A systematic approach for dynamic security assessment and the corresponding preventive control scheme based on decision trees

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Abstract—This paper proposes a decision tree (DT) based systematic approach for cooperative online power system dynamic security assessment (DSA) and preventive control. This approach adopts a new methodology that trains two contingency oriented DTs on daily basis by the databases generated from power system simulations. Fed with real-time wide area measurements, one DT about measurable variables is employed for online DSA to identify potential security issues and the other DT about controllable variables provides online decision support on preventive control strategies against those issues. A cost effective algorithm is adopted in this proposed approach to optimize the trajectory of preventive control. The paper also proposes an importance sampling algorithm on database preparation for efficient DT training for power systems with high penetration of wind power and distributed generation. The performance of the approach is demonstrated on a 400-bus, 200-line operational model of the western Danish power system.

Index Terms—Decision tree, dynamic security assessment, importance sampling, phasor measurement unit, preventive control

NOMENCLATURE

CHP Combined heat and power plant.
CPP Central power plant.
DT Decision tree.
RF Random forest.

ODT Observation decision tree.
PDT Prevention decision tree.
OC Operating condition.
G_CPP MW-output of central power plant x.
P_x_y, Q_x_y MW- and MVar-power from bus x to bus y.
A_x_y Voltage angle of bus x minus that of bus y.
p(t) Probability of class i in node t.
i(t) Impurity index of node t.
S Training database.
π_i Prior probability of class i.
IS, NS Importance sampling and normal sampling.
LS, TS Learning set and test set.
C_i Cost of reserve service from CPP i.
F_i Fixed cost of reserve service from CPP i.
P_{UPI}, P_{DNI} Prices of upward and downward generation rescheduling in CPP i.
ΔG_{UPI}, ΔG_{DNI} MW-quantities of upward and downward generation rescheduling in CPP i.
ΔG_{UPI max}, ΔG_{DNI max} Limits of upward and downward generation rescheduling in CPP i.
G_{i min}, G_{i max} Min. and Max MW outputs in CPP i.
G Set of generators participating in the preventive control.
P_{ex} Mismatch between scheduled and actual international power exchange.
P_{r} Price of international power exchange mismatch under range R.
C_{pen} Penalty of violating scheduled international power exchange.

I. INTRODUCTION

CONTINUOUSLY growing demand for electricity, driven by deregulated electricity markets, has forced modern power systems to operate closer to secure operating limits. Also, the increasing penetration of large scale renewable energy may impact transmission systems by bringing more uncertainties to grid operations. It becomes more challenging to protect a modern power system from insecurity by relying only on localized protection schemes. Hence, a power system should be secured proactively at the system level by advanced system protection schemes for online situational awareness and proactive wide area coordinating control [1]. For instance, an elaborated proactive system protection scheme may integrate both online DSA for identification of potentially insecure conditions and system level optimization and execution of control strategies for prevention of identified insecure conditions. Phasor measurement units (PMU) can provide high resolution real-time power system measurements
synchronized by global positioning system (GPS). Based on PMUs, wide area measurement systems (WAMS) have been built in many countries and would enable the development of aforementioned proactive system protection schemes.

Pattern recognition techniques, such as Artificial Neural Networks (ANN) [2], Support Vector Machine (SVM) [3] and Decision Trees [4]-[17] can be applied in DSA of power systems. Among them, some DT algorithms [18], especially those with the “white box” nature, have gained increasing interests because they not only provide the results of security assessment but also reveal the principles learned by DTs for security assessment. Those principles provide useful information required for the remedial actions against recognized insecure conditions. With the aid of WAMS and advanced computing resources, DTs may be integrated into online DSA tools for large interconnected complex power systems. For instance, reference [4] applies DTs in an online DSA method by adaptively updating the database to train DTs on daily basis for foreseen system conditions. In [5], a method for efficient database generation for DT training is introduced to enhance DT accuracy in DSA and decrease the computation burden in DT training. In [6], multiple optimal DTs are proposed to increase the accuracy for the assessment of static voltage security. In addition, DTs can also be used in adaptive protection [7], controlled islanding [8], [9], load shedding [10], loss of synchronization detection [11], quick restoration schemes [12] and energy markets [13]. In [14] and [15], DTs are used for preventive control (i.e. generation rescheduling) and for corrective control (i.e. load shedding) by determining the dynamic security regions. Then, the preventive control and the corrective control are optimized in terms of the fuel cost and the amount of load to be shed, respectively.

With the increasing penetration of renewable energy resources and other decentralized generation (DG), more uncertainties will be brought to the operation of transmission systems, since those resources are not as accessible for direct monitoring and control from control centers as conventional central power plants. Thus, a significantly increased number of scenarios need to be covered by DTs to address these uncertainties. However, it also becomes more important to minimize the computation burden with DT based online applications for real-time DSA and the associate sensitivity analysis. Most of the existing works apply DTs mainly for security assessment, whose predictors to be measured in real time are the system variables most effective in detecting security problems, e.g. line flows and angle differences. However, the DTs focusing on decision support for preventive control may employ a different set of predictors that are directly controllable, e.g. generation outputs, so it is advisable to build two DTs respectively for DSA and preventive control based on two sets of predictors selected separately.

