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The Impact of Various Upgrade Strategies on the Long-Term Dynamics and Robustness of the Transmission Grid

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***Abstract*— We use the OPA global complex systems model of the power transmission system to investigate the effect of a series of different network upgrade scenarios on the long time dynamics and the probability of large cascading failures. The OPA model represents the power grid at the level of DC load flow and LP generation dispatch and represents blackouts caused by randomly triggered cascading line outages and overloads. This model represents the long-term, slow evolution of the transmission grid by incorporating the effects of increasing demand and engineering responses to blackouts such as upgrading transmission lines and generators. We examine the effect of increased component reliability on the long-term risks, the effect of changing operational margins and the effect of redundancy on those same long-term risks. The general result is that while increased reliability of the components decreases the probability of small blackouts, depending on the implementation, it actually can increase the probability of large blackouts. When we instead increase some types of redundancy of the system there is an overall decrease in the large blackouts with a concomitant increase of the smallest blackouts. As some of these results are counter intuitive these studies suggest that care must be taken when making what seem to be logical upgrade decisions.**

***Index Terms*—blackouts, power system security, cascading failure, reliability, risk analysis, complex system, phase transition.**

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I. Introduction

THE recent large scale disruptions to the power transmission network [1] have once again focused a great deal of attention on improving the reliability of the network. However, because of the many different approaches that can be taken in moving toward the goal of improving the robustness of the Electric Power Transmission systems the understanding of the system wide effect of various improvement measures becomes a high priority task for the community. This is both because the expense of these improvements can be enormous and one would like some estimate as to their effectiveness as well as because it is possible that some of the improvements could have counter intuitive results [8].

In this paper we use a global dynamic model (OPA) [2, 3] for the evolution of a large transmission network with which we can explore the long time effects of various improvement schemes. This model is used because it has been found to exhibit long time dynamics with characteristics found in the real power transmission system [4]. As these characteristics include the long time correlations of the system and the frequency of blackouts of various sizes (the blackout PDF), it is appropriate for investigating the impact of the improvement schemes. Specifically, we can characterize the impact of these improvements on the probability or frequency of blackouts of various sizes. The schemes we investigate here are three. First we investigate the impact of increasing the reliability of individual components of the system. Due to the way the components are represented, it is not easy to discriminate from a second improvement method, namely changing the operating safety margin. Finally, we look at the impact of implementing component redundancy on the system. Because of the general nature of the model and because each of these techniques themselves have many ambiguities in their implementation, this should be thought of as an initial survey which perhaps highlights the complexity of the question and the need for further study rather than giving definitive answers.

In the next section we will briefly describe the model and present the results of the different improvement schemes. Finally there is a section on discussion, conclusions and suggestions for further work.

II. Modeling Reliability and Redundancy

A. OPA

The OPA model [2, 3] has been developed as a realization of the global complex dynamics briefly described in the previous section. The OPA model represents the essentials of slow load growth, cascading line outages, and the increases in system capacity caused by the engineering responses to blackouts. Lines fail probabilistically and the consequent redistribution of power flows is calculated using the DC load flow approximation and a standard LP re-dispatch of generation. Cascading line outages leading to blackouts are modeled and the lines involved in a blackout are predicted. The engineering response to the blackout is crudely modeled as an increase in line margin for the lines that were involved in the blackout. The OPA model clearly represents the processes in greatly simplified forms, although the interactions between these processes still yield complex (and very complicated!) behavior. The simple representation of the processes is desirable both to study only the main interactions governing the complex dynamics and for pragmatic reasons of model tractability and simulation run time. This also allows the study of various network configurations, from simple tree type networks that allow some analytic analysis, to a more realistic IEEE test networks such as those shown in Figures 1 and 2.

Blackouts in OPA are complicated events involving line outages and limitations in generation. We can characterize them by two limiting situations each with different dynamical properties [3, 5]. One type of blackout is associated with multiple line outages. The second type of blackout involves loss of load due to generators reaching their limits but no line outages. In general, both effects appear in most blackouts, but for a given blackout, one of these characteristic properties is dominant. The dominance of one type of blackouts versus the other depends on operational conditions and the proximity of the system to one of its two critical points [6]. The first critical point is characterized by operation with lines close to their limits. The second critical point is characterized by the maximum fluctuations of the load demand being near the generator margin capability. When the generator upgrade is suitably coordinated with the line upgrade, the critical points coincide and the model can show a probability distribution of blackout sizes with power tails similar to that observed in NERC blackout data [7]. Similar results are found in both the idealized tree network and a more realistic network (Figs. 1 and 2). One of the important results from these models is that even though the individual causes of each blackout event might vary, the statistics of these events remain remarkably robust. This is because the system rearranges itself to stay near the operational limit at which these statistics (PDFs etc) are characteristic. This rearrangement is likely the result of a combination of the social and economic pressures on the system interacting with the system design and operation and the engineering responses to the blackouts.

