Post-contingency corrective control failure: a risk to neglect or a risk to control?

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***Abstract*—This paper proposes a methodology for assessing the risk implied by the potential failure of post-contingency corrective controls. We express such risk in terms of service interruption socio-economic severity to the system end-consumers and argue for considering its magnitude not only in absolute terms, but most importantly in relation to a spectrum of socio-economic metrics fully describing the operation of an electrical power system as per the applicable reliability management approach (presently based on the N-1 criterion). We showcase the proposed methodology by presenting its application through case studies on the single area version of the IEEE-RTS96 benchmark. Our analysis establishes that the proposed assessment scope is quite informative in distinguishing whether the risk implied by the potential failure of post-contingency corrective control is noteworthy or negligible.**

I. Introduction

Reliance on post-contingency corrective control tends to become the standard practice in securing the operation of electrical power systems. Such paradigm shift, from the purely preventive approach of taking in advance all necessary actions to ensure that the system can withstand credible contingencies, is a well-documented reaction to the prominent changes characterizing the modern power system: increased uncertainty, operation closer to physical limits, novel technological opportunities, stronger push towards economic efficiency, *etc.* [1]. To avoid jeopardizing the overall level of system reliability and facing hidden risk, it is therefore necessary to verify that the planned corrective control actions are sufficiently dependable.

A. Literature review

Ever since the seminal work in [2] the focus of the literature has been on exploiting the utility of post-contingency corrective control in the context of Security Constrained Optimal Power Flow (SCOPF) formulations [3]. Notable works have developed the integration of post-contingency corrective switching actions [4], [5], of actions triggered on a conditional basis [6], of storage devices [7] and a practical solution approach for realistic large-scale systems while modeling discrete controls and the non-linear AC power flow [8]. References [9], [10] established the trade-off between the costs of preventive controls and the expected costs of post-contingency corrective controls as the decision making objective. The mathematical statement of the problem was enhanced in [11] with the proposal of a set of constraints relating to the system state following the occurrence of a contingency and prior to the application of the respective corrective controls, in order to warrant the feasibility of the control scheme. Further, [12] aimed at ensuring the feasibility of post-contingency corrective control by limiting the number of involved elementary operations and taking into account their implementation sequence. All the aforementioned works have assumed that post-contingency corrective control is perfectly dependable, in spite of the fact that it would be exercised under time pressure and while the system state is undergoing the deviations brought about by the occurrence of a contingency.

Contrary to this common assumption, in our earlier works we have progressively developed a probabilistic SCOPF framework explicitly acknowledging the potential failure of post-contingency corrective controls [13]–[15]. Our findings showed that, acknowledging this feature, the preventive and corrective approaches should not be seen as equivalent alternatives. Rather, reliance on post-contingency corrective control implies a less strict guarantee on maintaining the system operability.

B. Contributions

Formalizing corrective control failure risk as the expectation of socio-economic severity under uncertainty on i) the occurrence of contingencies, and (conditionally to the former), ii) the failure of the respective pre-selected corrective controls, we propose a comprehensive assessment methodology. This proposal includes a comparative analysis in relation to a set of identified socio-economic metrics characterizing the operation of a power system as per the used reliability management approach. We present a case study which not only serves to demonstrate the principles of our proposal but also to establish the relevance of its outcomes in reasoning about the noteworthiness of the corrective control failure risk.

C. Paper Organization

The remainder of this paper is organized as follows. Section II introduces the proposed methodology for assessing the risk of corrective control failure. Section III showcases the relevance of this proposal by means of a demonstrative case study, under a described set of models and assumptions, on the single area version well known benchmark IEEE RTS-96 [16]. Finally, section IV summarizes the main discussion points and identifies further research directions.

II. Proposed methodology

A. Preliminaries & compact notation

Let us abstractly describe the real-time operation of a power system as the repeated choice of decisions in compliance with the used reliability criterion through time $t \in \mathcal{T}$. In what follows, we will use the *N-1 criterion* as an example and without any loss in generality.

