SECURITY ASSESSMENT OF INTERCONNECTED SYSTEMS HAVING LARGE WIND POWER PRODUCTIONS

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Summary – This paper presents a new methodology to assess security of interconnected systems that have a large penetration of wind power production, through the evaluation of the impacts in the transmission lines of one control area following a sudden loss of wind power production. This approach exploits functional knowledge generated off-line and artificial neural networks to provide a way for fast evaluation of the security degree.

Keywords: Wind Generation, Dynamic Behavior, Security Assessment, Interconnected Systems

1 INTRODUCTION

The need to decrease CO_2 emissions is leading to an increase of the penetration of wind power and other renewable Dispersed Generation (DG) technologies in the power system generation mix. At the same time, the number of cross border power transactions is increasing due to an electricity market liberalization trend. The conjunction of these two facts creates an increased use of the interconnection and main transmission lines that may lead to very stressed operating conditions. In fact, the presence of large shares of wind power production, characterized by an intermittent nature and limited predictability may provoke an increase in deviations of power flows in tie lines regarding programmed flow exchanges among control areas. Changes in wind power production may also result from a sudden disconnection of a large number of wind generators as well as other DG units in one area, due to the triggering of their protection relays following grid disturbances. Although Automatic Generation Control (AGC) takes care of interchange power flow deviations, it will take some time to eliminate them, leading to quasi-steady-state overloads in main transmission lines, which may provoke a set of undesired cascading events like load curtailment or even system collapse.

Transmission System Operators (TSO) have been defining the levels of acceptance of wind generation and other DG on the basis of deterministic (n-1) steady-state security studies for worst case scenarios. More recently TSO have started conducting also dynamic behavior and stability analysis studies following grid disturbances and subsequent operation of DG protection relays. Again these studies have been conducted for worst case scenarios, leading to severe limitations on system wind generation integration. Therefore, in order to increase

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wind penetration, interconnected systems with large wind power production require a close system security assessment, through the prediction of electrical current flows in main transmission lines after the occurrence of system disturbances or changes in wind power production. Such prediction (for current or alternative operating conditions) requires full dynamic simulations of the interconnected system, including AGC operation, which is incompatible namely with the management of secondary reserves time frame requirements. This means that dynamic security assessment becomes a key functionality for such TSO dispatching centers, requiring new tools able to provide a fast and accurate forecast of interconnected systems security.

For this purpose an Artificial Neural Network (ANN) based approach was designed to emulate in a very fast way a set of security indices, characterizing the level of security of an interconnected system, following a disturbance that provokes the disconnection of a large share of wind power and other DG generation. In order to gather enough information about interconnected power systems behavior, an algorithm able to generate operating conditions in a two area control interconnected system was developed. This includes a full dynamic simulation stage where system behavior is computed and the variables of interest are kept in a knowledge data set to be further used for the ANN design.

This paper describes the first stages of the approach developed so far and its application to a two area control test system.