Here we look at some different responses and differently engineered systems in order to investigate whether these different systems have similar dynamics and statistics. Note that in this paper we are not studying the short-term effect of the different engineering measures on a fixed network. Instead we are investigating the effect of the different engineering measures on the complex systems equilibrium that is achieved after the system has rearranged itself on the time scale of the dynamics of load growth and network upgrade.

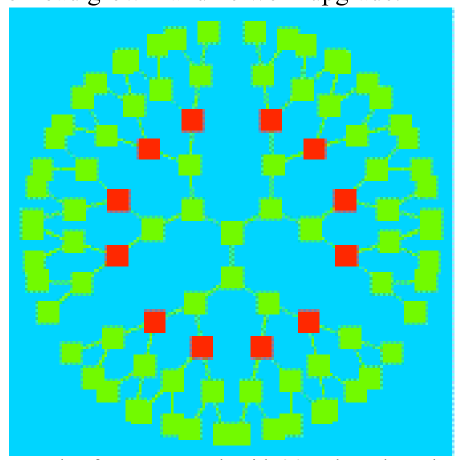

Fig. 1. Example of a tree network with 94 nodes. The red squares are generator nodes.

For the results presented here we work mainly with the IEEE 118 bus network, however, this network is modified for the redundancy studies.

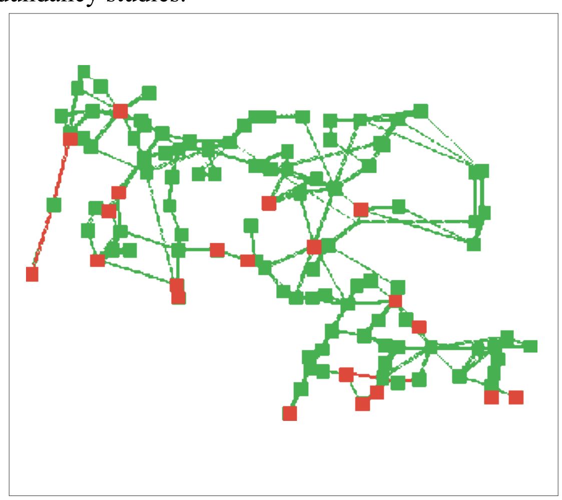

Fig. 2. The IEEE 118 bus network. The red squares are generator nodes.

B. Reliability/Margin Improvements

At the initial level of inquiry, the investigations of the improvements in component reliability are, in this model, an investigation of both component reliability and operating margin. This is because of the way we implement reliability improvement in the model. Due to the general nature of the model we do not model the individual components in any detail. For example, transmission lines and transformers are both considered as part of the lines joining nodes and in this paper when we refer to lines, we mean the lines and the components that make them up. The lines, and their constituent components, have failure probabilities for different situations. For example, each line has a certain probability of random failure (P_0). These can be thought of as failures caused by either uncontrolled external influences (a lightning strike, a squirrel in a transformer etc) or by the random failure of the line due to a defect or ageing. Each line also has a load driven or stress failure specified by P_1. We use the fraction of overloading, $M = F / F_{\max}$, as a measure of the stress on the line, where F is the power flow in a given line and $F_{\max}$ is the limiting power flow. When a component is within a given distance (margin) of its operating limit, M_R, it has a probability of failing (P_1) and then being upgraded. Reducing the random failure probability P_0 does little to the dynamics over a range of values. However changing the margin M_R at which P_1 starts to have an influence can have a significant effect on the system. The margin M_R for onset of P_1 can be interpreted in a number of ways. The first and perhaps most straightforward is that this onset margin is simply the operating margin that the operators strive to maintain given the knowledge that there is an increased failure probability above that point. Because the lines at their onset margins are not yet at their hard limits (emergency ratings) there is some additional margin engineered into the system. In this system if there is a line outage (even if there is no power shed) the line (component) is upgraded. This tends to keep the overall system farther from the critical point. The other way of interpreting the margin M_R is in terms of line reliability. If a line is made more reliable then it has a smaller probability of failing before its hard limit is reached. That can be thought of as a decrease in the margin to the hard limit. That is, a more reliable line can carry higher loadings that have no chance of loading induced failure. There could be a concomitant decrease in P_0 but, as stated before, that has a small effect.

