

On-line Functions for Security Operation of Interconnected Systems having Large Wind Power Production

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Abstract--This paper presents a methodology for the implementation of new EMS tools aiming to assist, in real time, transmission system operators to avoid dynamic security problems, after short-circuits that may lead to large wind power losses. In order to overcome high computational efforts, that are required by conventional dynamic simulation tools, the proposed methodology was developed using automatic learning techniques. The quality of this approach is demonstrated by the results that were provided to solve a security problem of an interconnected test system.

Index Terms-- Interconnected power system, Dynamic security assessment, Wind power generation.

I. INTRODUCTION

In recent years, a high growth rate of wind power production has been observed in interconnected power systems. It also happens that wind generators initially installed had not the capability to stay connected to the grid after short-circuits (the so called fault ride through capability - FRT), as it is presently required. According to several studies, carried out for expected near future operating scenarios of the UCTE interconnected system [1]-[2], simple line faults may provoke large and sudden power generation losses that violate the UCTE security criteria, due to the tripping out of these older wind power plants.

As a result of the increase of wind power production in Europe, the usage of the interconnected transmission lines has been growing. In fact, as described in [3], the high wind power production levels that are expected in Europe, in a near future, may cause steady-state grid bottlenecks on internal and cross border transmission lines of the UCTE interconnected system.

Regarding these two aspects, a simple line fault may provoke sudden and major wind power losses in a control area. This power unbalance may lead, due to the activation of the European primary control regulation, to overloads in transmission lines that may provoke a set of undesired cascading events that, afterwards, may involve load

curtailment or even system collapse in the affected areas. Automatic Generation Control (AGC) and tertiary control will take care of interchange power flow deviations and, therefore, will act to eliminate transmission lines overload problems in the post-fault steady-state conditions. However, these are typically slow control actions that take some time to eliminate interchange deviations and, therefore, do not avoid temporary overload problems in transmission lines.

The measures that TSO have been adopting, trying to overcome dynamic security problems in interconnected systems having large wind power production, include the definition of new grid codes that demand FRT capabilities for the new wind power generators. However, the implementation of such requirements took some time, leading to the present operation of part of the European system with high values of wind power production without FRT capabilities, which may lead to temporary overload security problems in transmission and interconnection lines. This is namely the case of the Iberian system, where TSO admit wind power curtailment when there is a risk of such problem.

In order to deal with such problems, specific security assessment tools, able to provide on-line security evaluation regarding transmission lines temporary congestions need to be developed. For insecure operating scenarios, these tools must also be capable of suggesting preventive control measures, in order to avoid the overload detected problems. This paper describes the approach developed to design such tools.

To measure the quality of the proposed approach, a performance evaluation was carried out by applying it to solve a security problem of an interconnected system with similarities with the Portuguese system, which was created for test purposes.

In order to follow on-line time requirements, the proposed approach was developed using Automatic Learning (AL) techniques. Artificial Neural Networks (ANN) were chosen to perform dynamic security monitoring functions, while Linear Regression Models (LRM) were selected to provide preventive control measures, by solving linear optimization problems. This work also shows that, for the dynamic security problem under evaluation, more accurate linear security structures may be obtained by exploiting a hybrid technique, denominated in this work Linear Regression Trees (LRT).

The developed work includes the following main steps:

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- STEP 1: Creation of an Interconnected Test System;
- STEP 2: Data Set Generation;
- STEP 3: Security Evaluation with AL Techniques;
- STEP 4: Preventive Control Measures Supply;

which are properly described in the remaining sections of this paper.

II. STEP 1: CREATION OF AN INTERCONNECTED TEST SYSTEM

The single-line diagram of the created test system is presented Fig. 1, where control area 1 corresponds to an approximation of the Portuguese transmission system. This research was focused on the security of control area 1. Therefore, in order to model the interconnections with neighboring systems, an equivalent of the Spanish/European UCTE system was modeled, in control area 2, by using one busbar with equivalent generating units.

In order to reduce power system dimension, without losing relevant information for the simulation of the dynamic behavior under evaluation, all the generating units of control area 1 are equivalent machines modeling similar generators operating in parallel in the same power plant. In control area 2, nuclear units were considered as must run units and not participating in secondary frequency control. All the hydro and thermal units were considered to participate in primary and secondary frequency control. Fig. 1 also presents two graphics, reporting the considered values of installed capacity for each type of generating unit, maximum import value provided from control area 2, and minimum and maximum load in each control area.

In order to obtain the dynamic behavior of thermal, hydro and nuclear units, the usual corresponding local frequency regulator models as described in [4] were used, including also the voltage regulator behavior adopting an IEEE1 model type. Wind generators were modeled by a

classical 3rd order asynchronous machine model. The AGC system response was also modeled, adopting the traditional integral control approach and using the configuration described in [5], which includes a participation factor for each generator in order to maintain generating unit's at the most economic operating conditions. For all the parameters of the power system model, typical values were considered, and extracted from the full Portuguese - Spanish interconnected system.

