dis,0}_{e,t}\right)c_e+\sum_{f\in F}\left(P^{inc,0}_{f,t}+P^{dec,0}_{f,t}\right)c_f+\sum_{n\in R}\left(Rc^0_{n,t}\right)c^{Gcurt}_n+$$

$$\sum_{n\in N}\left(Lc^0_{n,t}\right)c^{Lcurt}_n\Bigg]+\sum_{s\in S}\sum_{k\in K}\pi_{s,k}\Bigg[\sum_{g\in G}\left(P^k_{G_{g,s,t}}-P^0_{G_{g,t}}\right)c_g+\sum_{e\in E}\left(P^{ch,k}_{e,s,t}+P^{dis,k}_{e,s,t}\right)c_e+\sum_{f\in F}\left(P^{inc,k}_{f,s,t}+P^{dec,k}_{f,s,t}\right)c_f+$$

$$\sum_{n\in R}\left(Rc^k_{n,s,t}\right)c^{Gcurt}_n+\sum_{n\in N}\left(Lc^k_{n,s,t}\right)c^{Lcurt}_n\Bigg]\Bigg\} \tag{1}$$

$$\sum_{g\in G}P^k_{G_{g,s,t}}+R_{n,s,t}+\sum_{e\in E}\left(P^{dis,k}_{e,s,t}-P^{ch,k}_{e,s,t}\right)+\sum_{f\in F}\left(P^{dec,k}_{f,s,t}-P^{inc,k}_{f,s,t}\right)-Rc^k_{n,s,t}+Lc^k_{n,s,t}=P_{D_{n,t}}+P^k_{inj_{n,s,t}}\ \forall n\in N \tag{2}$$

$$\sum_{g\in G}Q^k_{G_{g,s,t}}=Q_{D_{n,t}}-Q_{c_{n,s,t}}+Q^k_{inj_{n,s,t}} \qquad \forall n\in N \tag{3}$$

$$P^k_{n,m,s,t}=g_{nn}(V^k_{n,s,t})^2+g_{nm}\frac{(V^k_{n,s,t})^2-(V^k_{m,s,t})^2}{2}-b_{nm}(\theta^k_{n,s,t}-\theta^k_{m,s,t})$$
$$+P^{L,k}_{n,m,s,t}(V^k_{n,s,t},V^k_{m,s,t},\theta^k_{n,s,t},\theta^k_{m,s,t},V^{k,0}_{n,s,t},V^{k,0}_{m,s,t},\theta^{k,0}_{n,s,t},\theta^{k,0}_{m,s,t}) \tag{4}$$

$$Q^k_{n,m,s,t}=-\left(b_{nn}+b_{sh,n}\right)(V^k_{n,s,t})^2-b_{nm}\frac{(V^k_{n,s,t})^2-(V^k_{m,s,t})^2}{2}-g_{nm}(\theta^k_{n,s,t}-\theta^k_{m,s,t})$$
$$+Q^{L,k}_{n,m,s,t}(V^k_{n,s,t},V^k_{m,s,t},\theta^k_{n,s,t},\theta^k_{m,s,t},V^{k,0}_{n,s,t},V^{k,0}_{m,s,t},\theta^{k,0}_{n,s,t},\theta^{k,0}_{m,s,t}) \tag{5}$$

$$P^k_{n,m,s,t}+\tan(\pi/6)Q^k_{n,m,s,t}\le(1-\beta^k_{mn,s,t})S^{\max}_{nm} \tag{6}$$

$$P^k_{n,m,s,t}-\tan(\pi/6)Q^k_{n,m,s,t}\le(1-\beta^k_{mn,s,t})S^{\max}_{nm} \tag{7}$$

$$P^k_{n,m,s,t}+\tan(\pi/6)Q^k_{n,m,s,t}\ge(\beta^k_{mn,s,t}-1)S^{\max}_{nm} \tag{8}$$