The effect of changing the probability P_1 was studied in detail in [8]. The expectation from this form of increase in the reliability of the lines is an overall decrease in the frequency of the blackouts. Furthermore, large blackouts with many failures are also expected to be less likely because of the decreased probability of cascading line failures. As expected, we saw in previous work [8] that reducing P_1 reduces the probability of large blackouts. However, this is not the only change observed in the dynamics. With the decrease of large blackouts, there is a concomitant increase in the number of small blackouts. The overall result is that there is hardly any change on the frequency of blackouts. As discussed in [8], the increase of reliability through P_1 induces only a logarithmic decrease in cost of the blackouts

When the margin $1\text{-}M_R$ is changed a very noticeable change in the distribution of power shed and outages is seen. Figure 3 shows a large reduction in the largest blackouts when $1\text{-}M_R$ is increased from zero (i.e. it is at the hard limit) to 20%. That is, the local load point at which failures start and upgrades can occur is in the best case 0.8 times the hard limit for the individual lines. This decrease in the largest event probability is up to a factor of five for the largest blackouts. Looked at in the other interpretation, this implies that increasing the component reliability can increase the probability of the largest events by a significant amount.

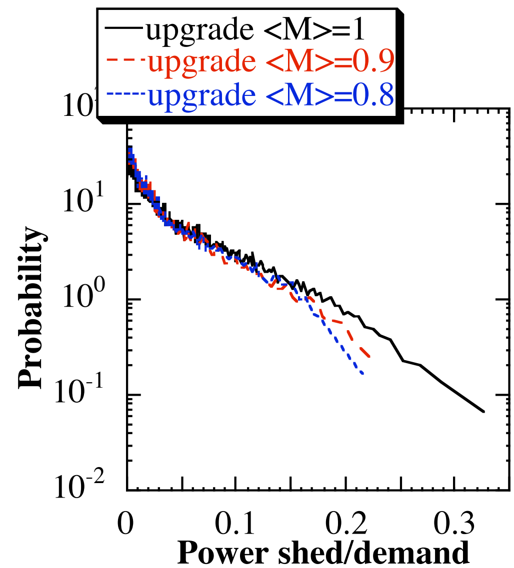

Fig. 3. The probability distribution of blackout size for 3 operating margins, 0, 0.1 and 0.2. The blackout size is measured by the power shed normalized by the total power demand. A marked decrease is seen in the cases with an increases margin, or conversely, a marked increase in the largest events is seen when the system has the most reliable components.

In Fig. 4 the probability distribution of line outages is plotted for the same cases. This shows clearly that as the margin increases the largest outages (those that often cause blackouts) are decreased while there is a concomitant increase in the smaller outages. This is consistent with the power-shed results and again suggests that the increased margin makes the system less prone to large failures, which could be interpreted making the system more robust. Once again, the other way of interpreting this is that as the line reliability increases, the probability of large failures increases which is perhaps a counterintuitive result.

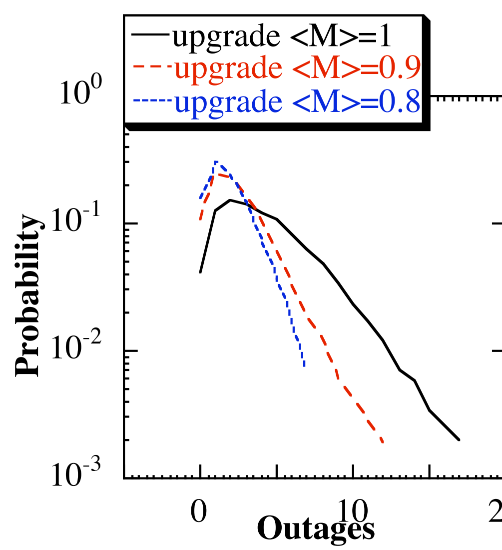

Fig. 4. The probability distribution of number of line outages for 3 operating margins, 0, 0.1 and 0.2. A marked decrease in the largest sizes and an increase in the smallest sizes is seen in the cases with an increased margin, or, conversely, a marked increase in the largest events is seen when the system has the most reliable components.