The DT-based approach proposed in this paper aims at addressing the aforementioned problems. First, this paper studies the database preparation for training accurate DTs for power systems with high penetration of wind generation and other DG. Without losing generality, the paper focuses on a power system supported by three types of generation: traditional central power plant (CPP) generation, wind power generation and other DG mainly from combined heat and power plants (CHP). An importance sampling technique, considering the random distribution of various generation resources, is developed and applied in the proposed approach to enhance the information contained in the databases for DT training. Second, the approach is designed to be a systematic integration of cooperative online DSA and preventive control. The approach adopts a new methodology that offline trains two contingency-oriented DTs by databases generated from power system simulations. Fed with real-time wide-area measurements, one DT is employed for online DSA to identify potential security issues and the other DT provides system operators with the online decision support on allowed preventive control strategy to guide the operating point from a potentially insecure state to a secure state. Then the optimal control trajectory is searched out by minimizing the total economic cost incurred by generation rescheduling.

The rest of the paper is organized as follows. Section II presents the flowchart and stages of the proposed approach. Section III introduces the fundamental knowledge of DT. In Section IV, database preparation with due considerations to power systems with high penetration of wind power generation and other DG is described. An importance sampling technique is adopted and presented in the approach. Section V describes in detail the cooperative application of proposed two types of DTs to predict and prevent the potential insecure issues with the least economic cost implication. Then, the proposed approach is demonstrated in Section VI using an operational model of the western Danish power system, which is characterized by its large scale penetration of wind power generation and other DG. The concluding remarks are provided in Section VII.

II. PROPOSED APPROACH

The flowchart of the proposed DT-based systematic approach is shown in Fig. 1 and the proposed approach is executed in the following stages:

Stage I: Identification of the Security Boundary. Since wind forecasts are not highly accurate and DG is unpredictable, the power flow pattern in a next period is highly uncertain. However, a security boundary separating secure operating conditions (OCs) from insecure ones at each load level can be estimated and presented in multiple-dimensional space with coordinates of aforementioned stochastic variables, such as CPP generation, CHP generation and wind power generation.

Stage II: Importance Sampling. Considering the intermittency of wind power generation in wind farms and the variation of power generation in CPPs, importance sampling is used to bias a number of samples of OCs towards the security boundary by revising the sampling distribution function.

Stage III: Offline time domain (T-D) Simulation and DT Training. A large number of T-D simulations for each “n-1” contingencies and selected “n-k” contingencies are carried out to form a database, from which a series of operating guidelines are obtained by DTs.

Stage IV: Online Preventive Control. If online measurements violate pre-formulated guidelines, available preventive control
Prior adjusted probability is used effectively to control the splitting rules over the tradeoff between the class purity and class accuracy. The probability that a case lands in node $t$ is

$$p_t = \sum_{i=1}^{L} (n_i / N_t) \pi_i$$

(1)

where $\pi_i$, $N_t$ and $n_i$ ($i = 1, ..., J$) is the prior probabilities, the number of cases in LS, number of cases contained in node $t$ for class $i$, respectively. Then the conditional probability of class $i$ given that a case reached node $t$ is defined in (2)

$$p_i(t) = (n_i / N_t) \pi_i / p_t .$$

(2)

So the probabilities $p_i(t), p_d(t)$ that the cases in node $t$ going to left descendant node $t_L$ and right descendant node $t_R$ are defined as (3) and (4) respectively

$$p_L(t) = p_L / p_{parent}$$

(3)

$$p_R(t) = p_R / p_{parent} .$$

(4)

As mentioned earlier, the optimal splitting rule $\delta$ is selected to maximize the decrease of impurity $\Delta \imath(i, \delta, t)$ after the split so as to minimize the overall impurity, as defined in (5), where $i(t), i_L(t), i_R(t)$ are the impurity indice of parent node, left descendant node and right descendant node respectively.

$$\max \{ \Delta \imath(i, \delta, t) \} = \max \{ i(t) - p_L(t)i_L(t) - p_R(t)i_R(t) \}$$

(5)

Hence, by adjusting prior probabilities $\pi$, one can adjust the splitting rules to find the overlapping region, as shown in yellow in Fig. 3. Accordingly, the regions in red and blue are with probability of exception lower than $\pi_L$ and $\pi_R$ respectively.

$$\pi_r >> \pi_l \quad \pi_l = \pi_r = 0.5 \quad \pi_r >> \pi_l$$

Fig. 3. The thresholds of DT w.r.t. prior probability adjustment.

Other extended techniques, such as random forest (RF), are adopted to improve the accuracy of classification in [20] and [21]. Random forest is a multitude of de-correlated DTs such that each tree depends on a sub-vector randomly selected from the full-vector of predictors. The output (Secure or Insecure) of RF model is the voting result from a large number of DTs, which may benefit from aggregation-based variance reduction. Bootstrap sampling is used in RF to assist in better estimating the distribution of the original dataset. For each DT in RF, about one third of the cases are left out from the bootstrap sampling called out-of-bag (OOB) data which can be used for testing the model. Details of RF algorithm can be found in [22]. The accuracies of RF and CART are compared later in this paper (see Table I for the results).