$$P^k_{n,m,s,t}-\tan(\pi/6)Q^k_{n,m,s,t}\ge(\beta^k_{mn,s,t}-1)S^{\max}_{nm} \tag{9}$$

$$\underline{P}_g\le P^k_{G_{g,s,t}}\le\overline{P}_g \qquad \forall g\in G \tag{10}$$

$$\underline{Q}_g\le Q^k_{G_{g,s,t}}\le\overline{Q}_g \qquad \forall g\in G \tag{11}$$

$$\underline{V}_n\le V^k_{n,s,t}\le\overline{V}_n \qquad \forall n\in N_G \tag{12}$$

$$\underline{V}_n\le V^k_{n,s,t}\le\overline{V}_n \qquad \forall n\in N\setminus N_G \tag{13}$$

$$\theta^k_{n,s,t}=0 \qquad \forall\ n=slack \tag{14}$$

$$\left|P^0_{G_{g,s,t-1}}-P^0_{G_{g,s,t}}\right|\le\Delta P_{G_g} \quad \forall g\in G \tag{15}$$

$$\left|P^k_{G_{g,s,t}}-P^0_{G_{g,s,t}}\right|\le\Delta P_{G_g} \qquad \forall g\in G,k\neq 0 \tag{16}$$

$$SoC^k_{e,s,t+1}=SoC^k_{e,s,t}+\Delta T\left(\eta^{ch,e}P^{ch,k}_{e,s,t}-P^{dis,k}_{e,s,t}/\eta^{dis,e}\right) \qquad \forall e\in E \tag{17}$$

$$SoC^{\min}_e\le SoC^k_{e,s,t}\le SoC^{\max}_e \qquad \forall e\in E \tag{18}$$

$$SoC^k_{e,s,T}=SoC^k_{e,s,0},\forall e\in E \tag{19}$$

$$0\le P^{ch,k}_{e,s,t}\le\overline{P}^{ch}_e,\forall e\in E \tag{20}$$

$$0\le P^{dis,k}_{e,s,t}\le\overline{P}^{dis}_e,\forall e\in E \tag{21}$$

$$\frac{P^{ch,k}_{e,s,t}}{\overline{P}^{ch}_e}+\frac{P^{dis,k}_{e,s,t}}{\overline{P}^{dis}_e}\le 1,\forall e\in E \tag{22}$$

$$\sum_{t\in T}P^{inc,k}_{f,s,t}=\sum_{t\in T}P^{dec,k}_{f,s,t},\forall f\in F \tag{23}$$

$$0\le P^{inc,k}_{f,s,t}\le\overline{P}^{inc}_f,\forall f\in F \tag{24}$$

$$0\le P^{dec,k}_{f,s,t}\le\overline{P}^{dec}_f,\forall f\in F \tag{25}$$

$$\frac{P^{dec,k}_{f,s,t}}{\overline{P}^{dec}_f}+\frac{P^{inc,k}_{f,s,t}}{\overline{P}^{inc}_f}\le 1,\forall f\in F \tag{26}$$

$$0\le Lc^k_{n,s,t}\le\ P_{D_{n,t}},\forall n\in N \tag{27}$$

$$0\le Rc^k_{n,s,t}\le\ R_{n,s,t},\forall n\in N \tag{28}$$

The objective (1) minimizes the expected cost of flexibility procurement for ancillary services (congestion and voltage control) in transmission grid operation, including normal operation and contingency states. The costs in normal and post contingency states pertain to the re-dispatch, with respect to the values cleared in day-ahead energy market, of conventional generators, ESSs, FLs, RES curtailment, and load curtailment (primarily to prevent numerical divergence for infeasible problems). k = 0 and k ≥ 1 indicate normal operation and contingency states, respectively. For the sake of space (to avoid duplication of almost similar constraints), the difference between here and now and wait and see decisions is not shown explicitly.