More specifically, let us begin with the *preventive* declination of the N-1 reliability management approach, wherein decisions correspond to the application of control actions *only prior* to the occurrence of any postulated contingency (*i.e.*, component failure or outage). We shall compactly denote such approach by means of an objective function $\mathcal{F}_P\left(u_{N1p}(t), x(t)\right)$ expressing the desirable order of priority in the choice amongst the several candidate decisions based on the available information $x(t)$, and of the constraint set $\mathcal{U}_{N1p}(t)$, expressing in technical terms the ability of the system to maintain its functionality upon realization of any contingency $c \in \mathcal{C}_{N1}$, as, $\forall t \in \mathcal{T}$,

$$u^{\star}_{N1p}(t) \in \underset{u_{N1p}(t) \in \mathcal{U}_{N1p}(t)}{\arg\min} \mathcal{F}_P\left(u_{N1p}(t), x(t)\right). \tag{1}$$

Moreover, we shall follow similar notational conventions to compactly state the *corrective* declination of the N-1 reliability management approach wherein elementary control operations may also be performed promptly after the occurrence of a contingency. To do so, we augment the decision making objective introduced in (1) with the expectation of the recourse priority in choice over the random variable $c \in \mathcal{C}_{N1}$ and introduce the constraint set $\mathcal{U}_{N1c}(t)$, to denote the admissible set of preventive (pre-contingency) *and* corrective (post-contingency) control actions, resulting in, again $\forall t \in \mathcal{T}$,

$$u^{\star}_{N1c}(t) \in \underset{u_{N1c}(t) \in \mathcal{U}_{N1c}(t)}{\arg\min} \Big\{ \mathcal{F}_P\left(u_{N1c}(t), x(t)\right) + \sum_{c \in \mathcal{C}_{N1}} \pi_c \cdot \mathcal{F}_C\left(u_{N1c}(t), x(t), c\right) \Big\}, \tag{2}$$

where π_c is the probability of occurrence of contingency c.

This formulation normally assumes that corrective control actions are fully dependable, and that the constraint set of the corrective approach in (2) is at most as restrictive as the constraint set of the preventive approach in (1), that is $\mathcal{U}_{N1c}(t) \supseteq \mathcal{U}_{N1p}(t)$. This makes the corrective N-1 approach preferable with respect to the preventive one. Formally, denoting as $C_{SE}\left(u(t), x(t)\right)$ the function measuring the *socio-economic cost* of reliability management decisions[1], the aforementioned should suffice to result in:

$$C_{SE}\left(u^{\star}_{N1c}(t), x(t)\right) \leq C_{SE}\left(u^{\star}_{N1p}(t), x(t)\right) \quad \forall t \in \mathcal{T}. \tag{3}$$

[1]Notice here that such function is not necessarily equivalent to the decision making objectives of the preventive and/or the corrective N-1 approach. Indeed, the decision making objectives in (1,2) would be defined as per the operational procedures for TSO reliability management. While, in principle, these should align with the societal interest, function $C_{SE}\left(u(t), x(t)\right)$ can be used to potentially measure the resulting socio-economic cost in a more refined manner.

As already stated, this paper concerns the stakes while neglecting the potential failure of post-contingency corrective controls. To do so, we consider that any elementary control operation (*e.g.*, the opening of a single breaker, change of a transformer tap, re-dispatch of a generating unit) may fail with a probability $p \in (0, 1]$. Further, we also consider that in the event of realizing the failure of corrective controls, the system operator may only rely on *emergency actions*, which are preferably avoidable in the presence of other alternatives, such as the shedding of the system load demand. We shall denote such emergency efforts to contain the impact of corrective control failures, $\forall c, t \in \mathcal{C}_{N1} \times \mathcal{T}$, as,

$$u^{\star}_{E}(t) \in \underset{u_E(t) \in \mathcal{U}_E(u_{N1c}(t), c)}{\arg\min} \mathcal{F}_E\left(u_E(t), x(t)\right). \tag{4}$$

