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Dynamic Security Assessment of Danish Power System Based on Decision Trees: Today and Tomorrow

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***Abstract*—The research work presented in this paper analyzes the impact of wind energy, phasing out of central power plants and cross border power exchange on dynamic security of Danish Power System. Contingency based decision tree (DT) approach is used to assess the dynamic security of present and future Danish Power System. Results from offline time domain simulation for large number of possible operating conditions (OC) and critical contingencies are organized to build up the database, which is then used to predict the security of present and future power system. The mentioned approach is implemented in DIgSILENT PowerFactory environment and applied to western Danish Power System which is passing through a phase of major transformation. The results have shown that phasing out of central power plants coupled with large scale wind energy integration and more dependence on international ties can have significant impact on dynamic security of Danish power system in future, if alternative measures are not considered seriously.**

***Index Terms*—Centralized and decentralized power plants, decision trees, high voltage direct current (HVDC), power system security, wind energy.**

I. Introduction

Renewable energy (RE), especially wind and solar power is experiencing tremendous growth across the globe. The European Wind Energy Association (EWEA) has set a target to meet 23% European electricity needs with wind by 2030. Over past decades Danish Power System has transformed from conventional predominated with central power plants to a decentralized one with around 40% dispersed generation. Denmark which currently produces more than 25% [1] of electricity from wind is experiencing major transformation in the grid. This transformation includes plan to realize 50% wind share of electricity production by 2020, 100% fossil fuel free society by 2050[2], phasing out central power plants by 2025 and promising plan to enhance already strong cross border interconnections.

Currently, Danish transmission system operator (TSO) has declared three must run central power plants (CPPs) in western Danish power system primarily to support ancillary services to ensure secure and stable operation, however in future, TSO is planning to reduce these must run power plants below three. It is pertinent to mention here that presently primary control actions of power system are mainly assigned to CPPs.

Different kinds of approaches based on DT have been applied to analyse various aspects of power system mainly related to dynamic stability and security [3]-[10]. This paper has adopted the approach of contingency dependant DTs to achieve higher efficiency and accuracy by maximizing the information available in database.

Main focus of the research work presented in this paper is to study the impact of three mentioned major changes happening in Danish power system together which include increase of wind energy share accompanied by decrease in central power plants to realize green electricity in the region. To accommodate large penetration of wind energy, Denmark has taken up the work of strengthening cross border interconnection with promising plan. Therefore the need of evaluating risk of power system security under such challenging conditions which includes phasing out of CPPs, large wind energy penetration and strengthening of HVDC interconnections, was strongly felt and has been analysed in the presented work.

The rest of the paper is organised as below. Section II describes western Danish power system and its modelling. Section III presents the proposed DT based methodology for security assessment. The results showing the impact of mentioned three major changes being experienced by Danish power system on dynamic security are discussed in Section IV followed by concluding remarks presented in Section V.

II. Danish Power System and Modelling

A. Danish Power System[11]

Danish power system is divided in two non-synchronous systems known as western and eastern Danish power system. Energinet.dk being the transmission system operator (TSO) in Denmark generally names western and eastern Danish power system as Energinet.dk West (ENDKW) or DK1 and Energinet.dk East (ENDKE) or DK2 respectively. Western Danish power system is synchronized with Germany and eastern Danish power system is synchronized with Nordic grid through Sweden. Key figures of Danish power system as

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of 2011 are given in Table I. DK1 and DK2 are interconnected by Great Belt High Voltage Direct Current (HVDC) link of 600MW capacity. Strong cross border interconnection network connects Danish power system DK1 to Germany (HVAC), Norway (HVDC), Sweden (HVDC) and DK2 to Germany (HVDC), Sweden (HVAC). To strengthen the cross border network new voltage source converter (VSC) based HVDC link to Norway is under construction in addition to new planned links to Germany and Netherland.

Denmark is witnessing very fast growth of wind power especially since last two decades [12]. Offshore wind farms are being taken up at priority with twenty six offshore potential sites of around 5,200 MW total capacities [13].