Constraints (2) and (3) express active and reactive power balance equations (for each node n, scenario s, time t and state k), which rely on active/reactive power flows defined in (4) and (5) where $P_{n,m,s,t}^{L,k}/Q_{n,m,s,t}^{L,k}$ denote the active/reactive power losses, which are linear approximations based on $((V_{n,s,t}^{k})^2, \theta_{n,s,t}^{k})$ variable space. The detailed formulas can be found in [3].

Constraints (6)-(9) represent the approximated linear version of hard physical limits on active and reactive powers of generator *g*. Soft operation constraints such as thermal and voltage limits are modelled by constraints (10) and (11). Eq. (12) and (13) impose limits on node voltage magnitude for nodes with and without generators respectively. Eq. (14) sets the voltage angle at the reference (slack) bus.

Eq. (15) expresses the ramp limit of generator *g* between two successive time intervals in normal operation. Eq. (16) is the active power coupling constraint of generator *g* between normal operation and post-contingency states.

The ESSs operation is modeled by the set of constraints proposed in [1]. Eq. (17) describes the dynamics of the State of- Charge (SoC), (18) is the SoC limit for each ESS, (19) maintains the SoC of ESS equal on first and last time periods, (20) and (21) are limits on ESS' active power charging and discharging in each period, and (22) prevents the simultaneous charging and discharging of storage e for each period. Note that (22) is a tractable exact approximation, to avoid introducing binary variables to model the charging and discharging statuses of an ESS.

The FLs operation is captured by the following set of constraints. Eq. (23) maintains the energy balance of a FL over whole time horizon, (24) and (25) are the limits on the increase and decrease of active power of a FL, respectively. Eq. (26) prevents simultaneous increase and decrease in the active power of a FL in each period. Observe that (23) uses the same assumption and approximation as for ESSs in (22). Lastly, (27) and (28) restricts the load and RES curtailments, respectively.

1.2.2. The Stages of the Proposed Tractable Methodology

The outline of the proposed tractable solution methodology is illustrated in Fig. 2.

1.2.2.1. Stage 1

The first linear approximation version of S-MP-AC-SCOPF problem is solved in a form of a lossless S-MP-LSCOPF. Specifically the problem formulation contains (1)-(12),(14)-(28). The main rationale of this stage is to obtain a good approximation of active power flows, which in general can be well approximated using a DC model. Then, after many experiments, we opt for starting with a problem which neglects the state dependent loss terms in Eq. (4) and (5), since these can change significantly between the initial point and the (unknown beforehand) optimum. To enhance the computational tractability of this first rough approximated model voltage limits at non-generator nodes are removed at this stage, as in (12), for each combination of scenarios, time, and operation states (*s*, *t*, *k*) (i.e. both normal and post contingency operation states) and the optimization looks first to remove congestion. Incidentally, this results in computation gain in systems where voltage issues are usually not present.