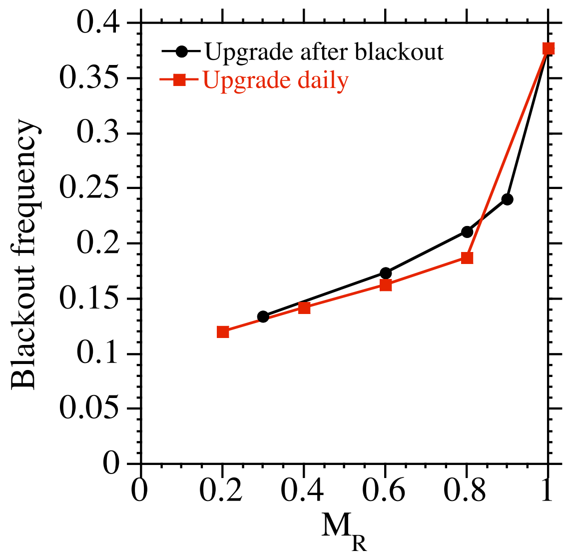

Fig. 5. Frequency of blackouts decreases as the fractional margin point decreases. The two upgrade schemes (failure based or daily prophylactic upgrades) give approximately the same improvement.

The upgrades to this system can be handled in two different ways. The standard method is to wait for a component failure and blackout and then upgrade the components after the failure. This is the standard implementation used for OPA in most cases. However, one can also envisage strengthening the network by increasing the operating margins of stressed lines before they fail. This implementation keeps track of the line loading and those lines that are in their margin region are upgraded preventatively at the end of the day. Surprisingly, both methods had the same effect on the system at least in the parameter range we are using. Figure 5 shows the blackout frequency as a function of the operating limit (M_R) for both upgrade methods. The daily, prophylactic upgrades are a little bit better but are effectively the same as the failure based upgrades in decreasing the blackout frequency.

Figure 6 shows that not only does the frequency of the blackouts decrease, but also the blackout size decreases as the margin is made larger. Once again the two upgrade schemes give approximately the same results.

It should be seen that for both of these measures, the blackout frequency and size, the largest improvement (a factor of more then 2) is found in going from no margin to the 20% margin. After that, the improvement with increasing margin is much slower. Stated using our reliability interpretation of the margin, this means that improving line reliability up to a point does not seriously impact the statistics, but after that point it can have a major effect.

Figure 7 shows the number of blackouts of a given size for the various margins. This shows even more clearly that the largest change in the distribution comes in going from no margin (M_R=1) to a 20% margin (M_R=0.8). After this, the distributions change little except for a modest decrease in the smaller blackouts.

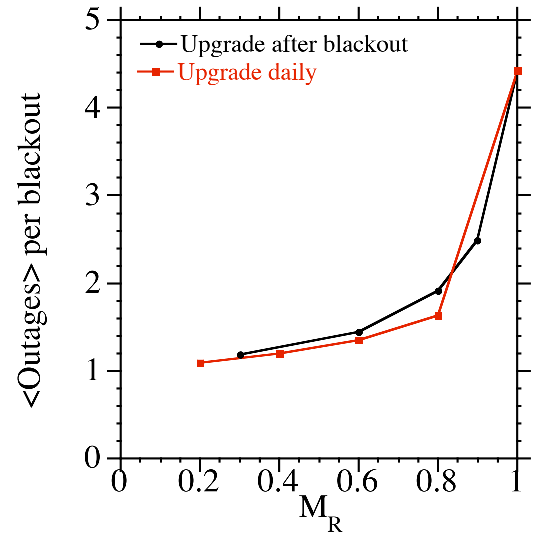

Fig. 6. The mean number of outages per blackout is also seen to decrease as the operating limit decreases. The two upgrade schemes (failure based or daily prophylactic upgrades) again give approximately the same improvement.

The actual power shed per blackout has a minimum around M_R =0.7-0.8. This is because after the largest events are removed, a further decrease in the smallest blackouts (which are more likely) actually increases the mean size since now the larger blackouts are reduced less. This can be seen in Fig. 7 looking carefully at the smallest sizes or much more easily in Fig. 8.