IV. DATABASE PREPARATION FOR DT TRAINING

For a two-class classification problem (Secure or Insecure), the concept of entropy, commonly accepted in the information theory, is used here to evaluate the information content in the database [23], as defined in (6).

$$\text{Entropy}(S) = -p_3 \log_2 p_3 - p_1 \log_2 p_1$$

(6)

Prior adjusted probability is used effectively to control the splitting rules over the tradeoff between the class purity and class accuracy. The probability that a case lands in node $t$ is

$$p_t = \sum_{i=1}^{L} (n_i / N_t) \pi_i$$

(1)

where $\pi_i$, $N_t$ and $n_i$ ($i = 1, ..., J$) is the prior probabilities, the number of cases in LS, number of cases contained in node $t$ for class $i$, respectively. Then the conditional probability of class $i$ given that a case reached node $t$ is defined in (2)

$$p_i(t) = (n_i / N_t) \pi_i / p_t .$$

(2)

So the probabilities $p_i(t), p_d(t)$ that the cases in node $t$ going to left descendant node $t_L$ and right descendant node $t_R$ are defined as (3) and (4) respectively

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$$\text{Entropy}(S) = -p_3 \log_2 p_3 - p_1 \log_2 p_1$$

(6)
where $S$ is the training database, $p_S$, $p_I$ are the proportions of $S$ classified as secure and insecure respectively. So, a general prediction of security boundary and good representation of sampling OCs on both sides of the boundary are desirable.

In this paper, bisection method is adopted to approximately identify a region that contains the security boundary. Thus, only OCs adjacent to that region are simulated so as to significantly decrease the number of simulations. As illustrated in Fig. 4, the security boundary region is searched out by repeatedly bisecting the slot over Predictor Variable 2. In each iteration, the slot is selected in such a way that one end of the selected slot falls in secure region and the other end in insecure region and the repeated process should eventually converge at the security boundary. Then a security boundary is created by polynomial curve fitting of those points located between a secure and an insecure case.

Through this approach, the security boundary is traced in a multi-dimensional space of involved influencing factors. For example, CPPs which have relatively more flexible controllability can be used to compensate the uncertainties of wind power generation and other DG. During the search of security boundary in the space of CPP generation, wind generation and DG generation, other fixed important factors such as load and international power exchange should be maintained at their scheduled values.

However, it is important to mention that consideration of all possible generation uncertainties would result in a huge database. Given that the security boundary lies in the rare probability region, a database containing the sampling OCs within this rare probability region conveys more information, as the cases closer to the security boundary affect the process of making splitting rules much more than the cases away from the security boundary. So importance sampling is adopted to select the cases containing more information by revising the sampling distribution function $f(d)$ towards the security boundary, so as to reduce the computational cost.

The Gaussian distribution $N(0, \sigma^2)$ with probability function $f(d)$ is adopted to sample the OCs, as defined in (7)

$$f(d) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{d^2}{2\sigma^2}}.$$  \hspace{1cm} (7)

where $d$ is the 2-norm distance from the sampled OC point $x$ to the security boundary $y$, as defined in (8)

$$d = \left( \sum_{i=1}^{n} |x_i - y_i|^2 \right)^{1/2}.$$  \hspace{1cm} (8)

As shown in Fig. 5, the sampling OCs in the space of involved factors subject to Gaussian distribution. The cases close to the security boundary have higher probability to be selected for database than that away from the boundary. So a number of OCs are selected and biased to the interested region adjacent to the security boundary. The parameter $\sigma$, the standard deviation of the samplings, controls the degree of convergence to the security boundary.

![Fig. 4. The prediction of the security boundary.](image)

(a) Bisection method  (b) Curve fitting of security boundary

![Fig. 5. The probability function of sampling OCs](image)

(a) 2-norm distance to the boundary  (b) Probability density function

As illustrated by Fig. 6 on a comparison between two sampling methods, the number of cases given by importance sampling (IS) is significantly reduced but they still contain the critical information for differentiating insecure cases from secure ones. Assume that the splitting of databases created by normal sampling (NS) and that created by IS have the same boundary, i.e. the equally accurate results. However, the DT with IS usually suggests a lower value of accuracy due to two main reasons: i) a number of secure and insecure cases by IS overlap each other in the interested region, which makes clear splits more difficult; ii), a large number of apparent secure or insecure cases from NS outside the interested region, have minor effect on the final splits but are counted in the denominator of the accuracy ratio. A detailed analysis on the accuracies due to NS and IS is given in Appendix.

![Fig. 6. The selection of operating conditions.](image)

(a) Conventional sampling  (b) Importance sampling

V. PREVENTIVE CONTROL SCHEME

When a power system at a given OC is detected to be vulnerable to a specific credible contingency, the operators are supposed to take preventive actions to ensure its security in post contingency condition. Generation rescheduling which involves shifting generation among centralized generators so as to restore the system from insecure state to secure state is usually adopted by operators.