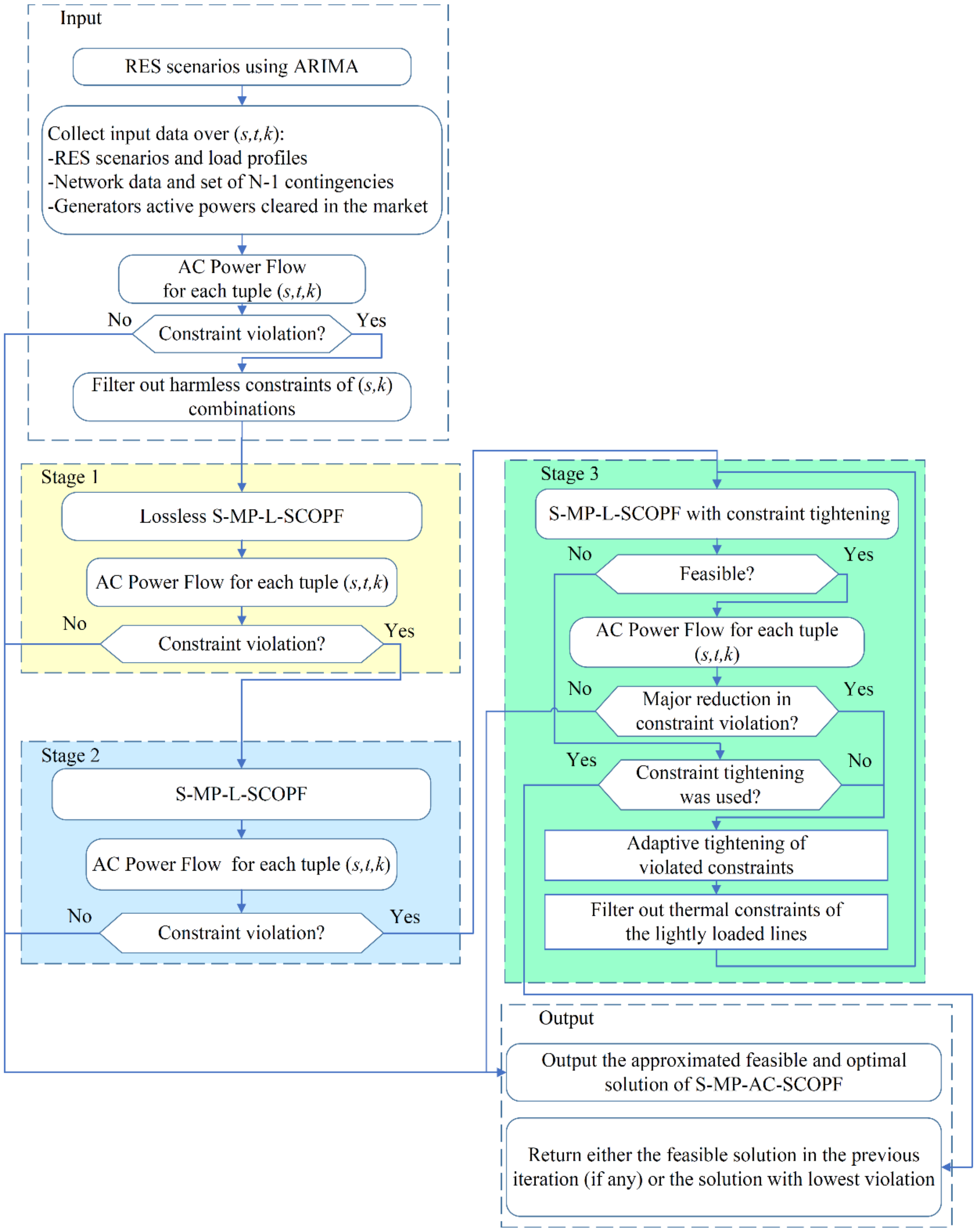

FIG. 2 THE PROPOSED TRACTABLE METHODOLOGY TO SOLVE S-MP-AC-SCOPF

The obtained solution feds an AC power flow module. If no violation is observed, the methodology terminates. Otherwise, this module computed as a by-product the power losses terms $P^{L,k}_{n,m,s,t}/Q^{L,k}_{n,m,s,t}$. As the AC power flow calculation for each element of the combination (*s*, *t*, *k*) is independent, parallel computation can dramatically reduce the computation time.

1.2.2.2. Stage 2

Using the first estimation of power losses, the second linear approximated version of the S-MP-AC-SCOPF is solved, i.e. the problem consisting of the following set of equations (1)-(28) fed with the calculated initial points out of stage 1. The key rationale of this stage is to make a first approximation of reactive power flows and voltages, based upon the good approximation of active power flows (further refined in this stage) and losses out of the AC power flow at stage 1. In this optimization, unlike the previous iteration, the mentioned refinement is achievable resort to no voltage relaxation to improve solution accuracy. As such, the optimization computes a solution that attempts to further relieve congestion and voltage violations.

The obtained solution is lugged in an AC power flow module. If no violation is detected, the methodology terminates. Otherwise, this module re-calculates the power losses.

