Why investments do not prevent blackouts

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Introduction
Power had not yet been fully restored following the recent blackout that some were already clamoring that increasing transmission capacity is the best way to avoid a repetition of these events. Others were laying the blame squarely on the deregulation of the electricity supply industry. Should the United States embark on a massive investment program? Should deregulation be abandoned on the grounds that it has a negative impact on the reliability of the electricity supply? Before trying to answer these questions, we must review how power systems are operated and discuss how and why blackouts happen.

Operating a power system
In dozens of control rooms around the United States, power system operators are constantly monitoring the state of the transmission grid and dispatching the output of generating units. If you were to ask these men and women to summarize their job, most of them would answer something like “keeping the lights on”. This is an important responsibility that all those we have met take very seriously. On the other hand, operators are also under considerable pressure to run the power system in the most economical manner. This means producing or buying electrical energy to meet the demand at the lowest possible cost and enabling as many transactions as possible. These economic considerations invariably put more stress on the transmission system because more power ends up being transmitted over longer distances. Balancing the greed for profit and the fear of blackouts is thus the essence of operating a power system.

Security criteria
To resolve this conflict and help operators perform what is a complex technical task, reliability councils have developed rules that transmission utilities and operators should follow at all times. The details of these rules can be lengthy and there are variations between the rules issued by the various reliability councils. However, the fundamental principle is simple: a power system should always be operated in such a way that no credible contingency could trigger cascading outages or another form of instability. This approach was chosen because all power systems are routinely affected by unpredictable faults and failures such as lightning strikes on transmission lines, mechanical failures in power plants, or fires in substations. Since events of this nature are unavoidable and relatively frequent, all power systems should be able to endure them without inconveniencing consumers. Avoiding blackouts and wide scale consumer disconnections
is possible only if the system is operated with a sufficient security margin. There must be
enough reserve generation capacity to make up for the loss of a generating unit and
enough transmission capacity to handle the power flows displaced by the outage of a line.
Note that it is always possible to dream-up a sequence of unfortunate events that would
bring any power system to its knees. Since securing the system against all possible
contingencies is clearly impossible, the fundamental principle only calls for securing
against all credible contingencies. So, what is considered credible? It is typically assumed
that the probability of two or more independent faults or failures taking place
simultaneously is too low to be considered credible. Most security rules therefore call for
the system to be able to withstand the loss of any single component. When a power
system satisfies this criterion, it is said to be “N-1 secure” because it could lose any one
of its N components and continue operating. Similarly, in a system that is “N-2 secure”,
no consumer would be disconnected even if two components were suddenly
disconnected.

A simple example

Let us illustrate these concepts using the simple example shown in Figure 1. In this
example, areas A and B are connected through a transmission corridor comprising three
identical lines, each of which has a capacity of 300MW. A load of 1200MW is connected
in area B. We assume that the generators in either area have a capacity that is sufficient to
supply the entire load. If the marginal costs of energy in area A is 20$/MWh, and
50$/MWh in area B, the cheapest way of supplying the load without overloading the lines
would be to generate 900MW in area A and 300MW locally. This dispatch and the
resulting line flows are shown on Figure 1-A.

But what happens if a fault occurs on one of the lines? In a fraction of a second, the
protection system for this line detects this fault and immediately removes it from service.
The power that flowed through this line is redistributed between the remaining two lines.
As Figure 1-B shows, this redistribution causes heavy overloads. These two remaining
lines are likely to be rapidly disconnected through the actions of their protection systems.
In order to prevent such cascading outages from leading to a blackout, the loading of the
transmission lines should be limited to a value well below their full capacity. Figure 1-C
shows this “N-1 secure” dispatch and the resulting line flows. The reader can easily
check that in this case, the sudden loss of one of the lines would not overload the
remaining circuits. However, the sudden loss of two lines would overload the last line
and would most likely cause a blackout.

The operation of some power systems is not limited by thermal limits on the capacity of
individual lines but by voltage and angular stability considerations. These stability
constraints also place limits on the amount power that can be securely transferred along
some transmission corridors. With the loss of a transmission line, the network
configuration changes, resulting in an increase in system impedance. As demonstrated in
our example the loading on the remaining circuits also increases. This increase in loading
together with the increase in system impedance increases the voltage drops and, under
extreme conditions, may destabilize the systems. Alternatively, if the power transfers are
excessive, a fault could destabilize the whole system and cause a separation between the
generation and load areas.
The cost of security

Making a system N-1 secure by reducing the amount of power flowing through each line comes at a cost. In the simple example of Figure 1, the output of the cheaper generators in area A has been reduced and the more expensive production in area B has been...
increased. Specifically, the hourly cost of operation for the insecure conditions of Figure 1-A is:

\[ C_1 = 900 \times 20 + 300 \times 50 = 33,000 \$/h \]

On the other hand, the hourly cost of operation for the N-1 secure conditions of Figure 1-C is:

\[ C_2 = 600 \times 20 + 600 \times 50 = 42,000 \$/h \]

The $9,000 per hour difference between these two values represents the cost of security.

