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Impact of Value of Lost Load on Performance of Reliability Criteria and Reliability Management

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***Abstract*—Evaluating the performance of various power system reliability criteria and their management is important in order to obtain a cost effective reliability level of the power system. However, the performance of reliability criteria depends on several parameters, of which one is value of lost load (VoLL). Value of lost load is typically difficult and complex to model, which hampers making a general conclusion about the most appropriate reliability criterion. This paper gives a methodology to assess the impact of VoLL on the performance of reliability criteria and their management. The assessment is made for a 5 node test system, based on the Roy Billinton reliability test system, using 4 different reliability criteria, i.e. 2 probabilistic and 2 deterministic approaches. The focus is on operational planning and real time operation.**

***Index Terms*—Power system reliability, Reliability criteria, Reliability management, Value of lost load**

I. INTRODUCTION

Due to the increasing amount of uncertainty in the power system, advantages of probabilistic reliability criteria and management strategies compared to currently used deterministic criteria come more to the foreground. However, it is important to evaluate the performance of different approaches, especially to quantify benefits of using more complex probabilistic techniques with a higher computational burden. Performance of reliability criteria and their reliability management depends on various parameters, of which one is value of lost load (VoLL).

Value of lost load (VoLL) is defined as a measure of the cost of unserved energy for consumers [1]. This measure is typically difficult and complex to model. It is dependent on location (What is the temperature at the location?), outage attributes (What is the duration, frequency, time, magnitude,... of the outage?) and customer attributes (Which sector is the customer part of?, How well is the customer prepared for an interruption?) [2]. VoLL can be modelled as demand bids of customers, which represent the willingness to pay of a customer for ensuring supply of a particular amount of electricity [3].

Various studies have investigated the willingness of customers to reduce their reliability level by accepting power interruptions and at which cost [4], [5], but exact values of lost load are difficult to determine and rarely taken into account in power system reliability management.

This paper investigates the impact of value of lost load in power system reliability studies, focussing on the performance of reliability criteria and their respective reliability management. The results can also be used to assess the impact of deliberate load shedding in the system compared to cost effective load shedding as indicated by the value of lost load. Furthermore, results indicate pathways for improvement of currently used reliability criteria and their management.

Approximate decision making processes according to 4 reliability criteria are implemented in Matlab using the MATPOWER tool [6]. The focus is on the time horizon of operational planning/scheduling and real time operation, i.e. day ahead up to real time. The Matlab implementation of the decision making processes is verified using GAMS. Section II contains a qualitative description and mathematical details of the implementation, together with the methodology for evaluating the performance of reliability criteria. Section III summarizes results of the application of this methodology to a 5 node test system [7], [8]. Finally, section IV concludes the paper.

II. MODEL SETUP AND METHODOLOGY

A framework is developed that on the one hand simulates the decision making process corresponding to a particular reliability criterion and, on the other hand, evaluates the resulting system state and the actions taken. The process is repeated for various reliability criteria and reliability management strategies [9], [10].

A. Simulation of the decision making process

Power system reliability criteria define whether a power system is reliable or not. They can be probabilistic or deterministic in nature and impose a standard to determine whether the reliability level of a power system is acceptable. Such a principle can be expressed as a set of constraints, which need to be satisfied by the decisions taken [11].

Reliability management is the decision making process aiming at satisfying the considered reliability criterion. Figure 1 shows different stages in reliability management. Reliability assessment quantifies the reliability level of the system using

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reliability indicators and checks these with the reliability criterion in order to conclude whether the system is reliable or not. Based on this conclusion, appropriate actions can be taken on different time horizons, balancing reliability and cost. This paper focusses on short term preventive actions, i.e. economic dispatch of the generators, and corrective actions, i.e. redispatch of the generators and load shedding. If corrective actions are required to satisfy the system constraints and to avoid a system breakdown, it is assumed that they take place immediately. During the planning of these actions, forecasts of uncertain variables, such as load, can be taken into account in a deterministic or a probabilistic way. This is included in the optimization formulation that is used for modelling the decision making process.