2 POWER SYSTEM MODELING

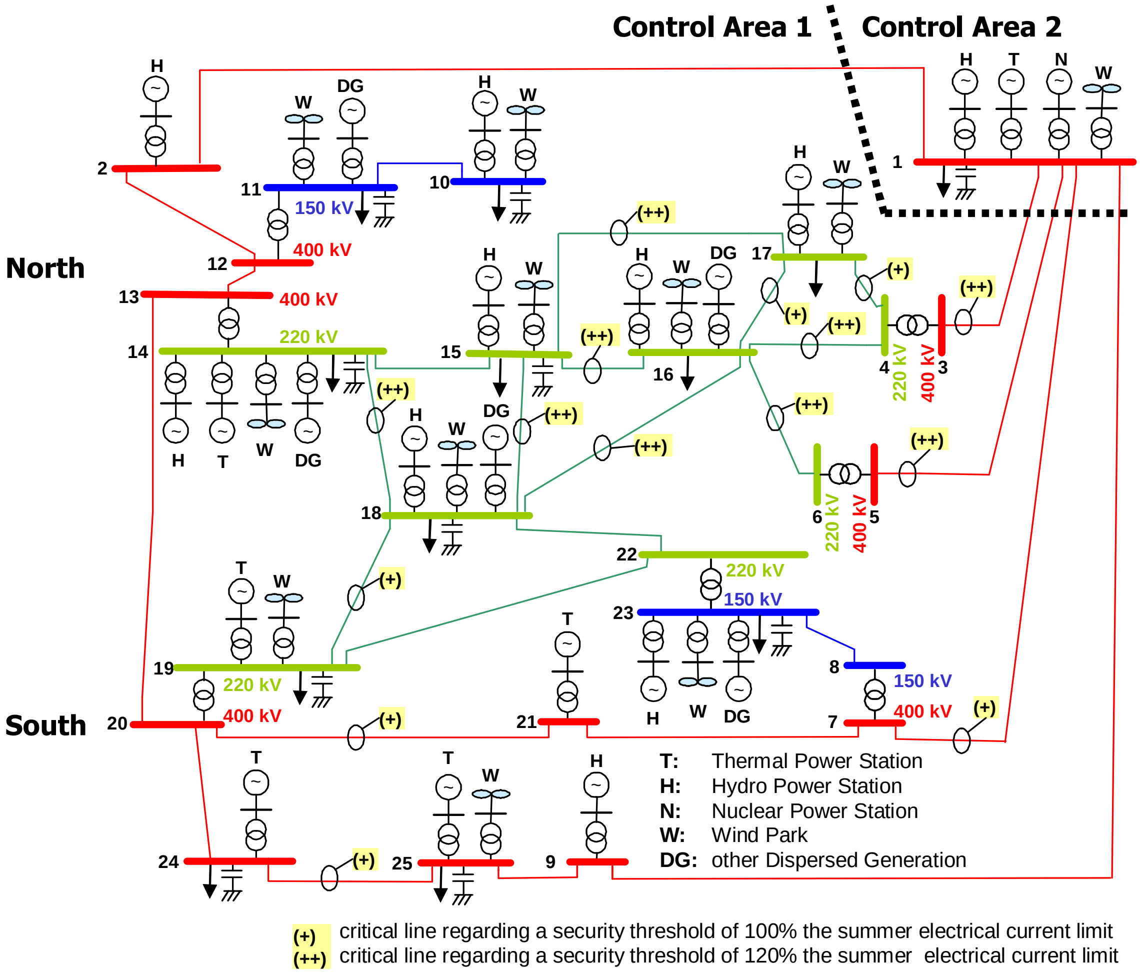

Fig. 1. Single-line diagram of the interconnected transmission system

In this research, a test system was created based on the Portuguese – Spanish interconnected system, meaning that two control areas were considered. The single-line diagram of the test system is presented in Fig. 1. Control area 1 presents one approximation to the Portuguese transmission system, and control area 2 represents an equivalent of the Spanish/European system. In order to reduce the power system dimension, without losing relevant information, all the generating units of control area 1 are equivalent machines modeling similar generators operating in parallel in the same power plant. Regarding that this research was focused on the security of control area 1, the neighboring system was modeled by one busbar with equivalent generation units.

In each control area, thermal (T), hydro (H) and wind (W) generating units were considered. In control area 2, nuclear (N) units were considered as must run units and not participating in secondary frequency control. A set of other DG power plants, considered in area 1, are related with mini-hydro and cogeneration units, which do not participate in frequency control. All the large hydro and thermal units were considered to participate in primary and secondary frequency control.

In order to obtain the dynamic behavior of thermal, hydro and nuclear units, the usual corresponding local frequency regulator models as described in [1] were used, including also the voltage regulator behavior adopting an IEEE1 model type. Wind generators were modeled by a classical asynchronous machine model. The other DG units were modeled as synchronous generators with voltage regulator and constant mechanical power.

The AGC system AGC response is also modeled, where the traditional integral control approach was used, adopting the configuration described in [2]. According to this configuration, besides keeping the system frequency and interchange power between control areas in the specified value, changes in power production are distributed among generators through participation factors in order to maintain generating units at the most economic operating conditions. In the adopted model, participation factors were calculated considering that thermal production cost is 10 times the hydro power production cost. A time frame of 2 seconds was considered for AGC operation [1]. For all the remaining parameters of the power system dynamic model, typical values were considered, and were extracted from the full Portuguese - Spanish interconnected system.