1.2.2.3. Stage 3

Using an enhanced estimation of power losses as well as tightening the original limits only of violated constraints (i.e. voltage magnitude constraints and line flow constraints), the third linear approximation of the S-MP-ACSCOPF problem is solved, using the same problem formulation from the previous stage. The rationale of this stage is to further refine the approximation of all problem variables and constraints from the previous stage by resorting to constraint tightening.

Furthermore, to improve computation efficiency without jeopardizing the accuracy, only the thermal constraints of those lines loaded above a specific percentage (i.e. 70%, which was calibrated after performing numerous trials) are modelled in the problem for each element of the combination (s, t, k). This is done based on the assumption that lines with large spare capacity will highly likely not be binding at the optimum. Consequently, removing these constraints will significantly improve the computational tractability. Input and output requirements The input and output data of developed S-MP-MILP based OPF tool is as follows.

The obtained solution is verified again by the AC power flow module. If no violation is detected, the methodology terminates. Otherwise, the steps of this stage are repeated again, with more refined estimation of losses and constraints tightening, until either the problem becomes feasible (i.e. all constraints are satisfied) or no further reduction of constraints violations is obtained with respect to the previous values.

1.3. Input and output requirements

This section briefly introduces the input and output of the developed S-MP-L-AC-SCOPF model as follows.

1.3.1. Input data

The input data of this tool is:

- i) Test cases which are developed in T2.3 (Test cases) of WP2. The test cases provide the necessary network data such as information related to network buses, lines, loads, transformers and generation units.
- ii) Set of postulated contingencies.
- iii) Set of renewables uncertainty scenarios.
- iv) Active and reactive power ranges as additional demand side sources of ancillary service provided by DSO at the TSO-DSO interface, which are modeled as FLs.

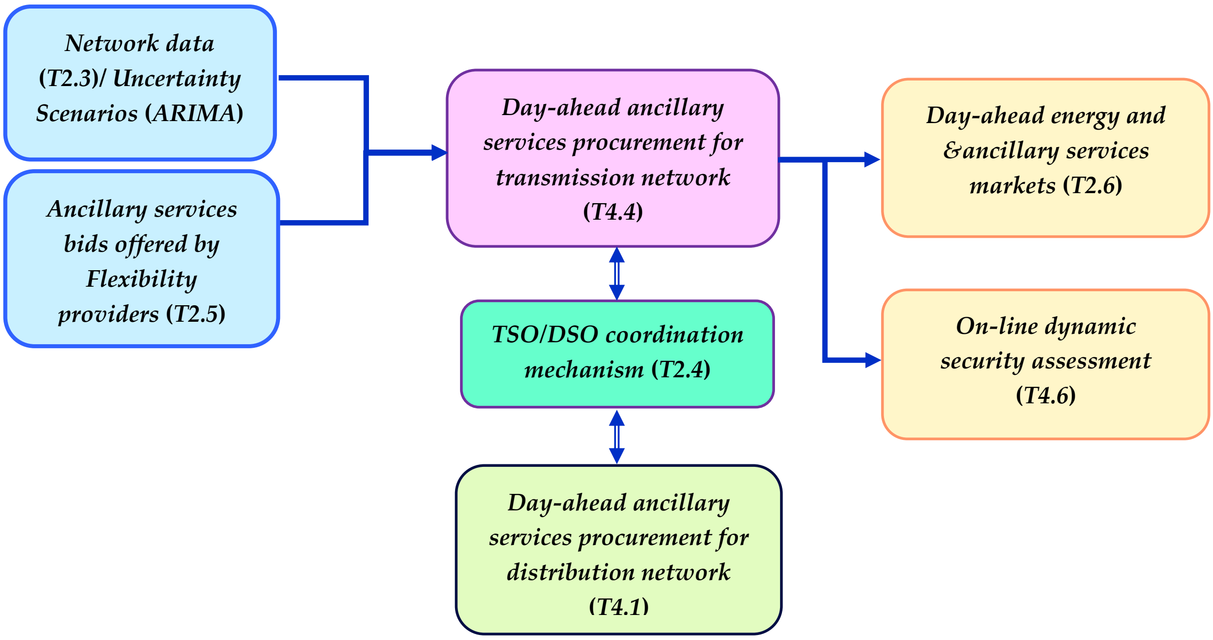

FIG. 3: INTERACTION WITH OTHER TOOLS

1.3.2. Output data

The output data of this tool is:

i) Expected ancillary service procurement cost of FLs, ESSs and redispatch of conventional generators
ii) Optimal set-points for each time period of the active and reactive power of: generators, FLs (i.e., optimal values of active and reactive power flow at the TSO-DSO interfaces), and ESSs.

1.4. Computational requirements

The developed tool is programmed in Julia under Windows platform with JuMP being used as a modelling layer and CPLEX as internal linear solver. CPLEX uses barrier method as the solution algorithm with different attributes such as benefiting pre-solve technique, CPX_PARAM_LPMETHOD, CPX_PARAM_SOLUTIONTYPE, and CPX_PARAM_BARORDER to respectively select the solution algorithm supporting barrier method, specify the type of solution (basic or non-basic) that CPLEX attempts to compute for a linear program (LP), and set the algorithm to be used to permute the rows of the constraint matrix in order to reduce fill in the Cholesky factor.

1.5. Interaction with other tools

The overall interaction of the current task 4.4 with other tools is illustrated in Fig. 3.

The input data of this task (T4.4) are the test cases developed in T2.3. This tool incorporates as input the ranges of FLs provided by the tool developed for DSO in T4.1, mimicking the TSO/DSO coordination.

The tool provides the information about buying bids for transmission network ancillary services for day-ahead energy and & ancillary services markets (T2.6).

A specific, i.e. deterministic single period AC SCOPF, version of the tool developed in T4.4 is integrated with task 4.6 tool for on-line dynamic security assessment to guarantee that real-time dispatch solutions meet the necessary volume of inertia (synthetic or synchronous) capable of limiting the rate of change of frequency (RoCoF) as well as the minimum primary frequency control power reserve that must be available to cope with postulated contingencies.

1.6. Implementation of S-MP-L-AC-SCOPF in Julia (User guide)

1.6.1.Tool components description

The developed tool package in the Julia programing language includes the following folders:

- data_conversion
- data_preparation
- functions
- input_data
- output_data
- repos

and the main code executer file named as "**main.jl**". Table summarizes the description of each file in the above-mentioned folders:

TABLE 2: DESCRIPTION OF FILES/FOLDERS/FUNCTIONS

Folder	File	Function	name	Description
			data_conversion	
■			HR	Includes both the .m and the .ods format of the Croatian test cases.
■			UK_v2	Includes both the .m and the .ods format of the UK test cases.
■			PT	Includes both the .m and the .ods format of the Portuguese test cases.
	■		data_converter_PT	Although the conversion is not automated, this file automatically converts the .m to .ods format.
			data_preparation	
	■		contin_scen_arrays	Builds arrays for contingencies based on the input data in .ods format
	■		data_correction	Correct the names of the buses in ordinal numbers
	■		data_reader	Includes an auxiliary function to read data from .ods
	■		data_set_selection	Select which test case is expected to run
	■		data_types	Build the mutable structures for the input data.
	■		data_types_contingencies	Construct contingencies
	■		interface_excel	Read the input test case data from .ods file
	■		node_data_func	Takes the nodes/buses information as an input and restructure the data into '**node_data**' and '**node_data_contin**' structures
	■		PROF_correction	Applies the correction on ordinal naming of buses in the '**_PROF**' data files.