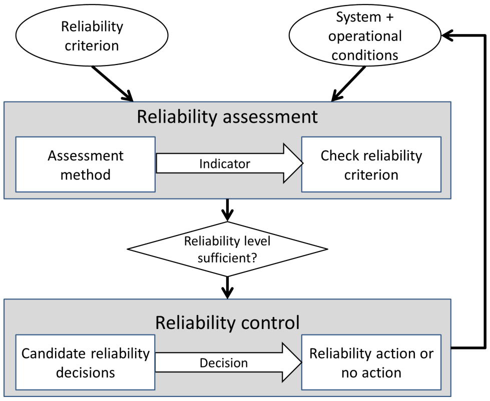


Fig. 1. General reliability management framework aiming at satisfying the reliability criterion

Nowadays, a deterministic N-1 criterion is mostly used, which states that the system should be able to withstand at all times the loss of any of its main elements without significant degradation of service quality. In this study, service quality is assumed to be degraded if load needs to be curtailed in real time in order to satisfy system constraints in one of the credible contingency cases. However, alternative reliability criteria could be optimized values of or limits on socio-economic or reliability indicators, such as maximal social welfare, minimal cost for society, Expected Load Curtailed (ELC) $\leq$ x MW,...

Deterministic N-k criteria are quite conservative, as they do not allow any load shedding up to all N-k system states. Probabilistic criteria on the other hand allow load shedding, eventually limited by an upper bound on total expected load curtailment. They take into account a sufficiently high number of credible system states, covering contingency cases as well as various forecast scenarios, together with their corresponding probability of occurrence. In this manner, they can incorporate probabilistic effects arising in the power system, due to increasing use of renewable energy sources, events, random failure of power system components,... By contrast, deterministic N-k criteria consider all contingency cases up to N-k system states as equally likely and equally severe [12]. Furthermore, they do not give any incentive based on economic principles.

Following reliability criteria with their respective management are compared in this paper:

- **Criterion 1**: N-0 criterion, i.e. no load curtailment allowed in N-0 system state, assuming inelastic demand;
- **Criterion 2**: Minimal cost for society, i.e. load curtailment allowed according to economic equilibrium between demand and supply, taking into account different load scenarios;
- **Criterion 3**: Minimal cost for society, i.e. load curtailment allowed according to economic equilibrium between demand and supply, taking into account different load scenarios, but upper limit on expected load curtailment;
- **Criterion 4**: N-1 criterion, i.e. no load curtailment allowed in N-0 and N-1 system states, assuming inelastic demand, minimum outage cost outside of criterion.

B. *Mathematical formulation of the decision making process*

A two stage decision making process covering operational planning and real time operation is simulated. The objective is to minimize cost for society, while satisfying the specified reliability criterion.

Operational planning is applied in order to plan preventive and corrective actions ahead of real time that avoid violation of the system constraints and satisfy the reliability criterion in real time at the lowest expected total system cost. However, during the operational planning decision making process, the real time system state is uncertain. Therefore, forecasts are used, potentially modelled using a distribution function in order to make more accurate decisions at the cost of a higher computational burden. Furthermore, credible contingencies are considered to keep the system reliable in case of an outage. Taking into account contingency cases and forecasts of the real time state leaves the opportunity for real time corrective actions, which might be cheaper than the preventive actions planned in the operational planning stage and can be used to overcome differences between forecasts and real values. The objective function of the operational planning stage is mathematically formulated in (1).

$$
\begin{aligned}
min \sum_i [P_{G,sched,i} \cdot C_{G,i} + \sum_q \pi_q (r^+_{G,i} \cdot E\Delta P^+_{G,i,q} \cdots \\
+ r^-_{G,i} \cdot E\Delta P^-_{G,i,q})] + \sum_q \sum_j \pi_q \cdot VoLL_j \cdot EP_{shed,j,q}
\end{aligned} \tag{1}
$$

with $P_{G,sched,i}$ the scheduled active power generation of generator i [MWh], $C_{G,i}$ the marginal cost of generator i [€/MWh], $VoLL_j$ value of lost load of type j [€/MWh], $EP_{shed,j,q}$ the expected load shed of type j in real time state q [MWh], $E\Delta P^+_{G,i,q}$ the expected upward deviation of generator i in real time state q [MWh], $E\Delta P^-_{G,i,q}$ the expected downward deviation of generator i in real time state q [MWh], π_q the probability of occurrence of the considered real time state q and $r^+_{G,i}$ and $r^-_{G,i}$ the respective upward and downward redispatch cost of each generator i [€/MWh]. Considered system states q differ for each reliability criterion. Additional

TABLE I
CREDIBLE SYSTEM STATES AND CONSTRAINTS CONSIDERED IN THE DECISION MAKING PROCESS ACCORDING TO DIFFERENT RELIABILITY CRITERIA