TABLE I. KEY FIGURES OF WESTERN & EASTERN DANISH POWER SYSTEM

Description	ENDKW	ENDKE
Minimum Load(MW)	1400	900
Maximum Load(MW)	3700	2700
Primary Power Stations(MW)	3400	3800
Local CHP Plants(MW)	1643	640
Wind Turbines(MW)	2840	960

B. Modeling of Western Danish Power System.

411 bus Western Danish power system has been modeled in DIgSILENT PowerFactory. Western Danish power system data for the study has been provided by Danish TSO Energinet.dk. Aggregate load model for each distribution feeder has been considered connected mainly at 60KV level. The overall idea of western Danish power system modeling in DIgSILENT Power Factory is provided in Table II.

TABLE II. KEY FIGURES OF DIGSILENT MODEL OF WSTERN DANISH POWER SYSTEM

Total No. of Buses	411
Total No. of Synchronous machines (including CHPs*)	140
Total No. of Asynchronous Machines	56
Total No. of full scale converter based wind farms	30
Total No. of Transmission Lines	124
Total No. of Loads	70
Total No. of 2 winding Transformers	317
Total No. of 3 winding Transformers	9
Total No. of Shunts (Inductive & Capacitive)	40

*combined heat and power plants

III. PROPOSED METHODOLOGY

A. Decision Trees

Decision tree (DT) is a decision support tool which uses a binary structured tree graph or model to predict their possible consequences. As shown in Fig. 1, given a set of measurements on a case or object, the result of what class the case or object is in (i.e. Secure or Insecure) can be predicted by dropping the object downward from a root node to a terminal node of a DT. The vector of predictors can be composed of both numerical variables (e.g. A) and categorical variables (e.g. B). Variables are called numerical variables if their measurements are real numbers, while called categorical variable if it takes values in a finite set not having any natural ordering.

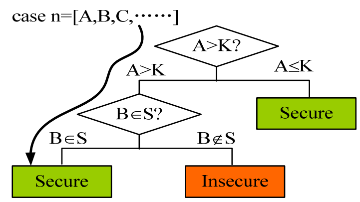


Figure 1. A simple illstrative DT.

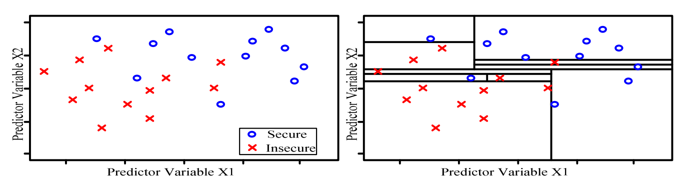
B. Training of DTs

The data mining algorithm named Classification and Regression Trees (CART), developed by Breiman *et al.* [14], is adopted to train the DTs. The training process is the building of classification rules at each node of DT. Therefore the total data set is divided optimally in training data set (TS) and a test data set (TS). The training data set is the data that is used to train the DT. The test data set comprises of an appropriate portion of the whole available data that should be reserved to evaluate the accuracies of the created DTs. In general, appropriate portion between 20-30% of all available data should be used to form test data set and the remaining data is used for training set.

In a database of N_{OC} cases, each case include a vector of measurements before the disturbance which serves as predictors and the result of time domain(T-D) simulations after the disturbance (Secure or Insecure) which serve as the target for aforementioned predictors. The key criterion of a successful DT is the prediction accuracy of the cases in TS.

C. Splitting Rules of Decision Trees

A database composed of a number of cases is necessary for training the DTs. Each case which is built up by a vector of measurements acts as predictor and corresponding output acts as the target of classification. As shown in Fig. 2, the fundamental idea to select each split of a subset is such that, the cases in each of the descendant node are purer than their parent node.



(a) The TS of the database (b) The splitting rules of the TS

Figure 2. The optimal classification in two demensional vector space.

The GINI index depending on a node impurity measure has been adopted for finding the optimal splits. Given a node t with estimated class probabilities $p(j|t), j = 1,\ldots J$, a measure of node impurity is defined by $i(t)$ in (1).

$$i(t) = \sum_{i \neq j} p(i|t)p(j|t) = \left(\sum_j p(j|t)\right)^2 - \sum_j p^2(j|t) = 1 - \sum_j p^2(j|t) \quad (1)$$

If split δ of a node t sends a proportion p_L of the data cases to left node t_L and proportion p_R to right node t_R, the decrease of impurity is defined by $\Delta i(\delta, t)$ in (2).

$$\Delta i(\delta,t) = i(t) - p_L i(t_L) - p_R i(t_R) \tag{2}$$

The optimal selection of splitting rules can be calculated by a repeated attempt to minimize the overall impurity of a DT, as defined by $I(T)$ in (3), in which T_t is the terminal node of the DT.