For each OC among $N_{OC}$ initially obtained OCs from IS, detailed T-D simulations for all the critical contingencies are executed. Specific security criteria such as transient instability,
two paralleled DTs for each critical contingency based on 24-hour horizon system prediction data, such as load forecast, weather forecast, unit commitment-based generation plan, network topology as well as the unavailability of system elements due to scheduled maintenance, etc. Fed with online measurements, ODT is employed for online DSA to identify the margins of predictors against their thresholds determined from DT training. If any online measurements of predictors violate the thresholds, ODT would provide situational awareness on insecurity if that contingency really happens. At the same time, PDT would provide system operators with preventive control schemes to drive the state to a new OC without insecurity under that contingency. Therefore, the parallel and cooperative utilization of PDT and ODT in the control schemes provides both the situational awareness and the preventive control against critical contingencies.

C. Control Strategy based on ODT and PDT

As illustrated in Fig. 8, two 2-dimensional (2-D) nomograms in (c) and in (d) are adopted to represent the secure operating regions determined by ODT in (a) and the PDT in (b) from the predictors and their thresholds, respectively. When the current OC ‘‘O’’ is in the insecure region shown in Fig. 8(c), the direction of preventive control can be easily found in Fig. 8(d), i.e. to reduce generation in CPP2. Moreover, the variation in generators’ outputs will definitely lead to the variation of the power flows in transmission lines, so the trajectory in PDT nomogram has its corresponding projection in ODT nomogram, for example the dashed lines in both Fig. 8(c) and Fig. 8(d).

Additionally, many constraints on OCs should still apply. For example, in order to maintain the international power exchange invariant, the sum of generation from involved CPP, CHP generation and wind power generation minus network loss and total load consumption must maintain as their
scheduled value, as defined by (9).

\[
\begin{align*}
\sum_{i=1}^{n} Gr_i + \sum_{j=1}^{p} Dr_j + \sum_{k=1}^{m} W_{rk} - P_{\text{loss}} - P_{\text{load}} \\
= \sum_{i=1}^{n} G_{s_i} + \sum_{j=1}^{p} D_{s_j} + \sum_{k=1}^{m} W_{s_k} - P_{\text{loss}} - P_{\text{load}}
\end{align*}
\]

*(9)*

where \( n, p \) and \( m \) are the total number of involved CPP generators, CHP generators and wind power plants respectively, \( Gr, Dr, Wr, Gs, Ds \) and \( Ws \) are real-time values and scheduled values of CPP generation, CHP generation and wind power generation in each generation unit respectively.

Thus, the process-cum-direction of preventive control can be represented by the trajectory shown in Fig. 8(d) by the solid line in PDT nomogram. “O’” and “O’’” are the original insecure OC. “A” and “A’’” represent the OC on the threshold of PDT, while “B” and “B’’” represent the OC on the threshold of ODT. The thresholds in ODT are more accurate than the thresholds in PDT, so the regions below “B” and “B’’” can be deemed as secure regions.

The block diagram shown in Fig 9 describes more clearly the detailed procedure of how ODT and PDT work in tandem to implement online DSA and preventive control scheme.

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**D. Prior Probability for DT**

As mentioned in Section III, prior probability is used to adjust the control guidelines over the tradeoff between dependability and security. By adjusting the ratio of prior probabilities of secure cases \( \pi_i \) and insecure cases \( \bar{\pi}_i \) from 0.5/0.5 to 0.99/0.01, one can find the security boundary in 2-D ODT nomogram with higher security. Conversely, by adjusting the ratio \( \pi_i/\bar{\pi}_i \) from 0.5/0.5 to 0.01/0.99, the security boundary with higher dependability can be found in 2-D ODT nomogram. The patch between these two boundaries is the fuzzy region, shown in yellow in Fig. 8(c). The regions below “C” and “C’’ have high security since the probability of exception (i.e. insecure case) is below 0.01.

Therefore, by monitoring the OC in ODT nomogram, the operators are informed of the exact amount of generation rescheduling that should be adopted.

**E. Optimization of Preventive Control**

As mentioned earlier, PDT and ODT are able to provide operators with the allowed range of generation rescheduling. Then the optimal control trajectory is searched out by minimizing the total economic cost due to generation rescheduling, as \( f(x,\bar{\lambda},\mu) \) defined in (10). A security constrained optimal power flow problem is formulated as

\[
\begin{align*}
\text{min.} & \quad f(x,\bar{\lambda},\mu) = c(x,\bar{\lambda}) + p(x,\mu) \\
\text{s.t.} & \quad g(x,\bar{\lambda},\mu) = 0 \quad \text{and} \quad h(x,\bar{\lambda},\mu) \leq 0
\end{align*}
\]

*(10)*

where \( x \) represents the variables in power flow, \( \lambda \) and \( \mu \) are control variables, e.g. generation outputs of CPPs involved in preventive control. \( \mathcal{R} \) is a set representing the allowed range of generation rescheduling to maintain international power exchange invariant. Two items on right side of (10) are respectively the cost of generation rescheduling and the penalty on violation of scheduled international power exchange, (11) gives equality constraints i.e. power flow equations and inequality constraints representing operational constraints, i.e. security criteria.