Reliability criterion	**N-k criteria** [1]	**Criterion 2**	**Criterion 3**
Load scenarios	Most probable load scenario	7 load scenarios according to probability distribution as indicated in table II	7 load scenarios according to probability distribution as indicated in table II
Contingency cases [4]	Up to N-k contingency cases with equal probability	Contingency cases up to cumulative probability of 99.99%	Contingency cases up to cumulative probability of 99.99%
Considered state probability [2,3] π_q	$\pi_q = \frac{1}{\text{number of contingency cases}}$	$\pi_q = \pi_{LS,y} \cdot \pi_{CC,z}$	$\pi_q = \pi_{LS,y} \cdot \pi_{CC,z}$
Load shedding allowed	Not in N-k contingency cases	Yes, if cost efficient	Yes, if cost efficient and ELC $\leq$ 5% of total load

[1] Criterion 1 and Criterion 4, with respectively k=0 and k=1
[2] $\pi_{LS,y}$: Probability of load scenario y
[3] $\pi_{CC,z}$: Probability of contingency case z
[4] Only branch outages are considered as contingency cases in this study

information about the constraints for the considered reliability criteria is summarized in table I.

The result of the operational planning stage is the active power production of generators in the system. However, operational planning is based on expected system variables, which differ from real time values of load, generation capacity, contingencies, ... Therefore, (2) needs to be minimized for the actual real time system state in order to determine real time redispatch and load shedding required to satisfy the system constraints. Scheduled generation after the operational planning stage according to a particular reliability criterion is used as an input together with the actual real time system state.

$$min \sum_j VoLL_j \cdot P_{shed,j} + \sum_i r^+_{G,i} \cdot \Delta P^+_{G,i} \cdots + \sum_i r^-_{G,i} \cdot \Delta P^-_{G,i} \quad (2)$$

with $P_{shed,j}$ the real time curtailment of load of type j [MWh] and $\Delta P^+_{G,i}$ and $\Delta P^-_{G,i}$ the respective upward and downward deviation in real time of generator i compared to the scheduled generation. Real time redispatch also has to satisfy constraints posed by the applied reliability criterion, in order to guarantee that acceptable corrective actions are possible if unforeseen contingencies might take place in real time. This real time decision stage results in generation redispatch and load shedding required to keep the system up and running. If a contingency leads to a system breakdown, the load and scheduled generation that are curtailed are determined.

Objective functions (1) and (2) are subject to power flow constraints, redispatch limits, generator limits and limits posed by the reliability criterion [3], [9], [10]. In this study, a non sequential analysis is performed using a DC power flow formulation. Therefore, interlinking constraints between subsequent time instants are not taken into account explicitly.

C. Performance evaluation and indicators

In order to assess the performance of each reliability criterion and its management, the final state of the power system and the actions taken in order to reach this state need to be evaluated. The actions taken at each instance depend on the applied reliability criterion and the reliability management in place. Performance can be quantified using many different socio-economic and reliability indicators, such as social welfare, total cost, amount of load curtailed,... and this using instantaneous, average, expected or extreme values of the different indicators.

To evaluate the economic value of reliability and the expected reliability level, all states, also outside the criterion, need to be evaluated and weighed against their probability. For large systems, considering all system states might be cumbersome, which asks for a credible selection of system states. In this study, indicators are evaluated using an approximate analytical contingency enumeration approach [12]. Contingency cases are considered, as well as different real time load scenarios following the probability density function of the system load. For these system states p, appropriate reliability actions and the final system state are determined using (2) taking the outcome of the operational planning stage as an input. Afterwards, outcomes of all considered system states are combined in expected indicator values taking into account probability of occurrence of the system state π_p. The system states p considered for evaluation are the same for all criteria.

Expected total system cost (ETC) is used as economic indicator:

$$ETC = C_{scheduled} + \sum_p \pi_p \cdot [C_{redisp,p} + C_{LC,p}] \; [€] \quad (3)$$

which consists of the cost of scheduled generation $C_{scheduled} = \sum_i P_{G,sched,i} \cdot C_{G,i}$ resulting from (1), the redispatch cost $C_{redisp,p} = \sum_i r^+_{G,i} \cdot \Delta P^+_{G,i,p} + r^-_{G,i} \cdot \Delta P^-_{G,i,p}$ and the cost of load curtailment $C_{LC,p} = \sum_j VoLL_j \cdot P_{shed,j,p}$ in real time system state p, which result from (2).