$$I(T) = \sum_{t \in Tt} I(t) = \sum_{t \in Tt} i(t) p(t) \tag{3}$$

The criterion to stop splitting is given by (4), when the improvement of impurity is less than a threshold value β.

$$\max_{\delta \in S} \Delta I(\delta,t) < \beta \tag{4}$$

D. Strengthen the Decision Trees

The univariate DT may result in large trees as CART attempts to approximate the hyper-planes by multidimensional rectangular regions. To cope with this situation, the DT can be strengthened by combination of variables by searching the best split of the form, as defined in (5)

$$\sum_m a_m x_m \le c \tag{5}$$

The best splits is selected by the objective that maximizes the decrease of impurity, as defined in (6)

$$\Delta i(\delta^*(\mathbf{a}^*),t) = \max_{\mathbf{a}} \Delta i(\delta(\mathbf{a}),t) \tag{6}$$

where $\mathbf{a} = (a_1, \cdots, a_m)$ such that $\|\mathbf{a}\|^2 = \sum_m a_m^2 = 1$.

E. Prior Adjusted Probability

Prior adjusted probability is used to effectively control the splitting rule over the tradeoff between the class purity and class accuracy, which is defined as the probability that a case lands in node t as given by (7)

$$p_t = \sum (n_i / N_i) \pi_i \ . \tag{7}$$

where

π_i ($i = 1,\ldots,J$) is the prior probabilities for class i,

N_i ($i = 1,\ldots,J$), is the number of cases in LS which is class i, n_i ($i = 1,\ldots,J$), is the number of cases contained in node t which is class i.

Then the conditional probability of class i given that a case reached node t is defined in (8)

$$p_i(t) = (n_i / N_i) \pi_i / p_t \ . \tag{8}$$

So the probabilities $p_L(t)$, $p_R(t)$ that the cases in node t going to left descendent node t_L and right descendent node t_R are defined by (9) and (10) respectively

$$p_L(t) = p_t^{left} / p_t^{parent} \tag{9}$$

$$p_R(t) = p_t^{right} / p_t^{parent} \ . \tag{10}$$

By adjusting prior probabilities π_i, one can find the overlapping zones between two classes, as shown by green patch in Fig.3. The zones in red and blue are with probability of exception lower than π_r and π_b respectively.

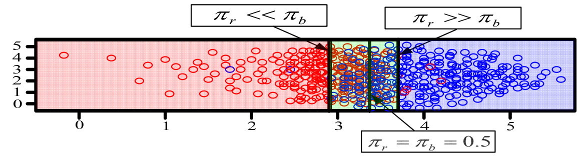


Figure 3. The thresholds of DT with respect to prior probability adjustment.

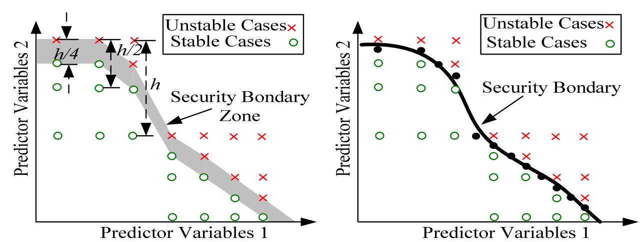
F. Assessment of Security Boundary

For a two-class 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 [14], as defined in (11).

$$Entropy(S) = -p_S \log_2 p_S - p_I \log_2 p_I \tag{11}$$

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 is required and good representation of sampling OCs on both sides of the class boundary is desirable.

Bisection method is adopted to approximately predict the security boundary , which significantly decreases the number of simulations. As illustrated in Fig. 4, the security boundary zone 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 and the other end in insecure zone and the repeated process eventually converges at the security boundary Thereafter curve fitting algorithm is used to create final and finely tuned security boundary by fitting the points located between a point of stable and unstable case at security boundary zone.



(a) bisection method (b) curve fitting

Figure 4. The prediction of the security boundary.