3 DATA SET GENERATION

In the research presented in this paper, a general Data Set (DS) generation methodology was developed, in order to gather knowledge about the dynamic behavior of two interconnected power systems regarding a pre-defined disturbance. In this procedure, a structured Monte Carlo sampling method [3] was applied, because it provides a well distributed and highly resolved DS throughout a pre-defined operating range. In fact, security assessment techniques based on automatic learning demand a DS enclosing enough functional knowledge. However, although trying to cover all possible operating conditions of the power system, several operating restrictions were mandatory to be considered in order to filter out unrealistic scenarios, and therefore decrease computational time without compromising the knowledge data quality. Besides, this also avoids power flow convergence problems, in face of unfeasible conditions.

The developed automatic procedure consists of the following main steps:

- Structured Monte Carlo Sampling: Based on typical operating conditions, a sampling method is applied in order to produce several realistic operating scenarios of the system, characterized by different settings of: system load level, wind power production levels, other DG production levels, and import/export levels. These conditions were defined regarding their potential influence on the interconnected system dynamic security. Based on available statistical data about wind power production of the Portuguese power system, the following dependencies were considered among wind parks of area 1:

$$CF(Wind\ Park) = b + CF(Wind\ Production\ in\ area\ 1) \times m \qquad (1)$$

where CF is the capacity factor, being defined has the power production divided by the installed capacity of the units in operation; m and b are the slope and the y-intercept of the best linear regression relating $CF(Wind\ Park)$ to $CF(Wind\ Production\ in\ area\ 1)$. In order to introduce diversity in the DS, in each sampled scenario, m is randomly sampled between $\pm 3 \times standard\ deviation(m)$ and b between $\pm 3 \times standard\ deviation(b)$.

- Scheduling of conventional units: For each sampled scenario, the identification of a pre-define number of different scheduling solutions is performed. To obtain a scheduling solution, in each control area the units are sequentially connected, until the load supply is satisfied, constrained by:
  - pre-defined connecting order among power plants of each control area;
  - minimum and maximum number of available units in each power plant, being the availability of some specified units sampled in order to provide diversity among scheduling solutions;
  - minimum and maximum technical limits of each unit;
  - primary control reserve criteria of each control area: $PR >$ capacity of the largest unit in operation;
  - secondary control reserve criteria of each control area [4]: $SR > \sqrt{a \times L\,max + b^2} - b$; being Lmax = maximum estimated load in that period; a = 10 MW and b = 150 MW.
- Dispatch of conventional units: For each created scheduling scheme, a dispatch module randomly distributes the insufficiency of power production by the conventional units that were defined to be in operation by the scheduling module, considering again their production limits.
- Power Flow: For each dispatch solution, a load flow is solved in order to identify all the system operating conditions.
- Feasible Steady-State Solution: Before starting the dynamic simulation, the feasibility of the power flow solution is checked regarding the following operating restrictions:
  - min and max allowed voltage values in the transmission system: $V \in [0.93;1.1]$ p.u.;
  - MVA capacity of synchronous generators;
  - by acting on the following parameters:
  - power factor in PQ synchronous generators;
  - voltage in PV synchronous generators.
- Dynamic Simulation: For each steady-state operating point, the evaluation of system dynamic behaviour is performed in order to obtain the system security indices following specified system disturbances that affect wind power generation.
- Data Set Recording: After each dynamic simulation analysis, a pattern is added to the DS, being characterized by a set of candidate attributes and security indices. In this study, the following security indices were analysed:
  - quasi-steady-state post-fault value of electrical current in the transmission lines: Iif_{FINAL} (120 s after the disturbance, involving therefore AGC operation).

The following candidate attributes were considered:

- Active load in area 1;
- Import level from area 2;
- Number of connected units and active power, in each power station of area 1 and 2;
- Initial pre-fault value of the electrical current in the transmission lines: Iif_{INI}.

For the security structure design, the DS gathered in this way was afterwards randomly splitted in two sets, creating a learning set (LS), with 3/5 of the patterns used for training, and a testing set (TS), with the remaining patterns used for over-fitting control and performance evaluation. An ANN was then designed to provide numerical estimates of the currents in the system transmission lines, following the selected disturbance, exploiting as inputs the attributes mentioned before.