During the test system definition, a major concern was to obtain typical dynamic behaviors of power flows in transmission lines. To validate this issue, the dynamic simulation results provided by the created test system were compared with the ones provided by the PSS/E program [6], for a complete model of the Portuguese - Spanish interconnected system, including an equivalent of France.

Fig. 2 illustrates some of the obtained dynamic results from simulating a short-circuit, in a critical busbar of the Portuguese transmission system, that provokes the loss of 522 MW of renewable power generation in the Portuguese system, for a typical operating scenario of winter peak in the year 2006. Model validation was performed by comparing the dynamic results of the interconnected test system with the ones provided by the complete model of the Portuguese - Spanish transmission system, as illustrated in Fig. 2.

III. STEP 2: DATA SET GENERATION

After validating the created test system, a Data Set (DS) was generated, consisting on a high number of pre-analyzed scenarios, aiming to obtain a complete characterization of the dynamic security of control area 1 regarding a severe wind power disturbance. This data was necessary to extract the AL security structures.

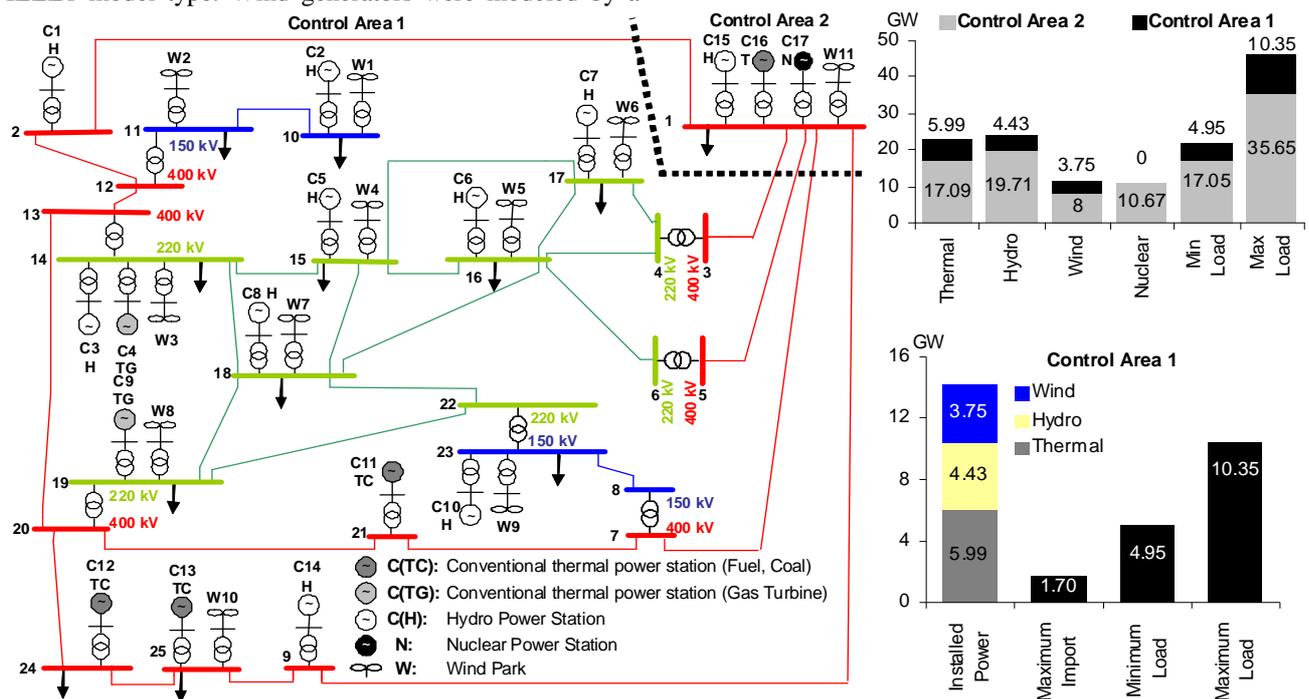


Fig. 1. Interconnected test system (single-line diagram, installed capacity, maximum import value, minimum and maximum load)

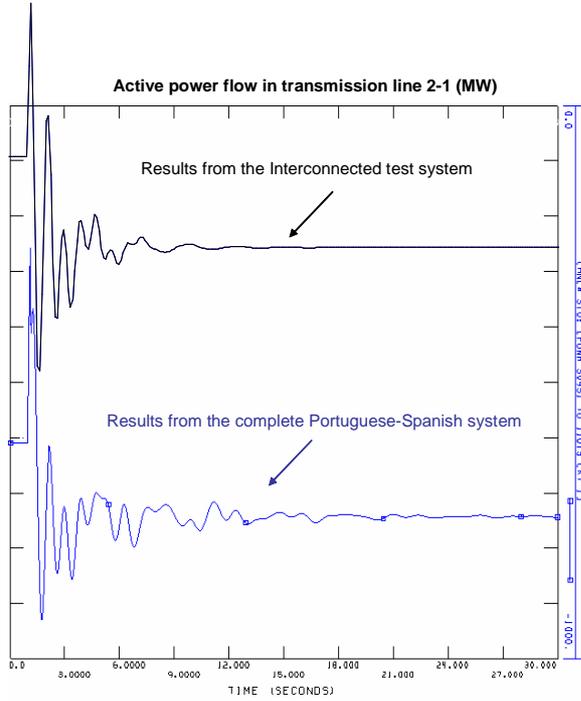


Fig. 2. Dynamic results for the active power flow in transmission line 2-1 (a 30 seconds simulation without AGC operation)