Through this approach, the security boundary is traced in a multi-dimensional space of involved influencing factors. To be more specific with respect to the study case of ENDKW, for all possible combinations of wind power generation (0-100%) and CHP generation (10-100%), the security boundary is searched out by repeatedly bisecting slot over CPP generation (30-100%). As mentioned earlier, in each iteration, the slot is selected in such a way that one end of selected slot falls in secure and the other end in insecure zone and the repeated process eventually converges to the security boundary which is followed by curve fitting technique. Additionally, the number of cases in insecure zone and secure zone are controlled to be same to maximize the entropy of the database, defined by (11). During the search of security boundary in 3D space other important factors such as total load, total generation should be maintained at their scheduled values.

IV. Results and Discussion

The proposed DT based methodology is applied to western Danish Power System. The training of DTs is 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 database contains both predictor values such as active power, reactive power, phase, voltage, current before the contingency and also the target values which are the results of T-D simulation secure (S) or insecure (I) based on criteria as given below:

- *Transient instability*: For a given contingency, the system is considered as transiently unstable if the transient stability index (TSI) defined by (10) is lower than 10%, where $\Delta\delta_{max}$ is the maximum angle separation of any two rotor angles in degree [15].

$$TSI = \left[\left(360 - \Delta\delta_{\max} \right) / \left(360 + \Delta\delta_{\max} \right) \right] \times 100\% \qquad (10)$$

- *Dynamic voltage security*: Should the duration of any bus voltage going out of range from 0.8p.u. to 1.1p.u. exceed 0.5sec,the system is considered to be insecure.

In this research work, security assessment of present Danish Power System and upcoming future Danish power system which will be characterized by least presence of CPPs under high penetration of wind energy has been studied. Since ENDKW is strongly interconnected with neighboring Nordic countries exclusively through classical HVDC links, therefore the influence of cross border power exchange through these HVDC links, on the dynamic security has also been analyzed. The entire study has been carried out on ENDKW.

Sequence of phasing out of CPPs has been considered as planned by Danish TSO. It is pertinent to mention here that throughout this study, current grid codes have been considered to assess the security of future Danish power system and subsequently highlight the need of new and promising grid codes for maintaining grid security in future.

The three aforementioned changes being experienced by Danish power system have been considered together while assessing the security using proposed DT based methodology. During the entire study, any steady state change in generation or power exchange across HVDC links was met by Germany which acts as slack bus to ENDKW.

A. Impact of CPPs on Dynamic Security

As mentioned in Section I, most of CPPs are planned to be phased out by 2025, a process in this regard has been already initiated by Danish TSO. Since the primary ancillary services like active power reserve, reactive power reserve/short circuit power and inertia support are mainly provided by CPPs, therefore Danish TSO has declared three minimum must run CPPs in ENDKW to maintain security of power system.

The influence of CPPs on synchronous stability based dynamic security is shown in Fig. 5. A vast range of operating conditions (OC) and contingency cases especially critical contingencies (Nc) were considered to predict the future ENDKW security, covering almost entire range of possible OCs in future ENDKW, which is supposed to carry negligible CPPS, more than 80% wind energy and strong HVDC interconnections. The security boundary as shown in Fig. 5 divides the OCs in upper zone of secure and lower zone of insecure regions. As expected the system is quite secure with more number of CPPs at lower share of wind energy characterized by higher security margin. The percentage on z-axis (CPP axis) is the MW generation of CPPs with respect to total installed capacity of all CPPs. Lesser the number of CPPs, more the compromise with security till total number is reduced to three beyond which the system collapses and hence enters the insecure zone below the security boundary. It was found that the least number of CPPs required for stable and secure operation of ENDKW is three which is in line with the practice currently followed by Danish TSO.

It can be also observed that the impact of CPPs is relatively more on voltage security as can be seen from Fig. 6. Since with the existing grid codes and mix of higher wind energy coupled with more HVDC cross border interconnection, the future system is expected to experience more scarcity of reactive power especially at transmission level and hence the more impact on voltage security.