Finally, we express the *risk* implied by the potential failure of post-contingency corrective controls as the aggregation of the product of the contingency occurrence probability times the corrective control failure probability, times the socio-economic service interruption severity, as in, $\forall t \in \mathcal{T}$,

$$\mathbb{R}_{N1c}(t) = \sum_{c \in \mathcal{C}_{N1}} \pi_c \phi\left(p, u^{\star}_{N1c}(t), c\right) S\left(u^{\star}_{E}(t), x(t)\right), \tag{5}$$

where $\phi\left(p, u^{\star}_{N1c}(t), c\right)$ denotes the probability of failure of corrective control in function of the chosen elementary post-contingency operations from (2) and of the aforementioned failure probability of any elementary control operation (p). Moreover, $S\left(u^{\star}_{E}(t), x(t)\right)$ denotes the socio-economic service interruption severity as a function of emergency control actions from (4) and available information $x(t)$.

B. Assessment Scope

Assessing in absolute terms the corrective control failure risk is hindered by the present lack of data and models on the probability of failure of an elementary operation (p) and of a set of chosen elementary control operations $\left(\phi\left(p, u^{\star}_{N1c}(t), c\right)\right)$ [17]. To overcome such limitations, we propose here the approach of generating a set of informative results on the potential extent of such risk, in relation to standard quantities characterizing the operation of a system in line with the applicable reliability criterion. More specifically, and again using the N-1 criterion as an example, we propose to analyze the risk implied by the potential failure of corrective control in relation to the following metrics.

1) Value of corrective control: As already introduced, relying on corrective control may generate a reduction in socio-economic cost with respect to following the purely preventive approach. Such impact reduction can be understood as the value of post-contingency corrective control and computed as, $\forall t \in \mathcal{T}$,

$$\mathbb{V}_{CC}(t) = C_{SE}\left(u^{\star}_{N1c}(t), x(t)\right) - C_{SE}\left(u^{\star}_{N1p}(t), x(t)\right). \tag{6}$$

As a first step in the analysis, we propose a worst-case approach to examine the value of corrective control in relation to the upper bound of its risk of failure. The latter quantity is termed *conditional risk of corrective control failure* and computed (under uncertainty on the occurrence of any contingency, and, upon condition that the respective chosen corrective control shall fail) as, $\forall t \in \mathcal{T}$,

$$\bar{\mathbb{R}}_{N1c}(t) = \sum_{c \in \mathcal{C}_{N1}} \pi_c \cdot \mathbb{1}_{\{u^\star_{N1c}(t),c\}} \cdot S\left(u^\star_E(t), x(t)\right), \tag{7}$$

where operator $\mathbb{1}_{\{u^\star_{N1c}(t),c\}}$ takes the value of one for any contingency $c \in \mathcal{C}_{N1}$ that is associated with the use of corrective control as per the chosen decisions $u^\star_{N1c}(t)$. To put the two quantities in perspective, the ratio

$$\underline{\phi}(t) = \frac{V_{CC}(t)}{\bar{\mathbb{R}}_{N1c}(t)}, \quad \forall t \in \mathcal{T}, \tag{8}$$

is of interest. This ratio can be interpreted as the corrective control failure probability above which conditional risk of failure $\bar{\mathbb{R}}_{N1c}$ of corrective control is larger than its value $\mathbb{V}_{CC}$.

2) Residual risk of the N-1 approach: While securing the system against the possible occurrence of any single outage, the N-1 approach is exposed to the risk implied by higher order outages. This latter quantity, which is known to be temporally variable, is termed *residual risk* and can be considered as an indicative order of magnitude to consider risk as negligible.