4 ANN TRAINING

In this research, an ANN based tool was chosen, since it performs generally better than concurrent tools in the fast dynamic security evaluation of power systems [5]. For ANN training, the MATLAB Neural Network Toolbox tool was used [6]. ANN parameters were found through the BFGS Quasi Newton Algorithm. Before starting the training stage, training and testing patterns were normalized to have zero mean and a standard deviation of one. This removes offset and measurement scale problems. To perform over-fitting control, besides considering a maximum epochs number, when the testing error increases for a specified number of iterations, the training is stopped.

The used ANN was a two-layer feedforward network, with tan-sigmoid transfer function in the hidden layer and a linear transfer function in the output layer. To choose de number of hidden units, a rule described in [7] was used. According to this rule, the number of hidden units of a single hidden layer network is given by:

$$\frac{N_{LS}}{A} \times \frac{1}{n+r+1} \tag{2}$$

where N_{LS} is the number of learning patterns; A is a constant factor $\in [5;10]$; n is the number of input attributes; and r is the number of output variables.

5 NUMERICAL RESULTS

5.1 DATA SET SETTINGS

Fig. 2 presents the considered installed capacity, for each type of generating power, and the minimum and maximum load values considered for the studied power system. For the DS generation, load was considered to change from light load scenarios to peak load scenarios. The import level from area 2 was considered to change between 0 and 1900 MW. For the scheduling and dispatch of the conventional units, two different situations were taking into account – a thermal based and a hydro based scenario – which defined two different connecting order solutions between conventional units in the scheduling procedure. System security was evaluated relatively to a short-circuit that occurred at a sensitive bus of the transmission system (bus number 15 of Fig. 1), with a duration of 100 ms, leading to the disconnection of the nearest disperse generating units (wind and other DG) due to the triggering of the under-voltage protection relays, which actuate if the voltage drops bellow 0.8 p.u..

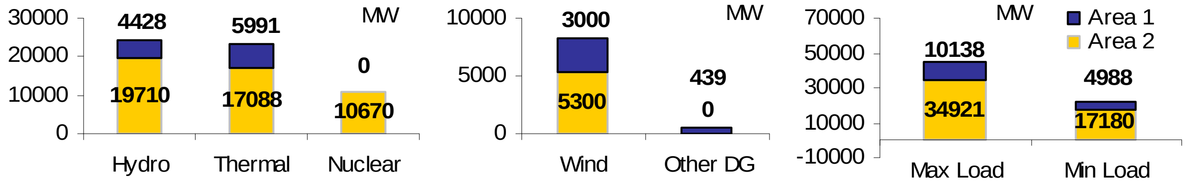

Fig. 2. Installed capacity and minimum and maximum load considered for the studied power system

5.2 DATA SET RESULTS

Using the methodology previously described, 9122 patterns were generated, divided by the following 4 scenarios: off-peak and peak hydro based scenarios, and off-peak and peak thermal based scenarios. The system was considered to be insecure if, 2 minutes after the disturbance, any transmission line current is above the electrical current technical limit. Obviously, the number of insecure patterns in the DS strongly depends of the acceptable over-current settings.

Table I. Number of DS insecure patterns

Scheduling and dispatch scenario	electrical current limit	Security limit 100%	Security limit 120%
Thermal	Summer	1390	280
Hydro	Winter		
Thermal	Summer	3675	810
Hydro	Summer		
Thermal	Winter	130	5
Hydro	Winter		

On the other hand, electrical current limit has a minimum value on hot summer days and a maximum value on cold winter days. The number of obtained insecure patterns, regarding all these aspects, is summarized in Table I. For instance, by considering a summer period for all the generated patterns and a line current security threshold of 120%, 810 patterns of the DS are classified as insecure. Regarding these settings, 9 lines were identified to lose security within the DS patterns, namely the ones identified in Fig. 1 with the (++) symbol. If a 100% line current limit is considered, 3675 patterns are classified as insecure, where 15 lines are identified to become overloaded, namely the ones identified in Fig. 1 with (+) or (++). These lines are also identified in Table II. As we can see from the analyses of this Table, the fact of being a hydro or thermal based dispatch scenario strongly affects each transmission line security. In fact, as it can be seen by the following analysis, the security of transmission lines is strongly dependent from the generation scheduling solution, interconnection import flows and wind generation level.