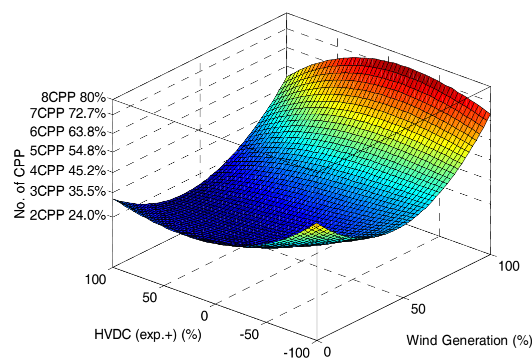


Figure 5. The security boundary for synchronous stability

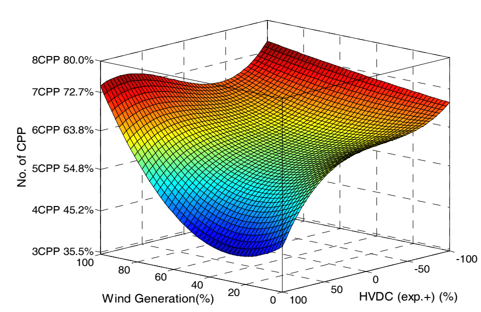


Figure 6. Voltage security boundary

Therefore in order to maintain the secure and stable operation of Danish power system in future, primary control responsibilities which are currently being carried out by CPPs need to be shifted to competitive alternative sources. A significant change in present day grid codes is one of the needs of hour to address such security related issues.

B. *Impact of HVDC on Dynamic Security*

ENDKW is strongly connected to Norway and Sweden through classical HVDC links. A new voltage sources converter (VSC) based HVDC link of 700MW capacity to Norway is under construction and is expected to be commissioned soon. Therefore it is the need of hour to evaluate impact of HVDC cross border interconnections on the security of Danish power system. Albeit, HVDC interconnections could be used for dynamic support from technical point of view, however due to current market regulations, these HVDC interconnections are not capable of providing dynamic support to ENDKW. These regulations of Nordic market does not allow change of power flow direction within each transaction hour, though reduction in power flow in predetermined direction is allowed on quarter hourly basis[16].

Fig.7 and Fig.8 where lower and upper portion of security boundary represent secure and insecure zone respectively for a three phase short circuit close to German interconnection, shows the impact of HVDC on dynamic security of ENDKW. It is important to note that during this short circuit, the power exchange from Germany reduces to a low value because of the low voltage level. It can be observed from Fig. 7 that transient stability margin is reduced by power exchange across HVDC links, import being relatively more important area of concern. In case of power import across HVDC links from Norway, there is surplus of net generation during the aforementioned contingency, hence the system is more unstable. However in case of power export across HVDC link, there is net deficit in generation during the same contingency close to German interconnection and hence the system is relatively more stable as the HVDC export acts as an additional load during the fault.

The impact of HVDC power exchange on dynamic voltage security is shown in Fig. 8. Since the converters of classical HVDC link consumes power irrespective of direction of power flow, therefore voltage security boundary for both import and export case is lower than the isolated case where exchange across HVDC is zero and so is the reactive power consumption by converter station. In case of import, there is surplus power flowing in the system during fault hence additional reactive power consumption due to higher reactive power losses in transmission system and vice versa in case of export. Therefore security level in case of HVDC import is relatively less than export case. Therefore it can be concluded that classical HVDC power exchange with current market regulations compromises power system dynamic security of Danish Power System.