The second step of the proposed methodology relies on an upper bound on the residual risk of the N-1 approach (denoted henceforth as $\bar{R}_{N1}(t), \forall t \in \mathcal{T}$) to focus on the failure probability of any elementary post-contingency operation and its effect on the significance of the corrective control risk of failure. In particular, we seek to compute an indicative value of the elementary control operation failure probability that would imply that the risk of failure of a chosen set of corrective actions can be safely neglected. We denote such indicative probability value as $(p_{\bar{R}})$ and propose to compute it by solving the following equality,

$$\sum_{t \in \mathcal{T}} \sum_{c \in \mathcal{C}_{N1}} \pi_c \phi\left(p_{\bar{R}}, u^\star_{N1c}(t), c\right) S\left(u^\star_E(t), x(t)\right) = \sum_{t \in \mathcal{T}} \bar{R}_{N1}(t). \tag{9}$$

3) Expected cost of corrective control: To complete the analysis, the final step investigates the risk of corrective control failure in contrast to its expected utilization cost, the latter expressed as in the recourse term of (2). In a similar manner to the precedent aspect, it is of interest to also compute an indicative value for the elementary operation failure probability that would make the corrective control failure risk at least as significant as its expected utilization cost. Similarly to the precedent, we denote such indicative probability value as (p_{EC}).

III. Case Study Results & Discussion

A. Models & Assumptions

To show the stakes for assessing the implications of the potential failure of corrective control, we rely on a set of physical models and assumptions to yield a self-contained representation of power system real-time operation.

In this context, we use the linear DC power flow approximation, while treating each hourly instance of real-time operation independently of its precedent/forthcoming instances (*i.e.*, by neglecting couplings between successive instances). Further, to avoid any assumption on operational planning decisions and/or on the commitment status of generating units as per the clearing of day-ahead and forward markets, we consider all dispatch-able units as available with a minimum stable generation level of zero.

1) Preventive N-1 approach: We model decision making as per the preventive N-1 approach by means of a Security Constrained Optimal Power Flow (SCOPF) wherein the network constraints refer to the Kirchof laws and the branch thermal ratings, under the intact network configuration and following the outage of any single network branch. The pre-contingency dispatch of generating units is the main decision variable, constrained from above by the respective unit capacity and accounted for in multiplication with a marginal cost coefficient in the cost minimization objective. Pre-contingency load shedding is also modeled as the last resort option to treat instances wherein the N-1 criterion is unattainable. To do so, load shedding variables per load bus are introduced. Such variables are penalized in the objective function via a common, appropriately high cost coefficient ensuring that they would take non-zero values only for those problem instances wherein load shedding is indeed an absolute necessity.

2) Corrective N-1 approach: To model the corrective N-1 approach, we expand the aforementioned formulation with the inclusion of per contingency recourse variables for generation re-dispatch. Such variables are upper bounded by the ramping capability of each unit, while the per contingency adjusted output (*i.e.*, preventive dispatch +/- corrective re-dispatch) is also bounded between zero and the respective unit capacity. The recourse term in the objective function for generation costs is the probability weighted re-dispatch cost, summed over all contingencies. We model the network constraints in the pre-contingency stage, the intermediate stage between contingency occurrence and corrective control deployment and the (final) corrective stage per contingency. Once again, load shedding is treated as a measure of last resort, both in the pre-contingency stage as well as in any corrective post-contingency stage.

3) Socio-economic cost evaluation: In order to measure the socio-economic cost of the preventive and corrective N-1 approaches, we account for the generation costs in a similar fashion to the objective functions of the respective decision making problems. However, we employ load-specific *value of lost load* (voll) coefficients to evaluate the severity of a potential service interruption (as per the load shedding variables from the optimal solution of the SCOPF problems) while adopting an interruption duration of one hour. Again, all post-contingency costs are probability weighted.

4) Corrective control failure probability & severity: We assume that any elementary control operation may either work or fail, and that the failure of any single elementary control operation makes corrective control completely ineffectual for the respective contingency [14]. The resulting corrective control failure probability is computed in function of the number of chosen elementary control operations. Following the solution of the corrective SCOPF, we identify all correctively

TABLE I

SOCIO-ECONOMIC COST C_{SE} OF SYSTEM OPERATION

Criterion	peak load (MW)	2400	2600	2800	3000
N-0 only	μ $(k\$/hr)$	10.10	11.84	13.93	16.50
	σ $(k\$/hr)$	4.30	5.20	6.68	8.78
N-1 Prev.	μ $(k\$/hr)$	12.72	14.96	19.48	28.51
N-1 Corr.	μ $(k\$/hr)$	12.13	13.94	15.97	18.42

secured contingencies. Per correctively secured contingency, we remove from service all those branches that would be overloaded without the successful application of the corrective re-dispatch. We then solve an optimal power flow with the resulting network topology to minimize total load shedding (in MW), while generating units ramp-down in proportion to their preventive dispatch. The socio-economic severity of the load shedding actions is computed again via the load-specific voll coefficients.