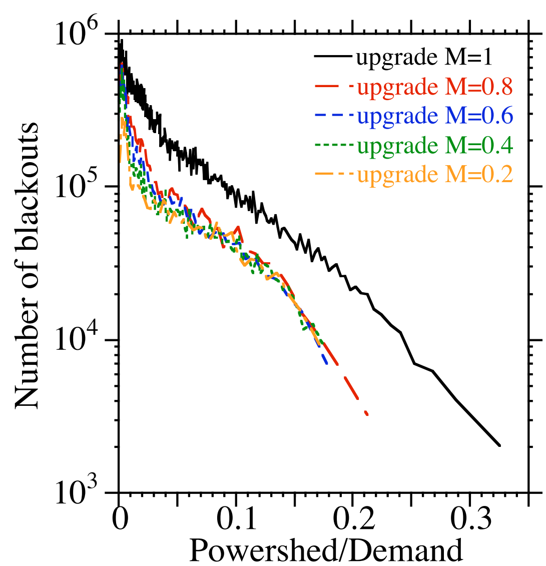

Fig. 7. The number of large blackouts as a function of blackout size for various operating limits M_R The overall decrease in the number of blackouts is much larger for the first 20% increase in margin.

Figure 8 shows the stark difference between the distributions in the first 20% margin increase followed by the overall reduction of the frequency and a slow decrease in the larger events.

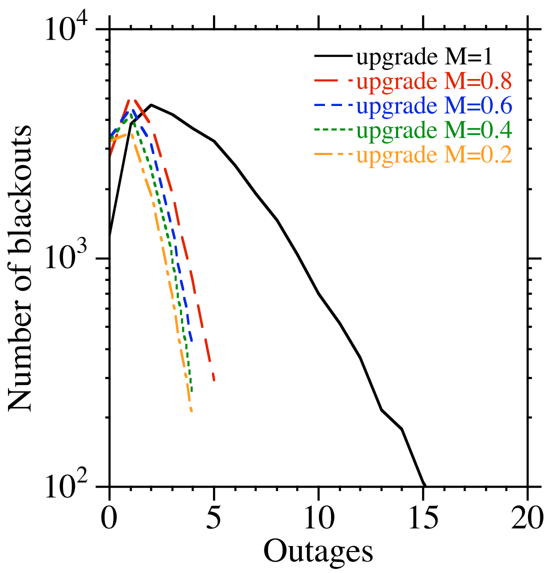

Fig. 8. The maximum number of outages decreases dramatically for the first 20% increase in margin, then the smallest number decreases faster (note the vertical log scale)

This suggests that a working margin of 20-30% is for this model near optimum in terms of both robustness of the overall system and economic efficiency. Likewise, if the component reliability becomes such that the upgrades are not done until just before their hard limit, the system is likely to be more susceptible to large cascading failures.

C. *Redundancy*

Within the OPA model, investigating redundancy has even more ambiguities of definition. For example one can have redundant capacity without having redundant components (lines). This would be accomplished by making the operational margin at least 50%. This would be the same as increasing the margin as in the last section but would do nothing for the random failures. Another possibility is having parallel lines, each of which is able to carry the entire load. In normal operation they will each run at 50% capacity (i.e. with M_R for each line at 0.5). This allows for a failure in one line being fully mitigated by the other line. Finally there is a variant on the last option that involves having a fully redundant second component that is not used unless the main component fails. The first two cases have the difficulty of being susceptible to the strong social and economic pressures to utilize the unused capacity. This would tend over the course of time to remove the redundancy from the system and simply end up with two parallel fully utilized components at which point the system is likely to be in a more vulnerable situation then before [10, 11]. The methods we have investigated are the first 2.

Figure 9 shows the effect of adding redundant lines. Adding the lines around the generators, which tend to be the limiting areas, reduces the frequency of the largest blackouts, with a modest increase in the smallest blackouts. However the largest change in large blackout frequency is seen when all lines are doubled (made redundant). In this case the large blackout frequency is reduced by almost 30% and the overall frequency of blackouts is not much changed.