Furthermore, the reliability level of the system is evaluated in terms of expected load curtailment (ELC):

$$ELC = \sum_p \sum_j \pi_p \cdot P_{shed,j,p} \; [MW] \quad (4)$$

D. Overview of the methodology

A global view on the methodology is given in Figure 2. Every evaluation cycle, a reliability criterion is chosen from the list of 4 candidate reliability criteria. This is satisfied by taking appropriate decisions using a particular management strategy. Resulting actions lead to a final operational state of the power system, which is evaluated together with the actions taken. The process is repeated with identical load, generator and grid data, but for a different combination of reliability criterion and management strategy. A post-processing stage compares results for various assumptions and combinations of reliability criterion and management strategy.

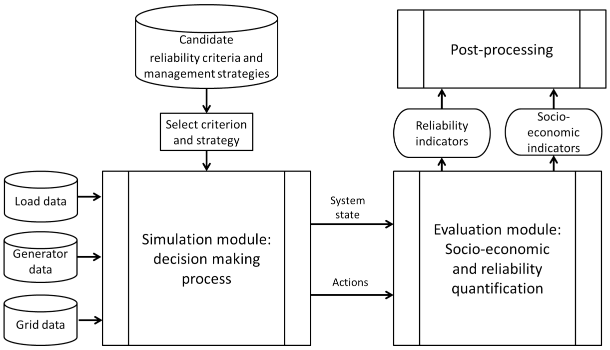


Fig. 2. Methodology for evaluating impact of VoLL on performance of reliability criteria and their management

III. APPLICATION OF THE METHODOLOGY

A. Test system

The methodology is applied to a 5 node test system, based on the Roy Billinton reliability test system (RBTS) [7], [8], as shown in Figure 3. Generator and load data used in this analysis are summarized in table II. The upward and downward redispatch cost equal:

$$r^{+}_{G,i} = C_{G,i} \cdot 1.5 + 5 \qquad (5)$$

$$r^{-}_{G,i} = C_{G,i} \cdot 0.5 + 5 \qquad (6)$$

Upward redispatch cost takes into account cost of additional generation as well as a redispatch fee. In case of downward deviation, only the redispatch fee needs to be considered as the generation cost is already included during scheduling. Generators with nearly zero marginal cost, i.e. generators 1, 4, 7, 8 and 9, have no possibility for upward redispatch.

The load uncertainty data in the left lower part of table II are used in the operational planning stage according to probabilistic reliability criteria 2 and 3. The analytical contingency enumeration method in the evaluation module uses a normal load distribution with an average value of 165MW and a standard deviation of 4%. Data concerning reliability of components are given by Billinton et al. [7].

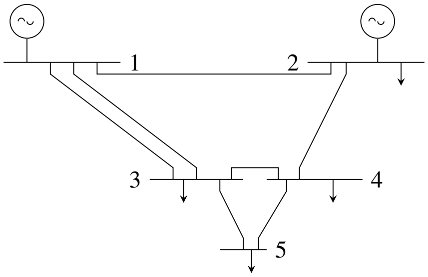


Fig. 3. Test system based on Roy Billinton reliability test system [8]

TABLE II
OVERVIEW OF DATA OF THE TEST SYSTEM IN FIGURE 3

Gen. number	Node	Capacity [MW]	Marginal Cost $C_{G,i}$ [€/MWh]
1	1	40	0.02
2	1	40	77
3	1	20	79
4	1	10	0.04
5	2	40	90
6	2	20	76
7	2	20	0.01
8	2	20	0.03
9	2	20	0.05
10	2	5	99
11	2	5	78

Load scenario y	Total load [MW]	Probability $\pi_{LS,y}$ [%]	Node	Average Load [MW]
1	165	38.2	1	0
2	158.4	24.2	2	20
3	171.6	24.2	3	85
4	151.8	6.1	4	40
5	178.2	6.1	5	20
6	145.2	0.6		
7	184.8	0.6		

[1] U_{base} = 230 V & S_{base} = 100 MVA

Value of lost load is taken into account in different ways in order to evaluate its impact on the performance of the different reliability criteria and their management. One possibility is to consider inelastic demand, thus setting the value of lost load, in theory, to infinite, assuming that customers want to guarantee realisation of their demand at all cost. In this case, the actual VoLL are taken into account in the evaluation module. Another approach is to take into account actual values of lost load in the economic (re)dispatch of the generators as well. The latter approach is applied in combination with criteria 2 and 3 and the first approach is used for criteria 1 and 4.

20% of the load at every node is considered to be curtailable if demand is elastic [7]. The performance of the reliability criteria and their management is evaluated for various VoLL of the curtailable part of the load. In practice, VoLL might vary over different nodes depending on the type of customers connected to a particular node, but is kept the same over the different nodes in this study. The non-curtailable part of the load has a very high value of lost load in order to keep load curtailment of this load as a last resort. VoLL is assumed to be constant in time.