**VI. CASE STUDY**

**A. Danish Power System**

The scheme proposed in this paper is tested on the operational detailed model of western Danish power system with about 400 buses, 200 lines, 8 CPP units and 150 CHP units. Denmark, which currently produces around 50% of electricity from wind, plans to realize 50% wind share of electricity production by 2025 with wind turbines, especially offshore wind farms. Currently onshore and offshore wind farms are integrated in the system with capacities of 2232MW and 369MW respectively. A new offshore wind farm (Anholt) with 400MW capacity is expected to be commissioned in 2013. Further, about 40% of today’s total installed capacity in Danish system is decentralized generation units, such as onshore wind farms and CHP units. The geographical map of western Danish transmission system is shown in Fig. 10.
Cross border interconnections of western Danish power system to external grids are strong. So the abundance of hydro power generation in Norwegian and Swedish power systems can cooperate with the wind power generation in Denmark and Germany. The 400kV transmission system acts as the power transmission corridor, which is subjected to significant amount of active power transport.

Under the circumstances of such high penetration of wind generation and other DG, the wind forecast and the prediction of DG are not accurate, which lead to considerable mismatch between the predicted power flow and the actual power flow patterns in real time, so the online wide-area preventive control scheme in Danish grid is of great significance.

B. Analysis Tools

In this research, four tools have been used to develop the proposed approach: DIgSILENT/PowerFactory is used to create system OCs and perform power flow analysis and T-D simulations, which is interfaced with Excel via DIgSILENT Programming Language (DPL) to manage simulations and the results; Salford Predictive Miner [24] including CART and RF sub-packages is used for data mining; MATLAB is used for data collection, database creation and surface fitting.

C. Creation of DTs

The training of DTs should be based on a database which is built offline by screening $N_c$ “n-1” contingencies and “n-k” typical contingencies from Danish transmission system operator’s (Energinet.dk) historical record and experience on each OC. The “n-1” contingencies are the three-phase faults at the terminals of 400/150kV transmission lines with clearing time of 0.12 seconds. The database contains not only the predictor values, e.g. active power, reactive power, phase angle, voltage and current, before the disturbances calculated by power flow, but also the results of T-D simulations, i.e. secure (S) or insecure (I) based on criteria as given below:

- Transient stability: The system is considered as transient unstable for a given contingency, if the systems transient stability index (TSI) defined by (12) is lower than 10%, in which $\Delta \delta_{\text{max}}$ is the maximum angle separation of any two rotor angles in degree.

$$ TSI = \left( \frac{360 - \Delta \delta_{\text{max}}}{360 + \Delta \delta_{\text{max}}} \right) \times 100\% $$ (12)

- Short-term voltage security: The system is considered to be insecure if duration of any bus voltage going out of range from 0.8p.u. to 1.1p.u. is longer than 0.5sec.

Other criteria e.g. frequency drop, reactive power starvation, oscillation damping, etc. can also be included in this approach by simple modification in the programming. However, due to the severity status and special requirement of Danish power system, other specific criteria are not included for examination. Out of all possible contingencies, only a small proportion can result in the insecurity of power system and only those corresponding critical OCs violate the security criteria. Hence, only those critical contingencies will be selected to generate the contingency-oriented DTs. To demonstrate the proposed approach, the maximum load contingency selected is short circuit in 400kV KAS_400_LAG overhead line close to KAS substation, as tagged in Fig. 10.

Based on bisection search technique programmed by DIgSILENT/DPL, the approximate security boundary for contingency near KAS substation under maximum loading scenario is drawn by MATLAB surface fitting toolbox, shown in Fig.11. The upper side is predicted to be the insecure region and the lower side is predicted to be the secure region.

Then, importance sampling is utilized to bias the sampling towards this security boundary so that the cases closer to the security boundary would have higher probability to be selected for final refined database. Additionally, the number of cases in insecure region and secure region are controlled to be generally the same to maximize the entropy of the database. As shown in Fig. 12, given the standard deviation $\sigma=0.1$, 330 OCs each in secure region and insecure region for offline study are generated by importance sampling respectively, in which each spot represents an OC for the corresponding percentages of total CPP generation. Moreover, generator outputs are subjected to random distribution and wind farm outputs are based on the probability distribution density of forecast error with respect to forecasted wind power generation in Danish power system [25]. The process considering randomization on generator outputs while maintaining the total generation can assist the PDT to automatically find the most effective units to reschedule.

It is assumed that measurements are available from entire 400kV transmission system including all CPPs’ generation outputs (G_CPP). 660 power flow calculations (P_x_y,
Q_{x,y} before the disturbance are conducted to create the predictors of the database and 660 T-D simulations are carried out for the results of security after the disturbance. 80% of the cases are randomly selected to form the LS, and the rest 20% form the TS. Finally, The PDT and an ODT created by CART are shown in Fig.13 and Fig.14, where inner and terminal nodes are respectively tagged with capital letters and numbers.