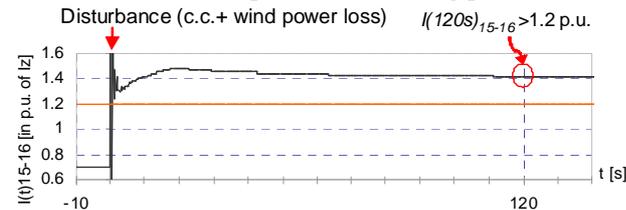
A. Analyzed Security Problem

In the developed work, system security was evaluated regarding a short-circuit that takes place in a sensitive line of the transmission system (one of the two parallel lines connecting buses 15 and 16 of the test system presented in Fig. 1). A time of 300 ms was considered before the disconnection of the faulty line, leading to the loss of the nearest wind generating units due to the triggering of their under-voltage protection relays (which operate if the voltage drops below 0.9 p.u.).

System was considered to lose security if, 2 minutes after the disturbance, any transmission line k of control area 1 is 20% above the maximum electrical current technical limit for steady-state operation I_{z_k} , i.e. if:

$$I(120s)_k > 1.2 \times I_{z_k} \quad (1)$$

where $I(120s)_k$ is the electrical current in line k 2 minutes after the disturbance. To illustrate an insecure situation, Fig. 3 presents the dynamic behavior of electrical current in transmission line 15-16 (the line that remains connecting buses 15 and 16), that resulted from simulating, at 0 seconds, the analyzed disturbance for one of the generated operating scenarios. This figure illustrates a typical situation where, although AGC operation is beneficial to reduce the initial large increase of load in line 15-16, this action is very slow and, therefore, the line remains with overload problems for a long period of time.



Iz: max. electrical current technical limit, in line 15-16, for steady-state operation.

Fig. 3. Example of an insecure situation

B. Data Set Generation Procedure

A special care was devoted to the DS generation procedure, in order to cover all possible operating conditions of the power system that have a relevant influence on the type of dynamic problem under analysis – congestions in quasi-steady state that violate the acceptable limits for temporary overloads in transmission lines, after a fault that may lead to major wind power losses.

To generate this data, an automatic and general procedure was implemented, able to generate a DS for any interconnected system with two control areas, whose main steps are properly described in [7] and [8]. This includes a full dynamic simulation, for each feasible generated operating scenario, comprising AGC operation in order to obtain an accurate value for the analyzed post-fault condition of each transmission line k : $I(120s)_k$.

After the computation of each dynamic simulation, a pattern is added to the DS, being characterized by all the variables needed to describe the system pre-fault operating conditions – the candidate input features for the AL security structures – and a vector containing the obtained value of $I(120s)_k$ for each transmission line k of control area 1 – the security indices to be evaluated by the AL security structures.

C. Data Set Settings for the Created Test System

In the DS generation procedure performed for the created test system, the load was considered to change from light load scenario to peak load scenario. For the wind power sampling procedure, a 0.8 value was considered for the probability of each wind park being in operation, the number of connected units in each wind park was sampled between 80% and 100% of the total installed number, and the wind generators capacitor factor was considered to change from 10% to 100%. The import level provided from control area 2 was considered to change from 0 to 1700 MW. For the scheduling and dispatch of the conventional units, 2 different situations were taken into account – a thermal based and a hydro based dispatch scenario. Also, special care was taken in order to generate scenarios with higher spinning reserves mainly provided by hydro power plants. The idea was to include the system behavior regarding likely preventive control solutions, having in mind the results presented in [9], where it was concluded that in systems with very high wind power production, where secondary control is mainly provided by thermal power plants, the operation of additional or faster secondary control (provided by storage - hydro production) is required in order not to compromise the quality of generation control.

D. Data Set Results

By applying the DS generation procedure with the previous described settings, 4596 patterns were generated for the created test system. From this set, a total number of 983 patterns (approximately 21 % of the DS) were classified as insecure, by presenting temporary overload problems for some of the 7 transmission lines that are

mentioned in Fig. 4. This figure presents the total number of obtained insecure/secure patterns for each one of the 7 transmission lines, which were identified to be critical for the disturbance under analysis. Obviously, the connection between bus 15 and 16 is the one with a major number of insecure scenarios, since it loses one of the two parallel installed lines.