Functions				
			AC_SCOPF_functions	Includes all function wise formulation of AC-SCOPF
			network_topology_functions	Includes all functions to define network topology in normal and post contingency states
			PF_functions_c	Includes all functions for power flow in contingency states
			PF_functions_common	Includes all common functions between normal and post contingency states
			PF_fucnrions_n	Includes all functions for power flow in normal operation
			tractable_SCOPF_functions	Includes all functions required for the tractable SCOPF problem
			DC_SCOPF	Function which implements the S-MP-L-AC-SCOPF. It takes respectively, the name of the model in string, the number of iteration, lossy/lossless version, highly loaded lines indicator, and constraint tightening indicator, the last three in 0/1 values.
input_data				
			scenario_gen	Reads the RES uncertainty data from '**scenario_gen.ods**' file
			'test case'.ods	The converted input data in .ods
			'test case'_PROF.ods	The converted additional data in .ods. The time periods, number of scenarios, contingencies, load bias coefficient and thermal limit coefficients are the main elements in these files
Output_data				
			'test case'_Costs.ods	Retrieves the values of different costs in post contingency state.
			'test case'_Normal.ods	Retrieves the values of decision and control variables for the normal operation state
			'test case'_OPF.ods	Retrieves all the values of decision and control variables after OPF model is solved
			'test case'_PContin_ActiveP.ods	Retrieves the values of the active power for each element of the (s,t,k) combination.
			'test case'_PContin_FL_dec.ods	Retrieves the values of the increasing FL

				active power for each element of the (s,t,k) combination.
			'test case'_PContin_FL_inc.ods	Retrieves the values of the decreasing FL active power for each element of the (s,t,k) combination.
			'test case'_PContin_LC.ods	Retrieves the values of the load curtailment for each element of the (s,t,k) combination.
			'test case'_PContin_ReactiveP.ods	Retrieves the values of the reactive power for each element of the (s,t,k) combination.
			'test case'_PContin_RES_C.ods	Retrieves the values of the RES curtailment for each element of the (s,t,k) combination.
			'test case'_PContin_STR.ods	Retrieves the values of the active charge/discharge power of each ESS for each element of the (s,t,k) combination.
repos				
			AC_OPF	Constructs the AC-OPF problem and calls the Ipopt optimizer.
			AC_SC_OPF	Constructs the AC-SCOPF problem and calls the Ipopt optimizer
			congestion_check	Finds the highly loaded (i.e. 80%) lines for each element of the (s,t,k) combination if needed.
			contin_filtering_new	Finds the radiality and islanding to construct the plausible set of contingencies.
			DC_SCOPF	Construct the proposed three stage linear approximation of S-MP-AC-SCOPF
			TRACT_SCOPF	Function which implements the three stage S-MP-L-AC-SCOPF

			network_layout	visualizes the topology of the test case if needed
			OPF_out	Generates the .xlsx output files after the AC-OPF is solved.
			remove_harmless_combinations	Before executing the DC_SCOPF removes the harmless combinations.
			SC_OPF_out	Generates the .xlsx output files after the AC-SCOPF is solved.
			Security_Assessment_tool	Execute a security assessment analysis.
main.jl				
			main	The main executable file to run the tractable tool. Before the first run, the following packages should be imported (added) JuMP, OdsIO, MathOptInterface, Dates, and LinearAlgebra

The current version of the developed tool has multiple functionalities namely:

- ✓ Contingency filtering
- ✓ Stochastic Multi-period AC Optimal Power Flow
- ✓ Stochastic Multi-period AC Security Constrained Optimal Power Flow
- ✓ Approximated Stochastic Multi-period DC security Constrained Optimal Power flow
- ✓ Security Assessment
- ✓ The above-mentioned functionalities are activated by inputs respectively from 0 (e.g. for contingency filtering) to 4 (e.g. security assessment).

The contingency filtering excludes islanding and radialities in the transmission branches.

The security assessment tool runs a simple OPF through the set of contingencies for the sake of voltage and/or load flow constraint violations.