5) N-1 residual risk: To estimate the residual risk of the N-1 approach, we take a *worst-case* perspective and multiply its residual probability (*i.e.*, the probability of any outage involving more than 1 component) by the severity of shedding the whole system load over the 1 hour time interval.

The supplementary material [18] provides the detailed set of equations used for all these computations.

B. Test case description

We consider the single-area version of IEEE-RTS96, while going through the hourly demand values for a full year and four different levels of annual peak load.

1) Test system parameters: The generation cost and nodal value of lost load coefficients are as in [14]. Further, as in [19], we have reduced all transmission ratings by 20%. All other parameters adhere to the original description of the test system and can be found in [16].

2) Reference values: In order to put results in perspective, we begin by briefly reporting some indicative values on the considered test cases. Table I presents the mean over the 8736 hours comprising a full year (1st row) and standard deviation (2nd row) of the hourly socio-economic cost of operating the system subject to the power flow constraints for the intact network configuration only (*i.e.*, the so-called N-0 criterion). It can be seen that the progressive increase in the system loading would imply a considerable increase of both the mean value of such cost ($\sim 64\%$ between the highest and lowest peak values) and on its standard deviation ($\sim 104\%$ between the two extreme values). The last two rows of this table show how this cost changes when operating the system according to the N-1 criterion, respectively when using only preventive controls and when using both preventive and corrective controls[2].

[2]Notice here that, while reporting the cost values for the N-0 criterion, by exception the risk associated to the potential occurrence of any single contingency has not been taken into consideration.

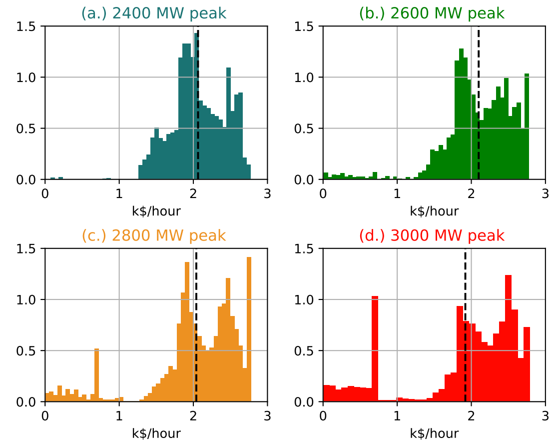

Fig. 1. Histogram of the impact of Corrective N-1 Security on C_{SE}

TABLE II

CONDITIONAL RISK $\bar{\mathbb{R}}_{N1c}$ OF CORRECTIVE CONTROL FAILURE

peak load (MW)	2400	2600	2800	3000
μ $(k\$/hr)$	0.47	0.5	0.51	0.50
σ $(k\$/hr)$	0.30	0.33	0.33	0.33

TABLE III

VALUE $\mathbb{V}_{CC}$ OF POST-CONTINGENCY CORRECTIVE CONTROL

peak load (MW)	2400	2600	2800	3000
μ $(k\$/hr)$	0.55	1.02	3.51	10.09
σ $(k\$/hr)$	0.59	3.87	12.40	26.35

Further, the histograms in Figs. 1(a - d) present the distribution of the additional socio-economic cost implied by the corrective N-1 approach with respect to the N-0 case. It is of interest here that the mean value of such costs, represented by the vertical dashed line, remains relatively stable across the four considered peak load levels ($\sim 2k\$/hr$). The increased system loading would however imply an increase in the standard deviation of the considered metric, which ranges from $0.37k\$/hr$ for the lowest peak value to $0.83k\$/hr$ for the highest peak value.