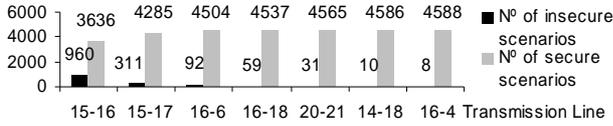
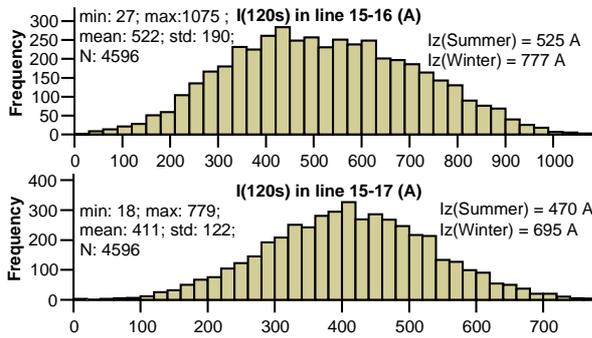


Fig. 4. Number of insecure/secure patterns in the DS

Fig. 5 presents the histogram for the obtained values of $I(120s)$ for line 15-16 and line 15-17. A similar well distributed values of $I(120s)$ was obtained for the remaining 5 critical lines (presented in [8]), which illustrates the quality of the generated DS.



Legend – min/max: minimum/maximum value; std: standard deviation; N: total n° of patterns; Iz(Summer/Winter): maximum electrical current technical limit, for steady-state operation, in Summer/Winter.

Fig. 5. Histogram of the obtained $I(120s)$ values for lines 15-16 and 15-17

IV. STEP 3: SECURITY EVALUATION WITH AL TECHNIQUES

A. Introduction

In order to obtain fast and accurate security evaluations, for the dynamic problem under analysis, the following AL techniques were tested: Artificial Neural Networks (ANN); Linear Regression Models (LRM) and Linear Regression Trees (LRT).

1) Candidate input features

Before extracting the AL structures, 63 pre-fault operating conditions of control area 1 were selected as candidate input features, describing:

- $P_{load,ac1}$ (MW): total active load in control area 1;
- Nc_i , Pc_i (MW) and Vc_i (p.u.): number of connected units, active power production and terminal voltage in conventional power station i (for $i = 1, \dots, 14$);
- Nw_j and Pw_j (MW): number of connected units and mechanical power in wind park j (for $j = 1, \dots, 10$).

These features were empirically selected, in order to consider all the SCADA available data that may be relevant to explain the dynamic behavior under analysis, namely, a feature set characterizing pre-fault steady-state conditions and the dynamic behavior of active powers. This input set was also defined to include all the necessary controllable operating conditions, in order to implement

the following type of preventive control measures:

- conventional units re-schedule and/or re-dispatch;
- wind generators disconnection and/or mechanical power reduction;
- with or without including interchange power flows modifications.

Besides, in order not to compromise the preventive control algorithm execution times, non-directly controllable conditions, like steady-state pre-fault value of power flows in transmission lines or any other system condition that results from a power flow solution, were discarded.

2) Partition of the DS

To avoid overfitting problems during the AL structures training procedure, and also to obtain a proper performance evaluation between extracted structures, the *Holdout* technique was applied. Regarding this technique, the generated DS was randomly divided in two subsets, being one of these sets used for training (the training set) and the remaining set (the *Holdout* or testing set) for performance evaluation. By following this procedure, 3596 of the generated patterns for the created test system were selected for training and the remaining 1000 patterns were left for testing. Within the ANN training procedure, 1000 of the training patterns were randomly selected to define the validation set.

B. Artificial Neural Networks (ANN)

In this research, an ANN based tool was applied taking into account the known superiority of this technique to provide accurate security evaluations, regarding other power system dynamic security problems (as presented in [10] and [11]).

1) Design of the ANN security structures

For ANN training, the MATLAB Neural Network Toolbox tool was used [12]. ANN parameters were found through the Levenberg-Marquardt backpropagation algorithm and by considering the usual data pre-processing procedures (normalization of inputs/outputs variables to have zero mean and standard deviation of one; random initialization of ANN parameters between -1 and 1). To perform overfitting control, besides considering a maximum epochs number, when the validation error increases for a specified number of iterations, the training is stopped. The used ANN structure was a two-layer feedforward network, with a tan-sigmoid transfer function in the hidden layer and a linear transfer function in the output layer. To choose the number of hidden units, an empirical rule, as described in [13], was used. According to this rule, the number of hidden units of a single hidden layer network is given by $(nt/k - no)/(ni + no + 1)$, where nt is the number of training patterns; k is a constant factor $\in [5;10]$; ni and no are the number of input and output variables.

2) Selection of the best ANN Input/Output set

For the ANN output set, two hypotheses were considered:

- to use only one ANN to evaluate $I(120s)$ for all the

critical lines;

- to use a different ANN to evaluate $I(120s)$ for each critical line.

For the ANN input set, the following hypotheses were considered:

- to use all the 63 candidate input features;
- to use only the candidate input features that are selected by an automatic Feature Subset Selection (FSS) procedure that is applied to extract a LRM – the LRM variable selection stepwise method.