**Operating tools**

For the last twenty years power system operators have had at their disposal sophisticated computer programs capable of performing a static security analysis on-line, i.e. based on the current condition of the power system. These programs are designed to warn the operator about any credible contingency that might cause a line to become overloaded and thus likely to fail. Great advances have also been made in the development of dynamic security analysis programs that alert operators to any contingency that would affect the voltage or angular stability of the system. Using these programs, operators can check that their system is in a state that satisfies the security rules.

With the advent of deregulation and open access to the transmission grid, software packages have been developed to determine the Available Transmission Capacity (ATC). This is the transmission capacity that ISO’s can release to parties wishing to trade electrical energy over the transmission network. Embedded within these ATC calculations are static and dynamic security analysis programs. ATC programs thus tell the operator how far the system can be pushed without breaching the security rules.

We can therefore say that economics drives the operation of a power system towards its limits. When the transmission system is most heavily loaded, usually but not necessarily during periods of high demand, the flows through some lines or corridors are at their limits. This means that the system might collapse if these flows were increased slightly and a critical (but credible) contingency did occur.

During periods of lower demand, there may be no component of the transmission system operating at its limits. The system is then more secure than what is called for by the rules. However, in a system where the optimal balance has been achieved between the operation and investment costs, every component is operated at its limit for at least part of the time.

**Why blackouts happen**

At this point, the reader might ask why blackouts happen in spite of these security rules. As Michel R. Gent, President and CEO of NERC, succinctly put it in a press conference shortly after the August 2003 blackout, “[…] either the rules were not followed or the rules are not adequate”. If it turns out that this blackout happened because the rules were not followed, it will become necessary to audit the security performance of transmission companies to ensure that the well-being of many is not endangered by the actions of a few. But let us assume that the rules are not flouted either voluntarily or involuntarily. A blackout will then occur only if a contingency that was not considered credible does
occur. For example, let us suppose that a power system is N-1 secure before a fault trips a transmission line. At that point the system is no longer N-1 secure and the loss of a second line might trigger cascading outages. Historical outage statistics suggest however that the probability of losing a second critical line before the operator has had time to re-secure the system is very low. We cannot rule out that blackouts might be caused by the combination of two or more independent faults or failures, but this should happen very rarely.

A review of reports on past blackouts\(^4\) confirms that most of them occur when the system is secure but under stress because of heavy power transfers. Many of these blackouts were triggered by a credible contingency whose effect was compounded by an internal failure in the power system. Typically, this internal failure involves a malfunction of the protection system in response to the external fault. Instead of removing from service the affected component only, one or more additional healthy components are unnecessarily disconnected. A routine incident that the system should be able to survive is suddenly transformed into a major problem that cascades out of control. The probability of this internal malfunction scenario is higher than the probability of non-credible contingencies because the external and internal failures are not independent events. A large proportion of blackouts are thus caused by the combination of a credible contingency and a system malfunction. Security criteria do not take into account the possibility of protection system malfunctions.

**Why adding transmission capacity does not improve security**

The idea that increasing the capacity of the transmission network should improve the security of the system and reduce the probability of blackouts is intuitively appealing. However, we believe that this intuition does not withstand scrutiny. Fundamentally, there are two ways of increasing the capacity of a transmission network: upgrading the capacity of the existing network and building new transmission lines.

Upgrading an existing network is usually the cheaper and environmentally-friendlier option because it does not require the acquisition of new rights-of-way. In many cases the transmission capacity is restricted by thermal limitations on some of the existing lines (i.e. by the number of megawatts that can flow without causing one of the lines to sag too close to the ground). Constraints of this type can be relaxed by replacing the existing cables with thicker ones that can carry more current (“reconductoring”). Engineers have also developed various techniques to upgrade the transmission capacity when it is limited by voltage or angular stability considerations. For example Static VAR Compensators (SVC) can be installed to provide dynamic reactive support. Series compensation can also be inserted to reduce the apparent impedance of long lines. Transmission capacity can also be increased by installing advanced control schemes, such as power system stabilizers or inter-tripping schemes that disconnect some customers in a controlled manner to limit disturbances.