Some parameters that influence the impact of VoLL on the performance of reliability criteria are the following:

- Uncertainty of load and generation forecasts
- Redispatch costs
- Availability of generation reserves
- Robustness of system design

These parameters are varied in the analysis and their impact is taken into account by weighing the outcomes by their probability of occurrence or by explicitly illustrating the impact.

B. Results

The independent variable in all figures is value of lost load ratio (VoLL-ratio). It is used in order to express the reliability and socio-economic indicators as a function of a dimensionless parameter of VoLL and is defined as:

$$\text{VoLL-ratio} = \frac{\text{VoLL}}{\text{Weighted average marginal cost of generators}} \tag{7}$$

The VoLL-ratio varies between 0.1 and 400. Reasonable average VoLL are between €8000 - 10000 /MWh [13], corresponding to a VoLL-ratio between approximately 150 and 200 with the given average marginal cost of the generators of €51 /MWh.

Figure 4 shows the evolution of relative expected total system cost (relative ETC) as a function of VoLL-ratio. The relative expected total system cost is calculated as the total system cost for a particular reliability criterion and a particular VoLL divided by the maximal total system cost encountered over all evaluated criteria and VoLL-ratios. Expected total system cost consists of cost of scheduled generation, expected redispatch cost and expected cost of load curtailment in real time.

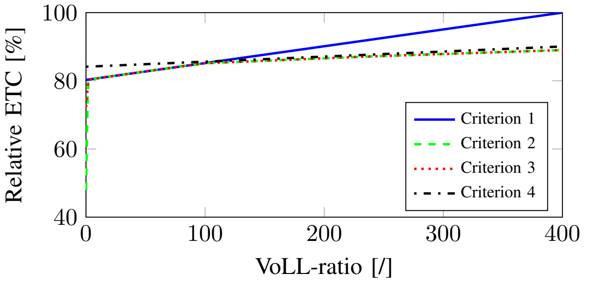
Figure 5 shows the relative expected load curtailment in the system according to different reliability criteria as a function of VoLL-ratio. The amount of load curtailed is expressed relatively to the average total load in the system.

C. Impact of VoLL on performance of reliability criteria

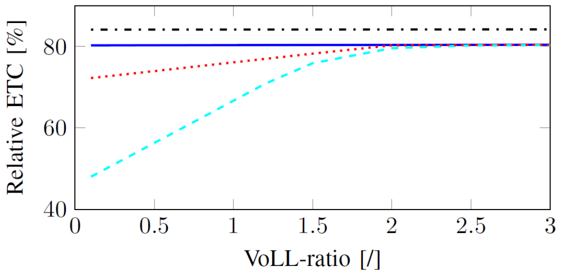
Figure 4 shows that with very low values of lost load, i.e. VoLL-ratio smaller than 2, the probabilistic reliability criteria have significantly lower ETC than the deterministic criteria, which do not allow load shedding up to the N-k system states. Therefore, criterion 1 and 4 are too conservative at these VoLL, with criterion 1 the cheapest of the two because it is less conservative than criterion 4. The conservatism of criterion 1 and 4 is shown in Figure 5, because even for extremely low VoLL the expected amount of load curtailment is very low in contrast to the load curtailment with probabilistic criteria 2 and 3. However, these extremely low values of lost load do not occur in practice in normal power systems.

For a VoLL ratio between 2 and 100, performance of probabilistic criteria 2 and 3 and deterministic criterion 1 are comparable, both in terms of economic and reliability indicators. In this interval of VoLL-ratio, criterion 1, 2 and 3 are up to 4% cheaper than criterion 4.

If VoLL-ratio becomes higher than 100, criterion 1 performs worse than criterion 4. In this case, criterion 4 leads to less expensive load curtailment due to a more conservative scheduling of the generators. However, the probabilistic approaches still operate equally performant as the deterministic N-1 criterion. The expected load curtailment corresponding to the probabilistic criteria converges towards ELC of criterion 4 in this interval of VoLL-ratio, reaching the level of criterion 4 at a VoLL-ratio of 200. Due to the high VoLL in these cases, expected load curtailment in certain contingency cases considered in the probabilistic approaches is very expensive and, even though they have a small probability of occurrence, their contribution to the expected total system cost becomes significant. Therefore, a more conservative reliability management is advisable.