To choose the input/output set solution that provides the most accurate ANN security structures, a comparative analysis was performed regarding the testing set regression errors provided from each considered solution. These applied methods (i.e., the FSS and the comparative analysis procedures) and the obtained results for the created test system are properly described in [7]. From this work, the main conclusions were the following:

- Using a different ANN to evaluate security for each critical line, is the most accurate option.
- The FSS applied method showed to be effective, since, for most of the evaluated lines, it was capable of improving ANN accuracy, while for the remaining lines its application never provoked a ANN accuracy deterioration.

C. Linear Regression Models (LRM)

The security problem under analysis regards quasi-steady state post-disturbance system behavior. Regarding this, it is appropriated to assume that the analyzed behavior could be accurately characterized by linear regression models (LRM). In the developed work, the main goal of this achievement was to use the obtained LRM as dynamic security linear restrictions. This enabled the implementation of an algorithm, for providing preventive control measures, based in the resolution of linear optimization problems and, therefore, by benefiting from the usual advantages of solving this kind of problems (i.e., small computational efforts and the capability to achieve the optimal solution).

1) Design of the LRM security structures

For the created test case, a different LRM was designed to evaluate $I(120s)$ for each critical line. These were extracted by the LRM training algorithm available in SPSS software tool [14] that includes the stepwise variable selection method. For the LRM input set, the 63 earlier described features were considered. However, the total active load in control area 1 ($P_{load,ac1}$) was replaced by the import value provided from control area 2 (Imp), calculated by:

$$Imp = P_{load,ac1} - \left(\sum_{i=1}^{14} P_{Ci} + \sum_{j=1}^{10} P_{Wj} \right) \quad (2)$$

In fact, by using the $P_{load,ac1}$ input feature, the values achieved by the LRM parameters showed to be inconsistent with the existing engineering knowledge of the cause/effect problem under analysis. This could turn out inefficient the use of LRM to obtain preventive control measures. By replacing $P_{load,ac1}$ (which has the problem to

enclose much of the relevance of the remaining input features) by the Imp information (which allows not to lose any information from discharging $P_{load,ac1}$), this problem became solved without deteriorating the accuracy of the LRM structures.

D. Linear Regression Trees (LRT)

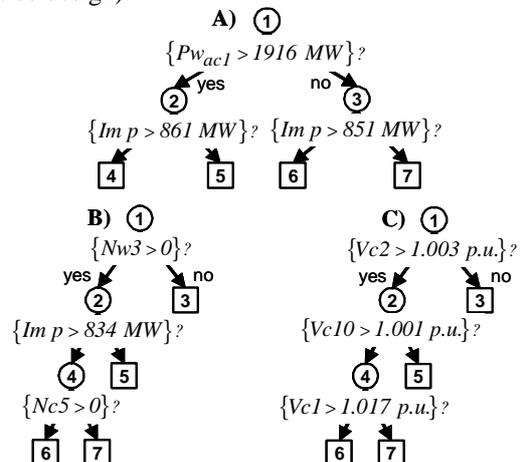
Within the general application of supervised AL methods, in [15] L. Torgo suggests to extract LRM in the leafs of a classical Regression Tree (RT, presented in [16]), in order to improve accuracy of LRM and RT. This hybrid model was named Linear Regression Tree (LRT). Motivated by this work, this type of AL technique was also explored to evaluate security for the created test system, aiming to achieve more accurate dynamic security linear restrictions.

1) Design of the LRT security structures

For the created test case, a different LRT with 7 nodes was designed to evaluate $I(120s)$ for each critical line.

The tree structure accuracy may be improved by considering input features with higher relevance and it is not jeopardized by having input features with strong relations among them. Regarding this, for the RT training, besides the 63 features earlier described, some extra candidate input features were also considered. However, the preventive control purposes introduced some restrictions to the type of input feature to consider for the RT design. In fact, in order to guard the linearity of the dynamic security restrictions, the tree structure can not include any preventive control variable. In order to illustrate this, Fig. 6 presents the tree structure of the LRT extracted to evaluate security for line 15-16, regarding the following preventive control alternative purposes:

- with no control measures restrictions;
- conventional units re-dispatch and wind power reduction (P_{Ci} and P_{Wj} were discarded for tree design);
- conventional units re-schedule/re-dispatch and wind units disconnection/power reduction, including interchange power flows modifications (N_{Ci} , P_{Ci} , N_{Wj} , P_{Wj} and Imp were discarded for tree design).



P_{wac1} : total mech. power developed by wind parks of control area 1.