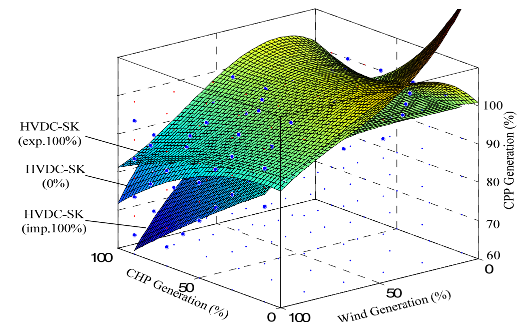


Figure 7. Transient stability boundary w.r.t power exchange in HVDC lines

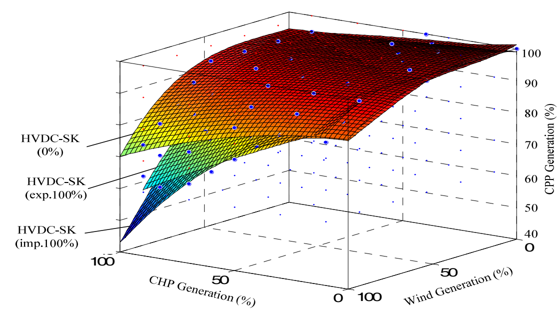


Figure 8. Volgae security boundary w.r.t power exchange in HVDC lines

C. *Impact of Wind Energy on Dynamic Security*

Wind energy is being integrated to Danish power system at tremendous pace with promising plan to experience 100% fossil fuel free society by 2050. Offshore wind farms of higher capacity are being added consistently to ENDKW to achieve 3800MW offshore wind power in future. It can be observed from Fig. 4 and Fig. 5 that both synchronous and voltage security are effected with the increase in wind power share. Higher the percentage of wind power lesser is the area of secure zone. Similar results can be perceived from Fig.6 and Fig.7. Since wind energy especially with existing grid codes does not support the grid primarily in ancillary services, the system becomes more insecure due to higher wind energy penetration. Intermittent nature of wind does not only increase the challenge of power balance in the system, but also enhances the frequency and other dynamic stability issues in the system. Therefore it can be concluded that large integration of wind energy increases the challenge of secure operation in future Danish power system.

D. *Futher Discussion on Dynamic Security Assessment.*

To provide deep insight of how to assess if a given contingency is secure or insecure using contingency oriented DT based technique, specific contingency based DT is demonstrated in Fig. 9. The contingency selected is three phase short circuit in 400kV overhead line close to the 400KV substation named as KAS. 660 power flow calculations 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. Finally contingency based DT is created by CART algorithm in Salford Predictive Miner Builder v6.6 [17] as shown in

Fig.9. In this DT, power flow over transmission lines and generation of CPPs are considered as predictors for assessing if a given OC is secure or insecure for aforementioned contingency. Therefore in this case, power flow of 400KV line FKNA400_KAS1 is measured from online measurements of the power system and dropped at node A of this specific DT, if the mentioned power flow is less than or equal to 842.59MW then the case will go to node-B, otherwise the case will go to node-G, in similar way by verifying the condition at each node , the give operating state will end up at one of the 13 terminal nodes(1-13) and hence conclude the state(secure or insecure) of ENDKW system. It is also important to mention that the proposed DT based technique is feasible for online dynamic security assessment.

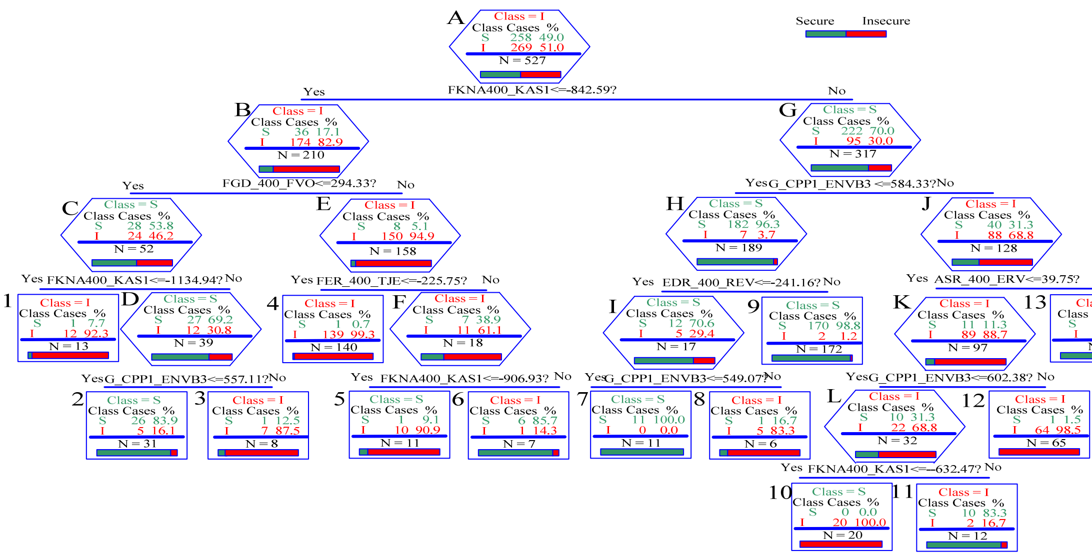


Figure 9. Contingency orientied DT for assessing security of western Danish power system

V. Conclusion

This paper has proposed contingency oriented DT based technique for online dynamic security assessment. The research work presented analyzed the dynamic security of present and future Danish Power system highlighting the importance of addressing power system security issues under the influence of large wind energy penetration, least no. of CPPs and more dependence on cross border exchange through HVDC links. It was concluded that ENDKW cannot operate with lesser than three CPPs until and unless alternatives to take the responsibility of ancillary services are sought out. The need of new grid codes as one of the possible solution has been also suggested.

VI. Acknowledgement

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