Table II. Number of DS patterns where insecurity was identified for each transmission line, regarding a security threshold of 100% the summer current limit

Transmission Line	Hydro based dispatch scen.		Thermal based dispatch scen.	
	Off-peak	Peak	Off-peak	Peak
1-3	57	-	1	-
1-5	223	3	13	425
1-7	-	-	1	-
15-16	219	480	148	525
15-17	53	972	183	-
17-16	-	57	15	-
17-4	25	-	1	-
16-4	93	-	3	2
16-6	223	3	13	427
14-18	28	226	336	53
15-18	343	1198	621	65
16-18	217	849	356	13
18-19	-	-	-	5
20-21	-	166	6	-
25-9	-	1	-	-

Two patterns were picked up from the DS. They correspond to peak load hours, with identical operating conditions but with different dispatch solutions – one with a hydro based dispatch and the other with a thermal based dispatch. In these two patterns, an import level from area 2 of 1400 MW is considered and approximately 2200 MW of DG power production is lost due to the simulated fault. In Fig. 3 and Fig. 4 the pre-fault and post-fault values of the electrical line currents and active powers are presented for some main transmission lines (in p.u. regarding the summer load limit).

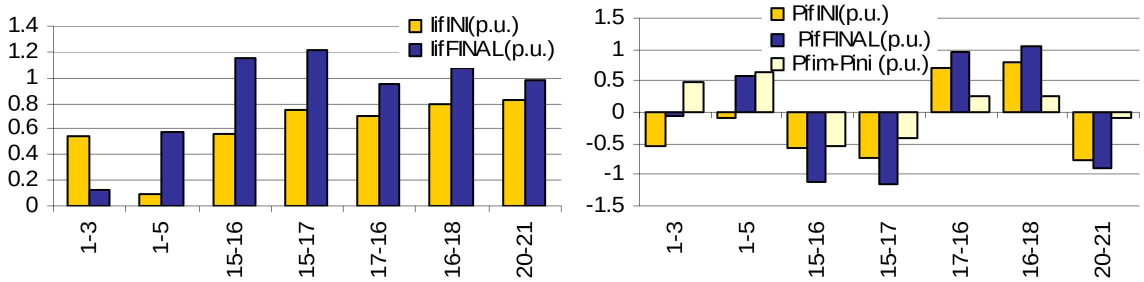

Fig. 3. Current and power flow results in some main transmission lines – pattern with hydro based dispatch

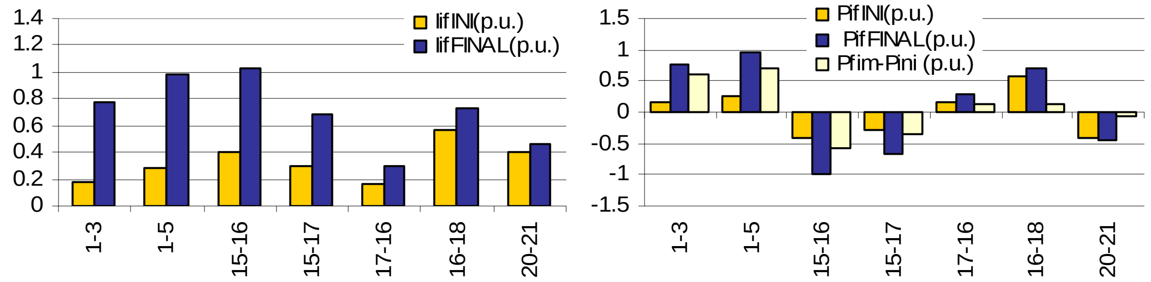

Fig. 4. Current and power flow results in some main transmission lines – pattern with thermal based dispatch

As it can be seen from Fig. 3, for line 1-3, the hydro dispatch improves the security level because, as this line was initially exporting active power the power loss only provokes an exportation reduction. However, if a thermal dispatch solution exists (Fig. 4), which corresponds to generation mainly located in the South of area 1, this line is initially importing from area 2 and, therefore, the disturbance reduces this line security by increasing the importation level. For line 1-5, in both patterns, the disturbance increases the line importation level, and therefore, both cases lead to a reduction of the line security. However, the thermal dispatch is the worst case scenario because, in this case, the line is initially importing, whereas with hydro solution the line is initially exporting. For the remained analysed transmission lines, the hydro dispatch is the worst case, mainly because in this situation, these lines are initially more loaded.