Fig. 6. Tree structure of the LRT extracted with linearity restrictions regarding alternative control measures - security evaluation of line 15-16

E. Security Structures Performance Evaluation

Fig. 7 presents the testing set regression errors provided by each type of extracted AL structure, to perform security evaluation for the created test problem. The considered regression error was the following:

$$RE = \frac{\sum_{i=1}^{np} (u_i - \hat{u}_i)^2}{\sum_{i=1}^{np} (u_i - \bar{u})^2} \quad (3)$$

where u_i / \hat{u}_i : real/emulated value of $I(120s)$ for pattern i ; np : n° of testing patterns; \bar{u} : mean value of $I(120s)$ in the testing set. These results show that, for the type of dynamic behavior under analysis, ANN were clearly the more accurate security evaluation structures. Therefore, ANN are the most suitable structures to perform on-line security monitoring functions. Fig. 7 also reveals that the LRT extracted with no control restrictions were more accurate than LRM.

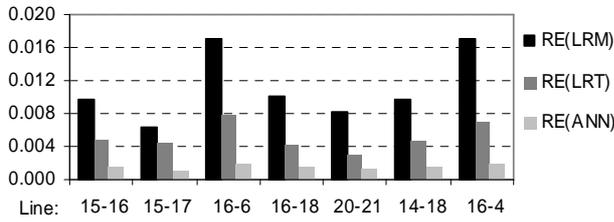


Fig. 7. Regression errors provided by LRM, LRT(alt. A) and ANN

Fig. 8 presents the testing set regression errors provided by the LRM and the several LRT extracted with linearity restrictions, regarding alternative preventive control purposes (tree structures presented in Fig. 6), to evaluate security for line 15-16. These results illustrate that, although needing to include linearity restrictions during training, LRT provide more accurate dynamic security linear restrictions than LRM.

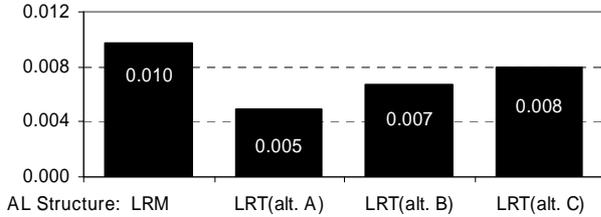


Fig. 8. Regression errors provided by LRM and the LRT extracted with alternative preventive control purposes (security evaluation of line 15-16)

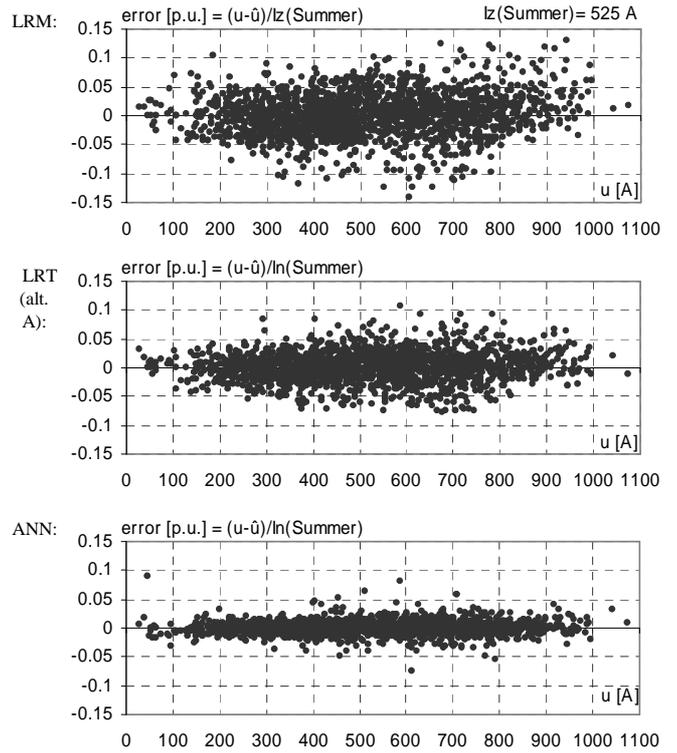
To obtain a better insight of the individual error provided by each type of AL structure, Fig. 9 presents the single regression error ($u_i - \hat{u}_i$) obtained for each testing pattern i , to evaluate security for line 15-16. These results show that, although ANN generally presents the most accurate evaluation, none of the security structures provide excessive security evaluating errors.

V. STEP 4: PREVENTIVE CONTROL MEASURES SUPPLY

A. Preventive Control Algorithm Design

The architecture of the developed security monitoring / preventive control approach is presented in Fig. 10. Under this architecture, security monitoring is performed using ANN, while preventive control measures are obtained through the solution of a linear optimization problem

where linear security structures are used as dynamic security restrictions.



Legend:
 u : known value of $I(120s)$; \hat{u} : emulated value of $I(120s)$; $I_z(\text{Summer})$: maximum electrical current technical limit in the line, for steady-state operation, in Summer.

Fig. 9. Testing set single regression errors provided by LRM, LRT(alt. A) and ANN - security evaluation of line 15-16

The objective of the implemented optimization problem was to minimize the amplitude and the number of preventive control measures required to reach system security. For a particular insecure operating scenario, the algorithm starts with a restricted type of preventive control measures, only allowing conventional units re-dispatch and wind power reduction with no interchange power flows modifications. Each time the optimization problem fails to reach system security, some extra control measures are allowed, like including interchange power flows modifications or wind generators disconnection or, even, conventional units re-schedule.