It is worth to mention that by considering phase angle differences between any two buses (A_{x,y}), the accuracy of DSA is improved. The comparison of accuracy between the measurement vectors with and without A_{x,y} shows the superiority of WAMS over SCADA by increasing the accuracy of about 3%, as shown in Table I. However, in a small power system with relative less line loading, the angle differences are relatively small which may result in erroneous judgment if it is not taken carefully during practical implementation. Some other advanced algorithms such as RF can also be used to predict the security with higher accuracy, as shown in Table I. However, the model trained by RF contains a large number of deep-grown DTs, which are difficult to be interpreted for preventive control. The combination of RF and preventive control is currently being pursued. As mentioned before, the values of accuracy still indicate with lower number than industrial requirement due to the implementation of importance sampling. A detail analysis regarding this issue is given in Appendix. Besides, one can easily adjust prior probability in the process of DT training to find the fuzzy region so as to significantly increase the reliability to achieve ‘3 nines’ reliability standard [26].

### Table I

<table>
<thead>
<tr>
<th>Datasets</th>
<th>Insecure (%)</th>
<th>Secure (%)</th>
<th>Average (%)</th>
<th>Overall (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS of ODT w/o A_{x,y} by CART</td>
<td>257/12</td>
<td>252/6</td>
<td>96.61</td>
<td>96.58</td>
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<tr>
<td>TS of ODT w/o A_{x,y} by CART</td>
<td>73/4</td>
<td>51/5</td>
<td>92.94</td>
<td>93.23</td>
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<tr>
<td>LS of ODT w/ A_{x,y} by CART</td>
<td>255/4</td>
<td>256/2</td>
<td>97.01</td>
<td>96.96</td>
</tr>
<tr>
<td>TS of ODT w/ A_{x,y} by CART</td>
<td>76/1</td>
<td>52/4</td>
<td>95.78</td>
<td>96.24</td>
</tr>
<tr>
<td>OOB test of ODT w/ A_{x,y} by CART</td>
<td>299/15</td>
<td>338/8</td>
<td>96.61</td>
<td>96.58</td>
</tr>
<tr>
<td>TS of ODT w/ A_{x,y} by RF</td>
<td>76/1</td>
<td>53/3</td>
<td>96.67</td>
<td>96.99</td>
</tr>
</tbody>
</table>

In Fig.13, ODT has five critical attributes of transmission lines, i.e. P_{FKNA_KAS1}, P_{FGD_FVO}, P_{FER_TJE}, P_{EDR_REV}, and P_{ASR_REV}, and one critical attribute of generator output G_{CPP1_ENVB3} which have been highlighted in Fig. 10. In Fig. 14, PDT has three critical attributes from three CPPs, i.e. G_{CPP1_ENVB3}, G_{CPP3_ESVB3}, G_{CPP7_FYVB7}. Most critical attributes selected by ODT for transmission lines belong to one backbone on Jylland Peninsula and one for the key transmission line on Fyn Island. All the critical attributes selected by PDT are generators in the southern part, close to the selected contingency. P_{FKNA_KAS1} is one of the paralleled key transmission lines connecting German grid.

### D. Preventive Control Based on DTs

The ODT and PDT in Fig. 13 and Fig. 14 can be reproduced to 2-D nomograms to depict the space and its regions, as shown in Fig. 15 and Fig. 16. In each region the percentage of correctness and the serial numbers of the corresponding nodes are indicated. The red regions are insecure regions tagged by (I), while the green regions are secure regions tagged by (S). The thresholds in ODT in Fig. 13 are highlighted by solid lines and blue figures in 2-D nomograms in Fig.15. The yellow regions between dashed lines are the fuzzy regions, in which the prior probability of insecure cases is between 0.01 and 0.99. As shown in Table II, the ODT has higher classification accuracy than that of PDT because fewer variables are selected as predictors of PDT. However, the lower accuracy of PDT does not affect the reliability of preventive control because PDT can successfully search out the most effective controllable variables and provide the control directions. As shown in Fig. 16, the PDT nomogram is capable of informing the most influential CPPs \(\text{ENVB3}, \text{FYVB7} \) and \(\text{ESVB3}\) that need to be controlled and their control directions, i.e. to reduce generation in \(\text{ENVB3}\) and \(\text{FYVB7}\) and simultaneously to increase generation in \(\text{ESVB3}\).

Fig. 17 shows the annual data of total CPP generation, total CHP generation and total wind generation represented by percentages based on their installed capacities [27]. At 09:00am, Feb. 2\textsuperscript{nd}, 2011, the OC is detected to be in the insecure region, shown by the dot tagged with “OC” in Fig. 18.

### Table II

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Insecure(S/I)</th>
<th>Secure(S/I)</th>
<th>Ave. (%)</th>
<th>Ove. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LS of ODT</td>
<td>257/12</td>
<td>252/6</td>
<td>96.61</td>
<td>96.58</td>
</tr>
<tr>
<td>TS of ODT</td>
<td>73/4</td>
<td>51/5</td>
<td>92.94</td>
<td>93.23</td>
</tr>
<tr>
<td>LS of PDT</td>
<td>184/85</td>
<td>199/59</td>
<td>72.77</td>
<td>72.68</td>
</tr>
<tr>
<td>TS of PDT</td>
<td>53/24</td>
<td>32/24</td>
<td>62.99</td>
<td>63.91</td>
</tr>
</tbody>
</table>

In order to maintain the constant value of total generation in Denmark, the equation (13) must be respected.

\[ G_{CPP1_ENVB3} + G_{CPP3_ESVB3} + G_{CPP4_FYVB7} = \text{Const.} \]

Other constraints such as PQ-capacity limits of each generator and individual limits of CPP generation rescheduling should also be applied, as given in Table III.