Fig. 5 presents the behaviour for the electrical current in line 15-17, following the considered disturbance, obtained from the pattern with hydro based dispatch with and without AGC operation. As it can be seen from this figure, by considering a line current security threshold of 120%, AGC operation avoids system insecurity for this line, since after 2 minutes the line current starts to become less than the operation limit.

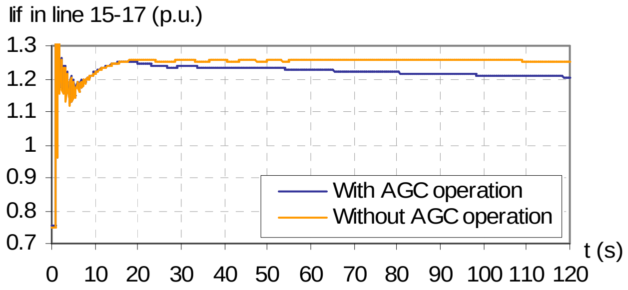

Fig. 5. Behaviour of the electrical current in line 15-17, obtained from the pattern with hydro based dispatch

Next figures provide an impact sensitivity analysis, for line 16-18, regarding wind penetration in area 1 and import level from area 2. As it can be observed, there is a strong correlation (0.723) between the final current value and the initial global import level from area 2. Also, a strong correlation can be observed (0.933) between the increase of this line current and the wind penetration level in area 1.

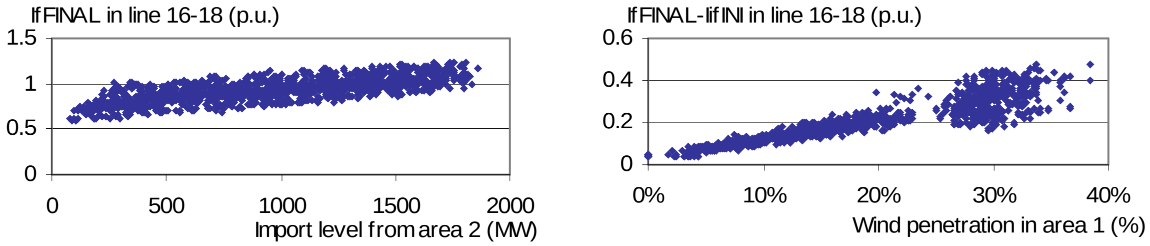

Fig. 6. DS generated patterns for peak load and hydro dispatched based scenarios

5.3 ANN RESULTS

The structure of the designed ANN involves 87 inputs, 11 hidden units and 15 outputs (post-fault values of the current on transmission lines presented in Table II). In order to evaluate the quality of this security structure, test set errors were computed for each ANN output, adopting a security threshold of 100% the summer current limit. The presented regression error (RE) is the Mean Square Error divided by the output variance. The presented classification errors are the Global, False Alarm and Missed Alarm errors.

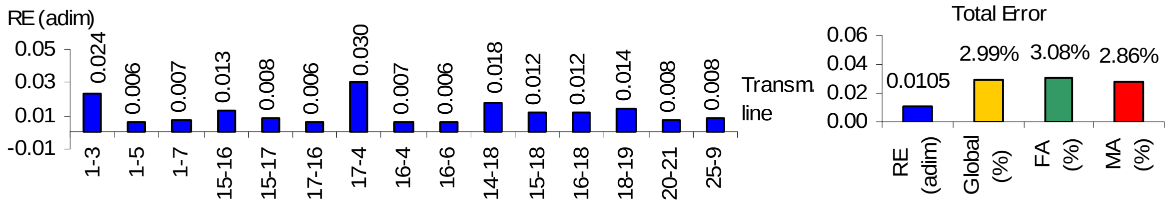

Fig. 7. Test set regression and classification errors of the security structure

6 CONCLUSIONS

The approach described in this paper develops a new dynamic security assessment concept and provides a new tool able to deal with the impact of the presence, in multi control area systems, of large shares of wind and other DG generation following system disturbances. This tool is able to provide, in a very fast way, a prediction about system robustness regarding disturbances that lead, namely, to the disconnection of large amounts of DG. From the results obtained it was possible to get insights on the operational variables that most affect security. The reduced testing errors obtained confirm the feasibility and quality of the approach and of the derived security assessment tool.

Further research is being developed in order to exploit the ANN structure for the derivation of preventive control measures, in a similar way as described in [5] for isolated systems.

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