Building new transmission lines is considerably more expensive, more time consuming and more difficult because of the need to acquire new rights-of-way. Additional lines alleviate transmission constraints caused by thermal limitations because the power to be transmitted is shared among more paths. They also enhance the system’s voltage and angular stability because they reduce the overall impedance of the network.
If everything else remained unchanged, building new lines or upgrading the existing ones would clearly enhance the security of the overall system. The security margin (i.e. the difference between the power that the system is designed to handle and what actually flows) would indeed be much higher. Even during periods of high demand, the system would be able to withstand more than just the credible contingencies.

It is very unlikely, however that everything else would remain unchanged. Additions and upgrades to the transmission network are immediately reflected in the models that engineers use to evaluate the security of the system and calculate the available transmission capacity. Unless the rules governing the usage of the system are changed, this additional transmission capacity would be made available to all users of the transmission network. Economic considerations dictate that this new capacity will inevitably be used for increased power transfers from regions with inexpensive generation to regions with a high demand. Security might be enhanced in the short run because new economic transactions using the existing generating plants might not absorb all the additional transmission capacity. In the long run, however, generating plants will be built in a way that makes full use of the transmission network. At that point, the system will again be operating at the limit dictated by the security rules and the probability of a blackout will not have diminished. We can therefore conclude that building new transmission lines and upgrading the existing transmission system do not inherently enhance the security of the transmission system. On the other hand, these investments have significant economic benefits because they relax some of the limitations that the transmission network places on the electricity markets.

**Upgrading the lines of our simple example**

These ideas can be illustrated and clarified using the simple example that we introduced above. Let us suppose that each of the lines connecting areas A and B has been upgraded in such a way that it can carry 400MW instead of the original 300MW. Figure 2 shows the state towards which the operation of this system will inevitably be driven by economic considerations. The amount of low cost power produced in area A increases from 600MW to 800MW, while the more expensive generation in area B decreases from 600MW to 400MW. Hence, the total amount of power transferred increases from 600MW to 800MW. Under these conditions, the hourly cost of supplying the load is:

\[
C_3 = 800 \times 20 + 400 \times 50 = 36,000\$/h.
\]

Since this cost is substantially lower than the one we calculated for the conditions of Figure 1-C, the economic benefits of this upgrade are clear. Let us now check the security of the operating state. If one line is taken out of service by a fault, the 266MW that it carries distribute themselves between the two remaining lines, bringing the flow in each of these lines to 400MW, which happens to be the maximum flow that they can carry. This system state is thus N-1 secure because the loss of any single component would not cause cascading outages. The security of the system has thus not been improved: it was N-1 secure before the upgrade and economic forces force it to be again exactly N-1 secure after the upgrade. A rigorous probabilistic analysis would show that the probability of a blackout has actually increased because the stability margin of the system has decreased due to the extra loading of the transmission lines.
Adding a line to our simple example

Let us now see what happens if we add a transmission line to the simple example of Figure 1. Assume that this new line, like the others, can carry at most 300MW. Figure 3 shows how such a system would be operated most economically if the rules of operation are unchanged. Because of the N-1 security criterion, each line can carry a maximum of 225MW. This means that 900 MW can be generated in area A and only 300MW in area B. The hourly operation cost is thus again significantly lower than what was possible with the system of Figure 1-C:

\[ C_4 = 900 \times 20 + 300 \times 50 = 33,000 \text{$/h} \]

While the economic benefits of adding a line are clear, this line does not improve the security of this system because the additional capacity that it provides is used to increase the power transfer between the two areas rather than to increase security. Again, when the system is fully loaded, the expanded network can handle only the outage of a single line. The loss of any two lines is likely lead to a system collapse.

Figure 2: Consequences of upgrading the transmission lines of the simple example of Figure 1.

Figure 3: Consequences of adding a transmission line to the simple example of Figure 1.
Whether or not the dynamic stability of the system is enhanced by the addition of this line is debatable. While the reduction in system impedance improves stability, the increase in power transfer is destabilizing. Furthermore, having more lines marginally increases the likelihood of outages simply because there are more elements that can fail.