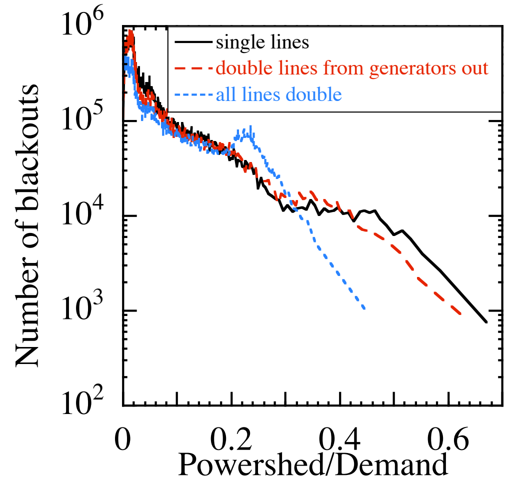

Fig. 9. Doubling lines from the generators decreases the number of large blackouts somewhat. Doubling all lines has the largest effect on reducing the number of large blackouts.

Adding levels of redundancy does little to further protect the system. Figure 10 shows a system in which the lines are doubled and then tripled. The improvement in the doubling of the lines is not enhanced in any significant way by tripling the lines.

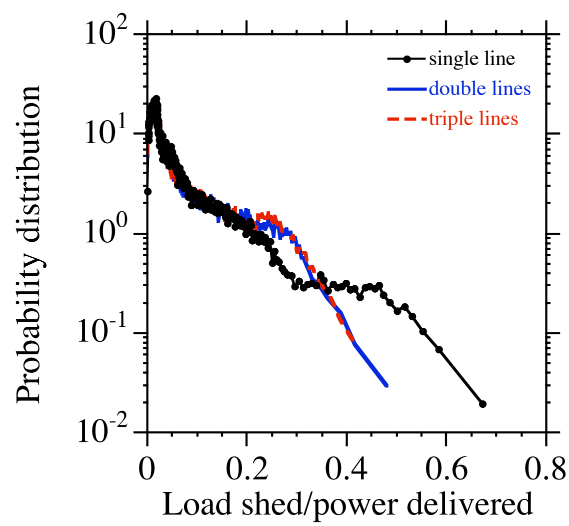

Fig. 10. Reductions in the largest blackouts are seen when adding a set of redundant lines. However adding additional lines beyond that does little additional good.

III. Discussion and Conclusion

In dynamic complex systems models of the power transmission system can reproduce the dynamics, power tails and apparent near criticality observed in the NERC data [4]. The complex system model, studied here includes a representation of the engineering and economic forces that drive network upgrades as well as leading to the cascading failure dynamics. These dynamics come from a competition between two forces. On one side, the increasing load demand and economic pressures that tend to add stress to the system. On the other side, as the system becomes more stressed, the blackout risk rises and the response to blackouts is upgrades to the system which then relieves the system stress. From the competition between the forcing and upgrades, the system tends to organize it self near to the critical point in a complex systems equilibrium. The utility of this type of model is not in the analysis of an individual blackout but rather overall system dynamics as the system responds to slow forcing.

This type of model allows the exploration of various changes in the system engineering and operation in order to investigate the effect of these changes on risk of large failures and system dynamics. In this paper we looked at two of these changes, line component reliability (or margin improvements) and redundancy. The result from these preliminary studies suggests that improving the reliability of lines (or line components) can have a counter intuitive effect. That effect is an increase in large blackouts as the reliability is increased (or the operating margin is decreased). Adding redundant lines on the other hand is found to reduce the probability of large blackouts.

This type of model, with these results, lead naturally to a series of areas for further/future research:

1) System upgrade schemes - Modeling of redundancy and reliability need to be improved and explored in more depth. This should include real reliability characteristics, various redundancy models and a combination of both. Reliability modeling should include at least 4 probabilities associated with component reliability; external random failure, defect failure, aging failure, and stress failure. In addition to these simple system upgrade explorations this type of model allows for the investigation the impact of various islanding schemes on blackout risk.

2) Interacting complex systems – In reality, the complex system model of the power transmission network is one part of the interacting infrastructure system that controls the transmission grid. These interacting infrastructures include economic systems, IT systems and human decision making systems. Incorporating these as separate interacting complex systems or as "agent based models" within the transmission network complex system model needs to be investigated to explore the effect on risk from the system interactions.

3) In order to both compare models to the real system and to develop for real time control and risk assessment techniques, new system state metrics need to be developed. These should be developed for system monitoring and comparison.

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