C. Conditional risk of failure vs value of corrective control

Let us now investigate the conditional risk of corrective control failure in relation to the value of corrective control. The former expresses the hourly risk of corrective control failure subject to the uncertainty on the occurrence of contingencies and while assuming that post-contingency corrective control will certainly fail. The latter is the hourly reduction of the socio-economic cost with respect to the preventive N-1 approach when using the corrective N-1 one.

Tables II and III present the yearly means and standard deviations of these two quantities under varying levels of annual peak load. Similarly to the costs of achieving corrective N-1 security, it can be seen that the mean yearly value for the conditional risk of corrective control failure remains relatively

TABLE IV
RESIDUAL RISK $\bar{R}_{N1}$ OF THE N-1 APPROACH

peak load (MW)	2400	2600	2800	3000
μ $(k\$/hr)$	0.16	0.17	0.19	0.20
σ $(k\$/hr)$	0.04	0.04	0.04	0.05

stable with the increased system loading ($\sim 0.5k\$$). Further, we also notice that the changes in its standard deviation are quite marginal. The implication, also manifesting in our detailed set of results, is that the number of correctively secured contingencies (in other words, those contingencies that contribute to the conditional risk of failure) is mostly dependent on the system topology rather than the annual peak loading level. Further, while the severity of corrective control failure does slightly increase with the increased loading, such change is *smoothed-out* with the multiplication by the contingency probabilities. As for the value of corrective control, the increase with system loading is rather prominent. Further analysis indicates that this increase is associated with the fact that, for the more heavily loaded conditions, the preventive only N-1 approach imposes more often to resort to preventive load shedding. Since such extreme measure is rather costly, there is a very high value in postponing it to the corrective control stage.

Figs. 2(a. - d.) plot the cumulative histograms of the ratio $\underline{\phi}(t)$ between the value of corrective control and its conditional risk of failure. Since the instances in which the latter is greater than the former are mostly of interest for our analysis, the x-axis of these cumulative histograms is limited to the range $[0, 1]$. These figures confirm that the value of post-contingency corrective control is incontestable, even while acknowledging the risk that it may fail. Indeed, only for less than $\sim 31-33\%$ of all instances, the conditional risk is found to be greater than the value of corrective control. The ratio $\underline{\phi}(t)$ may be regarded to be indicative of the lowest probability above which the corrective control failure risk becomes more significant than its economic benefit. With this perspective, we notice that even for the instances wherein the ratio of interest is lower than one, its value remains here at a level that can be reasonably considered unrealistic for the failure probability of corrective control. In our detailed results we have recorded a limited number of instances ($< 2\%$) wherein this argument would be made with limited confidence, as the ratio of interest takes values in the order of 10^{-2} or lower. Our interpretation is that the value of post-contingency corrective control is clear, even when acknowledging its risk as an extra precaution.

D. Corrective control risk of failure vs N-1 residual risk

Moving on, we also study the corrective control failure risk in relation to the residual risk of the N-1 approach. The data for the latter quantity is summarized in table IV. Examining the values listed in this table in relation to those in table II we may perceive that it would take 'fairly' low failure probability values for the corrective control risk of failure to be greater

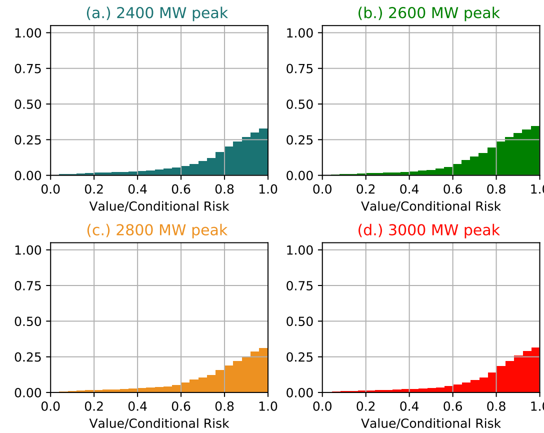

Fig. 2. Cumulated histograms of $\underline{\phi}(t)$ (values above 1 not shown)

TABLE V
FAILURE PROBABILITY – EQUIVALENCE TO THE N-1 RESIDUAL RISK

peak load (MW)	2400	2600	2800	3000
$p_{\bar{R}}$	0.0081	0.0077	0.0081	0.0088

or at least equal to the N-1 residual risk (in other words, questionable to be neglected).