(a) General

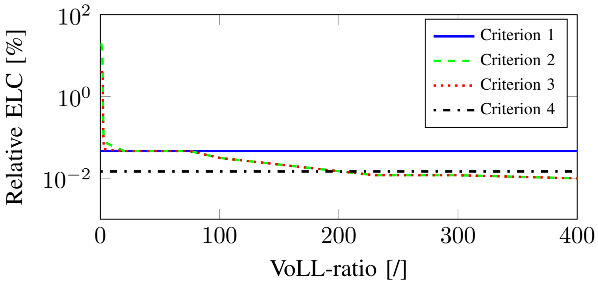


(b) Zoomed

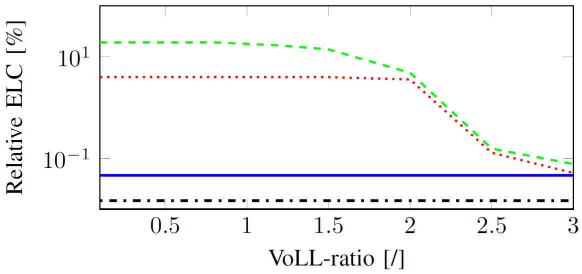
Fig. 4. Relative expected total system cost of operational planning and real time operation according to 4 reliability criteria as a function of VoLL-ratio

The analysis is repeated for a more robust system design with generator 6 moved from node 2 to node 3. The general conclusions remain the same in this case, but the interval of better economic performance of criterion 1 compared to criterion 4 becomes larger, i.e. a VoLL-ratio between 3 and 230. The more robust system design makes operation according to a less conservative criterion more cost effective for a larger range of VoLL. The difference in robustness of both systems is indicated by the risk of not satisfying reliability criterion 3. Load curtailment in cases of criterion violation is used as severity index, which is multiplied by the probability of occurrence of the violating cases. The robust system results in lower risk for violating criterion 3 as shown in Figure 6.

Figures 4 and 5 show that the socio-economic performance of reliability criteria and their management as well as the resulting reliability level in the system depend on VoLL.



(a) General



(b) Zoomed

Fig. 5. Expected load curtailment in real time system operation according to 4 reliability criteria relatively expressed to average total system load as a function of VoLL-ratio

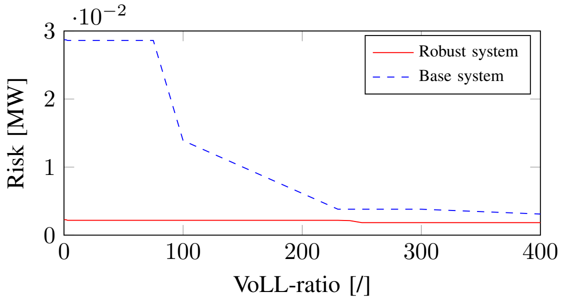


Fig. 6. Risk of not satisfying criterion 3 as a function of VoLL-ratio with load curtailment in case of criterion violation as severity index. The dashed line holds for the base system as shown in Figure 3, while the full line holds for a system with generator 6 moved from node 2 to node 3

If value of lost load is low, taking preventive actions is less valuable as they might be too conservative, while the relative difference reduces if VoLL increases. The probabilistic reliability criteria converge towards the most cost effective deterministic reliability criterion at every VoLL and adapt system reliability level according to VoLL. For currently used deterministic approaches, it might be useful to alter the reliability criterion and its management for different VoLL in order to decrease the total system cost. As VoLL depends on geographical, outage and customer attributes, diversifying the reliability criterion over different locations might be an option in the long-, medium- and short-term, while different criteria at different time instants could be used during operation and operational planning, if appropriate predictions could be made. However, an analysis needs to be made for every system individually due to the influence of system robustness on the relative performance of reliability criteria and their management as a function of VoLL.

IV. CONCLUSION

A methodology is developed to assess impact of VoLL on performance of reliability criteria and their management and to compare performance, focussing on operational planning and real time operation. Different criteria and VoLL lead to different actions. Results for a 5 node test system show that the analysed probabilistic reliability criteria and their management converge towards the most cost effective deterministic reliability approach in terms of expected total cost and expected load curtailment at reasonable values of lost load. If one wants to insist on a deterministic approach, altering reliability criterion as a function of VoLL might be beneficial in terms of expected total system cost. However, it is important to make an analysis for each system individually as performance of various reliability criteria is impacted by several other parameters, such as robustness of system design. Future work needs to focus on developing correct/optimal reliability criteria taking into account parameters influencing performance.

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