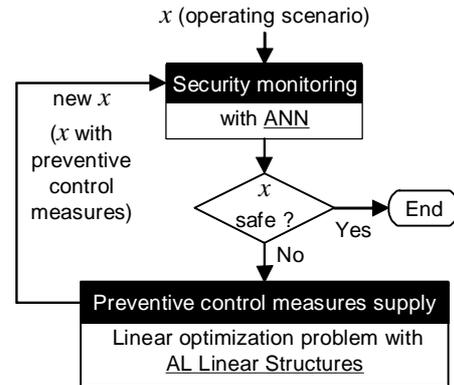


Fig. 10. Architecture of the security monitoring / preventive control approach

B. Preventive Control Results for the Created Test System

1) Performance evaluation results

To measure the quality of the proposed algorithm, a performance evaluation was carried out by applying this approach to solve the analysed security problem for the created test system. From this analysis, which is properly reported in [8], the obtained results showed that the proposed algorithm was extremely suitable regarding the following results:

- execution times;
- the quality of the provided control measures, measured by the total MW modifications and the number of generating units with operating conditions modifications.

The obtained results also showed that the rate of success of the proposed algorithm in finding any preventive control measures may be considerable increased by including, in a inferior merit order, some variants of the optimization problem using ANN security restrictions. In fact, for the analyzed test system, this provided an increase of the success rate from 58% (i.e., a solution was found for 575 of the 983 insecure patterns) to 95% (i.e., a solution was found for 937 of the 983 insecure patterns).

2) Suggested preventive control measures – Example

In order to illustrate the capabilities of this approach, an example is described and discussed next. Fig. 11 presents, in the column chart untitled “Initial insecure scenario”, the general steady-state conditions of control area 1 of the created test system, for an insecure situation. In fact, for this scenario, ANN identified temporary overload problems in line 15-16, by outputting $I(120s)_{15-16} > 1.2 \text{ p.u.}$ regarding the disturbance under analysis. For this scenario, the preventive control algorithm provided the control measures that are described in Fig. 12, namely: a total power reduction, of 186 MW, in the wind parks of control area 1, which must be totally compensated by an increase of the active power production in C5 hydro power station (resulting, therefore, in a same amount of spinning reserve reduction). The suggested wind power reduction results from a capacitor factor reduction of 16% (39 MW) in wind park W1, 15% (59 MW) in wind park W4, 17% (14 MW) in wind park W5, 18% (20 MW) in wind park W6, and 5% (54 MW) in wind park W7. The general steady-state conditions of control area 1 that result from applying these control measures are the ones presented in Fig. 11, in the column chart untitled “Modified scenario”.

In order to validate these control measures, dynamic simulations were also performed for the “Initial insecure” and the “Modified” scenarios. The dynamic behaviors of the electrical current in transmission line 15-16, for the two scenarios, are presented in Fig. 13. These results show that the suggested control measures were able to eliminate the temporary overload problem of line 15-16. This was provided by reducing the steady-state pre-disturbance value of the electrical current in line 15-16 (mainly by increasing the active power production in C5 power

station) and also by reducing the severity effect of the wind power loss (by reducing the wind power production before the disturbance).

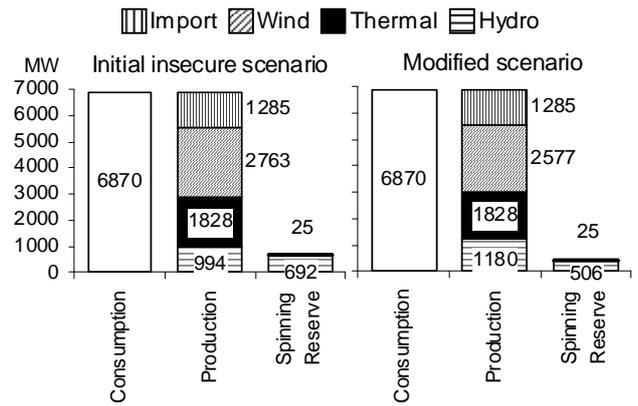
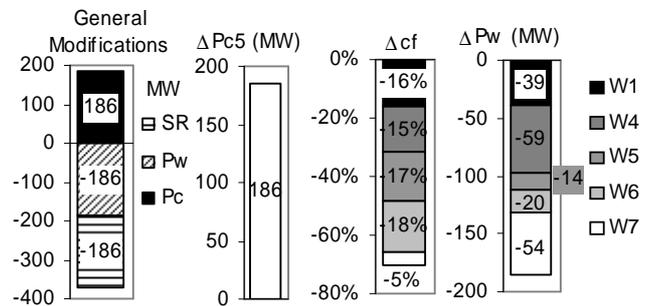


Fig. 11. Pre-disturbance steady-state conditions for control area 1 of the created test system



Legend:

- SR: total spinning reserve modification for control area 1;
- Pw: total mechanical power mod. in the wind parks of c. area 1;
- Pc: total active power prod. mod. in conventional units of c. area 1;
- $\Delta Pc5$: active power production mod. in C5 conv. power station;
- Δcf : capacitor factor mod. in each wind park of control area 1;
- ΔPw : mechanical power mod. in each wind park of control area 1.