1.6.2. Data sets

All the above problems are executable for twelve following data sets:

1) HR_Tx_01_2020_new_Koprivnica
2) HR_Tx_02_2020_new_NW_Croatia_WP4
3) HR_Tx_03_2020_new_Zagreb
4) Transmission_Network_UK_v2
5) Transmission_Network_UK_2020
6) PT_Tx_2020
7) PT_Tx_2030_Active

8) PT_Tx_2030_Slow
9) PT_Tx_2040_Active
10) PT_Tx_2040_Slow
11) PT_Tx_2050_Active
12) PT_Tx_2050_Slow

by self-explanatory inputs 1 to 12 respectively.

It is tried, in the current version, to avoid hard scalars and constraints for both data processing and optimizations. For this aim, all of the required data are accessible through input files. For each data set, two separate input files are provided in **.ods** format to be consistent with T4.1, one for extracting the data exactly as provided in T2.3 with **.m** version, and one for the additional required data such as flexible loads, energy storages, location of renewable energy sources (RES) etc. with the "**PROF**" suffix.

1.6.3. Format of outputs

The output files are provided in **.xlsx** format. For the AC-OPF all the results are gathered in a single file with different sheets for different optimal set points of the decision variables. However, for the AC-SCOPF and the approximated DC-SCOPF multiple Excel files (**.xlsx**) will be generated with the name of the data sets in the beginning and the included variable at the end when the problem is solved. This is an example of the output for two SCOPF problems:

- PT_Tx_2020_Costs
- PT_Tx_2020_Normal
- PT_Tx_2020_PContin_LC
- PT_Tx_2020_PContin_RES_C
- PT_Tx_2020_PContin_STR
- PT_Tx_2020_PContin_FL_dec
- PT_Tx_2020_PContin_FL_inc
- PT_Tx_2020_PContin_ActiveP
- PT_Tx_2020_PContin_ReactiveP

For instance, **LC** stands for load curtailment, and "**Normal**" includes all results regarding the normal state operation. The reset are self-explanatory. Since the results for the stochastic multi-period AC/DC SCOPF are multi dimensional (i.e. a combination of contingency, scenario, and time), multiple sheets in each Excel files are dedicated to a decision variable. For instance, the sequence of sheets are named for "PT_Tx_2020_PContin_ActiveP" as follows:

- Active_power_Contin_1_Scen_1
- Active_power_Contin_2_Scen_1
- Active_power_Contin_1_Scen_2
- Active_power_Contin_2_Scen_2

for a system with 2 contingencies and 2 RES scenarios.

1.6.4.General notes

- ✓ The tool is capable to correct the sequence inconsistency of the bus numbers and will regenerate all input **ods** sheets with the new data.
- ✓ The tool is capable to control the time horizon, the number of scenarios, changing the magnitude of the load profile, RES profile and changing the thermal limits of the transmission lines.
- ✓ The results are provided in p.u.
- ✓ The load profiles were missing for the following data sets. Thus, "PT_Tx_2030_Active_PROF" is adopted for them.
  - PT_Tx_2040_Active
  - PT_Tx_2040_Slow
  - PT_Tx_2050_Active
  - PT_Tx_2050_Slow
- ✓ The UK data set "Transmission_Network_UK_2020" includes many generators with zero costs. Accordingly, the objective value for this test case is almost zero.
- ✓ The tool will terminate before two AC/DC SCOPF problem if the first screening returns no harmful contingency-scenario combination.
- ✓ Since the tool will automatically remove the parallel lines and transformers and pile up multiple generators or loads in a single node before running the optimization problem, the results are return based on the diminished sets.
- ✓ The contingency in a parallel (or multiple) line is modelled as a connected line but with a single line characteristic (i.e. admittance and thermal limit). Contingency in a single line on the other hand equals removing that line.
- ✓ The status of the generators and lines is ignored, implying that all the components are supposed to be connected.
- ✓ The output for storages equals "charging-discharging" to avoid two different files for each "charging" and "discharging".
- ✓ The negative Pmin are substituted with zero for more coherency.
- ✓ It is noted that a sub-set (and not all) of plausible contingencies are added to the "_PROF" input files.

2. Bibliography

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