Hence for this particular case as defined by (13), a surface boundary can be found, within which the total generation is maintained constant, respecting the abovementioned constraints, as shown in Fig. 18. The trajectories “A”, “B” and “C” are some of the feasible control directions on the surface which would lead the system to the secure region.

As shown in Fig. 15, the surface of generation rescheduling in the 3-D space of involved generators can be reproduced by its corresponding surface in 2-D ODT nomogram, which shows the effect of generation rescheduling with more clarity in the feasible region as shown in Fig. 19(a) which is the enlarged version of Fig. 15(e). The green spots on the surface represent the secure cases, while the red spots represent the insecure cases. It can be observed that the trajectories “A”, “B” and “C” are the control directions which are able to reliably draw the system to the secure region.
Fig. 13. The ODT for contingency near KAS.

Fig. 14. The PDT for contingency near KAS.

Fig. 15. The 2D-nomogram of ODT

Fig. 16. The 2D-nomogram of PDT.

Fig. 17. Annual data of generation.

Fig. 18. Control constraint surface.
The prediction of DT is followed by its verification through T-D simulations. Only the criterion of transient stability is violated in this case, so Fig. 19(b) (c) and (d) show the rotor angle curves of the involved generators for OCs tagged with “0” to “6” on the control trajectories “A”, “B” and “C”, respectively, in which the disturbance near KAS takes place at 0sec, and lasts for 0.12sec.

The results successfully verified the prediction of power system security as well as the guidelines of preventive control scheme. By rescheduling the generators instructed by this systematic preventive control scheme, the power system insecurity can be averted.

According to the actual regulations of Danish power system, (giving considerations to the prices of domestic reserve services and the penalty in cases of international exchange mismatch) further optimization on the trajectory of preventive control is conducted to minimize the total cost incurred by generation rescheduling, as defined in (14).

\[
\min C = \sum_{i \in G} C_i + f(\Delta P_{EX})
\]  

1) Cost of reserve services
\[
C_i = C_{fi} + P_{API} \cdot |\Delta G_{API}| + P_{DOI} \cdot |\Delta G_{DOI}|, \quad \forall i \in G
\]

where
\[
\Delta G_{API} = \begin{cases} 
G_t - G_i & \text{if } G_t > G_i \\
0 & \text{if } G_t \leq G_i
\end{cases}
\]
\[
\Delta G_{DOI} = \begin{cases} 
G_t - G_i & \text{if } G_t \geq G_i \\
G_t - G_i & \text{if } G_t < G_i
\end{cases}
\]

s.t. \( G_{i_{\text{min}}} \leq G_t \leq G_{i_{\text{max}}} \) \quad \text{(15)}

s.t. \( 0 \leq \Delta G_{API} \leq \Delta G_{PRI} \) and \( \Delta G_{DOI} \leq \Delta G_{DID} \leq 0 \) \quad \text{(16)}

As defined in (15)–(17), the cost of reserve services is composed of fixed cost \( C_{fi} \) and variable cost depending on the actual quantity of generation rescheduling in effect, either upward or downward. The amount of generation rescheduling in each generator should also subject to the P-Q capacity and the limitations of the maximum available generation reserves in both directions, defined in (18) and (19).

2) Penalty due to mismatch of international power exchange
\[
\Delta P_{EX} = \sum_{i \in G} \Delta P_{UPi} + \sum_{i \in G} \Delta P_{DNi}, \quad \forall i \in G
\]  

\[
f(\Delta P_{EX}) = \begin{cases} 
P_{C_{i_{\text{max}}}} \cdot \Delta P_{EX} & \text{if } |\Delta P_{EX}| \leq 0.5 \text{MW} \\
P_{C_{i_{\text{pen1}}} \cdot \Delta P_{EX} + C_{\text{pen2}}} & \text{if } |\Delta P_{EX}| > 0.5 \text{MW}
\end{cases}
\]  

Assuming that the network loss is invariant during preventive control, the imbalance between generation and load introduced by generation rescheduling in Denmark is compensated by German power system, as defined by (20). For mismatch between actual and scheduled power exchange larger than 50MW or 100MW, penalties \( C_{\text{pen1}} \) or \( C_{\text{pen2}} \) are applicable respectively, as defined in (21). As given in Table III, the prices of reserve services from participating generators in Denmark and the cost of international power exchange with Germany are assumed based on typical data.

\[
\text{TABLE III}
\]