Some investments are truly security-driven

While increasing the transmission capacity does not reduce the likelihood of blackouts, making sure that all the components of the power system behave as expected could make a significant difference. In particular, modernizing the protection system to reduce the probability of malfunction diminishes the risk of major problems arising from minor incidents. Similarly, upgrading the communication, control and computation tools at the disposal of the operator would improve the speed and quality of the response in case of trouble. These types of investments do not increase the capacity of the transmission system but enhance its reliability.

Is deregulation to blame?

To the best of our knowledge, the security criteria that have guided the operation of power systems have not changed significantly since the introduction of competitive electricity markets. One can therefore argue that the level of security has not been affected by deregulation. However, as we discussed above, strict adherence to rules such as “N-1 security” does not guarantee that blackouts will not occur. There is always a possibility that a critical event that is considered “not credible” will happen. The risk associated with such non-credible events is much larger when the system is operating at or close to its limit because the power system is then much less stable. A transmission network that is operated at its limit is thus “secure” but much more at risk than a system that is not under stress.

Deregulation has resulted in a much more intensive use of the transmission system: more power is being transmitted over longer distances during a larger proportion of the time. Since the system is operated at its limits for longer periods of time, the probability of a blackout therefore increases. On the other hand, deregulation has encouraged a more economically efficient use of the existing generation and transmission resources. The consequences of this increased risk of blackouts should thus be weighted against the economic benefits of deregulation.

When a rule such as N-1 security is adopted, an assumption is implicitly made that abiding by this rule is enough to prevent blackouts and other major incidents. The system is then designed to minimize the sum of the investment and operation costs. If we want to be more rigorous and more realistic, we must acknowledge that blackouts will occasionally happen. The design and the operation of the power system should then involve not only the cost of building and running the system but also the cost to society of these unavoidable blackouts. Calculating the societal cost of blackouts requires not
only an estimate of their frequency, extent and duration but also an estimate of their direct and indirect costs to individuals, corporations and communities.\(^5\)

**The importance of rules**

N-1 security has the great advantage of not requiring such complex probabilistic calculations. It is also simple to monitor and implement. It worked reasonably well before deregulation because blackouts occurred infrequently enough to be tolerable. If competition significantly increases the level of stress in the transmission and the duration of the period during which the system is under stress, the approximation that N-1 security represents may no longer be acceptable. Security rules may then have to be reviewed and possibly tightened.

Tightening the rules, however, is not a cost-free recipe for enhancing security. To illustrate this, let us go back once again to our example of Figure 1. Let us suppose that instead of operating under an N-1 criterion, this power system must be operated with N-2 security. Figure 4 shows the most economical way of operating under these conditions. This change of rules reduces the amount of power that can be transmitted from area A to area B from 600MW to 300MW. In this case, losing any two lines would not overload the remaining one. Only the simultaneous loss of all three lines would cause a problem. System security is clearly enhanced and the probability of a blackout significantly reduced. Unfortunately, the economic performance of the system is also considerably reduced because the output of the low cost generation has been curtailed. The hourly cost of operating with N-2 security is:

\[
C_5 = 300 \times 20 + 900 \times 50 = 51,000\$/h.
\]

![Figure 4: Operation of the simple system of Figure 1 under an N-2 security rule.](image)

**Conclusions**

Increasing the capacity of the transmission network does not inherently enhance the security of the power system and reduce the probability of blackouts. This paradox arises because the level of security of a system is determined by the rules that govern its operation. If the transmission capacity is expanded without any adjustment in these rules,
nothing will have been gained from a security standpoint. This does not mean that there are no good arguments for upgrading the existing system and building new transmission lines. One must be aware, however, that these investments will benefit primarily the producers and consumers whose ability to obtain better prices in the electricity markets is currently limited by congestion in the transmission network.

Nominally, the level of security in power systems has not changed since deregulation. However, the increased level and duration of stress in the transmission network, which result from bigger, longer and more frequent transactions, has increased the probability of blackouts. Deterministic security rules that worked well before the introduction of competition, such as the N-1 criterion, may no longer be adequate. These rules may need to be reviewed and possibly replaced by probabilistic criteria that better reflect the risk of blackout.

Biographies

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1 We have used “should” rather than “must” because compliance with these rules is currently voluntary rather than compulsory in the United States. In other jurisdictions, such as the United Kingdom, compliance with similar rules is compulsory.
2 See for example www.npcc.org/criteria.htm for the reliability criteria for the Northeast Power Coordination Council or www.maac-rc.org/ for those of the Mid-Atlantic Area Council.
3 For the sake of simplicity, we have not taken into account the possibility that the operator might take corrective action after the first outage. Our dispatch is thus somewhat more conservative than what might happen in practice.