Fig. 12. Suggested preventive control measures

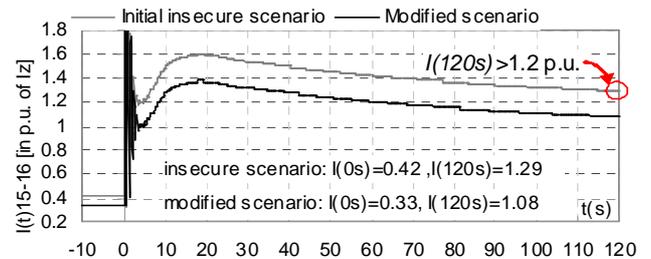
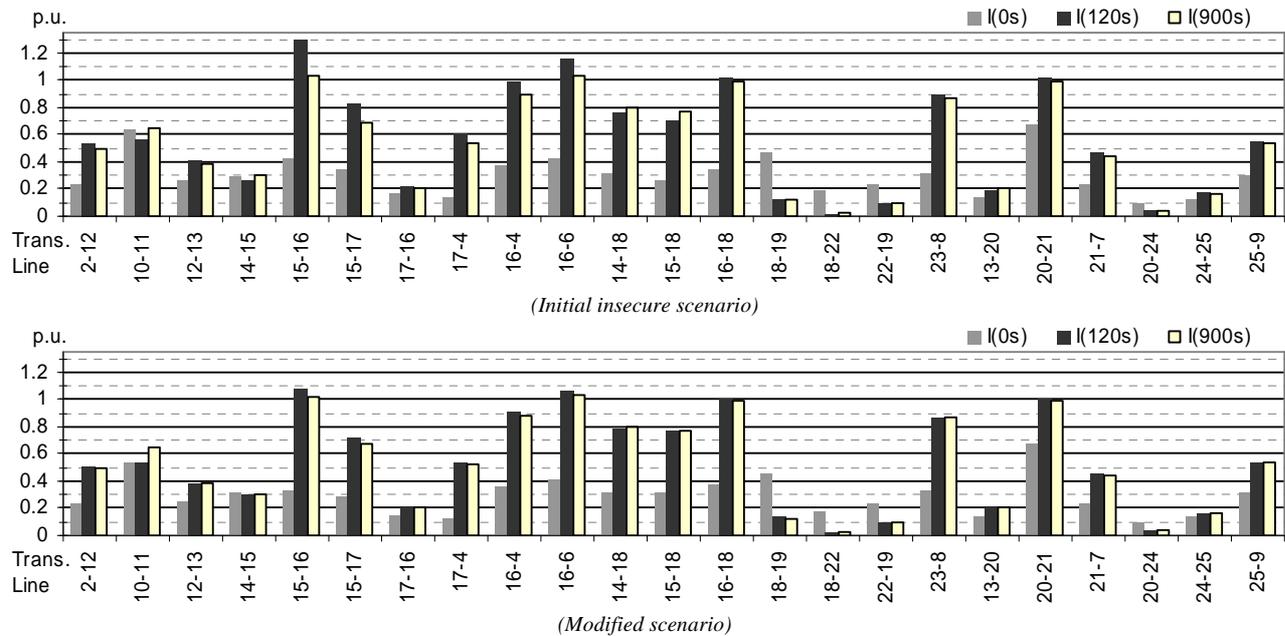


Fig. 13. Dynamic results for the “Initial insecure” and “Modified” scenarios

Fig. 14 presents an extended overview of the effect of the adoption of the preventive control measures. This can be understood by analyzing the behavior of the electrical current in each transmission line of control area 1, for the “Initial insecure” and the “Modified” scenarios.

These results show that the suggested control measures were also able to avoid temporary overload problem in all the transmission lines of the control area.

A similar analysis was performed for other insecure scenarios of the created test system (some results can be found in [8]), which resulted in the same type of conclusions regarding the effectiveness of the preventive control measures suggested by the proposed algorithm.



Legend – I(0s): steady-state pre-disturbance value of electrical current in the line; I(120s): electrical current in the line, 2 minutes after the disturbance; I(900s): electrical current in the line, 15 minutes after the disturbance (i.e., after AGC control action).

Fig. 14. Dynamic results for the “Initial insecure” and “Modified” scenarios (security evaluation for all the transmission lines of control area 1)

VI. CONCLUSIONS

This paper described the main steps needed to design a security assessment / preventive control tool to be used in EMS of power systems having to face large scale integration of wind generation that has no fault ride through capabilities. The adoption of Automatic Learning techniques is the key issue for the success of this approach regarding the on-line effectiveness.

VII. REFERENCES

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