<table>
<thead>
<tr>
<th>Price</th>
<th>CPP1_ENVB3</th>
<th>CPP2_ENVB3</th>
<th>CPP4_FYVB4</th>
</tr>
</thead>
<tbody>
<tr>
<td>( G_{\text{MAX}} ) (MW)</td>
<td>626</td>
<td>378</td>
<td>372</td>
</tr>
<tr>
<td>( C_{\text{MAX}} ) (MW)</td>
<td>188</td>
<td>98</td>
<td>110</td>
</tr>
<tr>
<td>( \Delta P_{\text{UP MAX}} ) (MW)</td>
<td>+39</td>
<td>+113</td>
<td>+32</td>
</tr>
<tr>
<td>( \Delta P_{\text{DOWN MAX}} ) (MW)</td>
<td>-75</td>
<td>-64</td>
<td>-38</td>
</tr>
<tr>
<td>( C_{F1} ) (DKK)</td>
<td>2230</td>
<td>1940</td>
<td>1880</td>
</tr>
<tr>
<td>( C_{F2} ) (DKK/MW)</td>
<td>535</td>
<td>390</td>
<td>450</td>
</tr>
<tr>
<td>( C_{F3} ) (DKK/MW)</td>
<td>328</td>
<td>208</td>
<td>286</td>
</tr>
</tbody>
</table>

Fig. 20 shows the cost of preventive control along trajectory A, B and C. After optimization, trajectory A is found to be the most economical trajectory and the optimal objective OC after rescheduling is below the threshold of reliable security boundary between “3” and “4” on trajectory A. The minimum cost is 42,392 Danish Kroners (DKK).

Fig. 20. Rotor angles curves of involved generators in Trajectory A, B and C.

To evaluate the overall reliability of this approach, multiple contingency-oriented DTs are created for eight most critical \( n-1 \) contingencies which have been screened out by critical clearing time (CCT) calculations of Danish power system in [28]. The size, overall accuracies of LS and TS of these DTs are shown in Table IV. Among these contingencies, only five events violate the transient stability or short-term voltage security criteria. For each contingency, 20 insecure OCs are randomly generated. 98% of the random generated insecure OCs can be controlled and guided back to the secure
region (across the fuzzy region), if international power exchange is maintained as invariant. The remaining 2% OCs can certainly be controlled by varying the international exchange power with Germany, however at the cost of penalty.

<table>
<thead>
<tr>
<th>Con. No.</th>
<th>Fault Event</th>
<th>Switch Event</th>
<th>DT Size</th>
<th>Ove.(%) of LS</th>
<th>Ove.(%) of TS</th>
<th>Suc. Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>KAS</td>
<td>KAS_400_LAG</td>
<td>13</td>
<td>96.38</td>
<td>93.23</td>
<td>20/20</td>
</tr>
<tr>
<td>2</td>
<td>KAS</td>
<td>KAS_400_REV</td>
<td>14</td>
<td>97.54</td>
<td>94.66</td>
<td>19/20</td>
</tr>
<tr>
<td>3</td>
<td>LAG</td>
<td>LAG_400_SVS</td>
<td>18</td>
<td>96.03</td>
<td>93.13</td>
<td>19/20</td>
</tr>
<tr>
<td>4</td>
<td>LAG</td>
<td>LAG_400_MAL</td>
<td>17</td>
<td>96.39</td>
<td>95.52</td>
<td>20/20</td>
</tr>
<tr>
<td>5</td>
<td>TRI</td>
<td>FER_400_TRI</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>6</td>
<td>TRI</td>
<td>MAL_400_TRI</td>
<td>21</td>
<td>97.87</td>
<td>96.52</td>
<td>20/20</td>
</tr>
<tr>
<td>7</td>
<td>NVV</td>
<td>NVV_400_VHA</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>8</td>
<td>NVV</td>
<td>FER_400_NVV</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

**TABLE IV**

**VERIFICATION OF THE MOST CRITICAL CONTINGENCIES**

**TABLE V**

**ACCEPTED BY IEEE TRANSACTIONS ON POWER SYSTEMS**

**ACKNOWLEDGMENT**

Authors would like to thank Energinet.dk (Danish national TSO) for providing the data of western Danish power system.

**REFERENCES**


**Biographies**

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**Per Lund** (M’95–SM’02) is Chief Engineer at Energinet.dk, the Danish TSO owned by the Danish Climate and Energy Ministry. For the last six years he has been focusing his research activities on the Danish Cell Controller Pilot Project, which seeks to create the prototype of the future Danish intelligent power system. During this period, Dr. Lund has in parallel worked with advanced PMU/WAMS technologies such as Early Warning Systems based on Voltage Angel Stability prediction, and contributed to the development of National Grid Codes for fossil fired power stations. He earned his M.S. and Ph.D. degrees in Electrical Engineering from the Technical University of Denmark in 1983 and 1985 respectively. He is author or co-author of more than 20 publications in international journals and conference proceedings and has a general background in power system planning in large utility-owned systems. For a period of 13 years Dr. Lund worked worldwide as a senior engineer at Danish Power Consult, a former Danish based international consulting engineering company. The assignments abroad and at various industrial clients in Denmark ranged from feasibility studies concerning the introduction of wind farms in diesel powered island systems, transmission system reinforcements and expansions, power system loss reduction to specialized transient analysis of shaft or gear wheel breakdown in combined cycle generation plants following major faults in the electrical transmission system as an previous 6 year employment in the Planning Department of the former Danish Electricity Consortium Elsam A/S he has gained comprehensive experience in utilizing computer programs for steady state and transient stability analyses used in the design and planning of power transmission systems. He has developed the SETPOS program system. Dr. Lund is a Senior Member of the IEEE and a certified European Engineer.