As listed in table V, the value for the failure probability of any elementary control operation that would make the two risks at least equivalent lies in the order of $8\text{x}10^{-3}$ across the different studied annual peak load conditions. Here it is of interest to stress that such indicative values have been developed to investigate an equivalence between the risk of corrective control failure as estimated with a *best-case* perspective (notably, assuming that the operator would be able to shed the very less required amount of load) and a *worst-case* estimate of the residual risk. This implies that, with less restrictive perspectives, the probability value in question should be anticipated to be even lower.

E. Corrective control risk of failure vs expected utilization cost

Finally, we conclude our analysis by briefly investigating the equivalence between the yearly average corrective control failure risk and its expected utilization cost. The elementary operation failure probability to make such quantities equivalent is listed in table VI. As anticipated, the listed values are much lower than those in Table V. Indeed, it takes considerably low elementary operation failure probability values for the corrective control risk of failure to be at least as prominent as its expected utilization cost. This finding suggests that, in the event that different elementary control operations have different failure probability values, taking the risk of failure into consideration while selecting amongst them can even be more relevant than their associated utilization cost.

IV. CONCLUDING REMARKS

In response to the increased uncertainty and stress in power system real-time operation, modern reliability management de-

TABLE VI
FAILURE PROBABILITY – EQUIVALENCE TO THE EXPECTED COST OF CORRECTIVE CONTROL

peak load (MW)	2400	2600	2800	3000
p_{EC}	1.3x10^{-5}	1.3x10^{-5}	1.5x10^{-5}	1.5x10^{-5}

pends more and more on post-contingency corrective controls. Notwithstanding the foregoing, the record of data on corrective control reliability is rather limited and the risk implied by potential corrective control failures remains invisible. In such a context, we proposed in this work a methodology to assess the corrective control failure risk in relation to a set of socio-economic metrics describing the operation of a system. In the context of the N-1 reliability management approach, we have shown the relevance of the proposed assessment scope and established that its outcomes can be quite informative in judging the prominence of the concerned risk. The same approach could also be applied to understand the risk of corrective control failures when using other (say probablistic) reliability management approaches.

Developing the proposed methodology from first principles, we placed in this work emphasis on establishing its scope and documenting its fundamental modeling components. To summarize here, we may classify such components as i) *decision making models*, which are (at least) necessary to identify the elementary control operations whose reliability is of concern, ii) *physical models* representing the power system behavior, iii) *socio-economic models*, which serve to quantitatively express the several concepts of different substance (*e.g.*, decisions, failures, *etc.*) in a common language, and iv) *reliability models*, notably serving to express the contingency occurrence and corrective control failure probabilities.

Identifying an efficient trade-off between computational complexity and modeling accuracy to facilitate the scope of the proposed assessment methodology, while also exploiting a *tailor-made* algorithmic structure, is an open research question to be pursued. The refinement of decision making-models and physical models, with respect to those used to facilitate our numerical demonstrations, is well facilitated by the very broad technical literature and considered by the authors as reasonably attainable. Refraining from any statement on the efficiency *vs* accuracy of the state-of-the art in socio-economic modeling, we anticipate any further advancement in this discipline, especially regarding the representation of spatio-temporal variations in electricity consumption utility, with great interest.

Let us conclude by underlining the need for advancements in reliability models and strongly motivate the detailed collection of data on the occurrence of contingencies and on the reliability of post-contingency corrective control actions. Indeed, our present work clearly shows the interest in progressively collecting the data required to take informed decisions on whether the risk of corrective control failure is to be controlled or neglected.

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