8th Mediterranean Conference on Power Generation, Transmission, Distribution and Energy Conversion
MEDPOWER 2012

Revealing Stability Limitations in Power System Vulnerability Analysis

Emil Hillberg, Jarno Lamponen, Liisa Haarla, Ritva Hirvonen

***Abstract*— Creating defense plans against extreme contingencies requires knowledge of the principal vulnerabilities of power systems. This paper describes the blackout phenomenon as a process with separate phases and distinctive transitions. The paper proposes two indicators that can help to identify vulnerabilities in a specific operating scenario and recommends that the dynamic behavior of a power system after successive faults should be analyzed. This analysis would reveal vulnerabilities connected to high impact low probability contingencies where the system response can change after several successive contingencies. These vulnerabilities cannot be captured by steady state analyses. Analyses of some recent large European blackouts, presented in the paper, indicate that a power system may collapse after only a limited number of contingencies, implying that these power systems are more vulnerable to multiple contingencies than the system operators may be aware of.**

***Index Terms*—blackout, cascading failure, $N-1$ criterion, power system security, power system stability, power transfer capacity**

I. Introduction

MAJOR disturbances resulting in wide-spread outages or total power system blackouts have been analyzed in several publications, e.g. [1]–[4]. Many published studies concentrate on a specific disturbance, giving a detailed description of causes, sequences and consequences, [5]–[14]. Attempts have also been made to identify generalized patterns, root causes and sequences of historical blackouts, as described in e.g. [15]–[17].

The methods for understanding and mitigating cascading failures in order to prevent blackouts are not yet well developed, and the dynamic processes related to large disturbances are insufficiently captured by the current analysis tools, [18, pp. 6–7] and [19, p. 8]. Different methods using power flow calculations are widely used when analyzing cascading failures [19]. However, power flow calculations can only give information on the pre- and post-contingency states, and not whether the transition from one state to the next is stable. Only when the transition is stable and the system finds a post-fault steady state, the analysis of a post-fault state is meaningful. Therefore, relying only on steady-state power flow calculations, inherently underestimates the vulnerability of the system against instability connected to successive or simultaneous contingencies.

It is a challenge to perform dynamic studies on an extended scale in large power systems with a sufficient level of modeling detail, [18], [20]. By far security analyses including dynamics security assessment are rare, [21]; performing dynamic simulations is time consuming, and creating the dynamic simulation model is laborious. It is however possible to limit the number of dynamic analysis by using contingency reduction techniques, as described in [22]. In [21], event and fault trees are used to model a cause for multiple contingencies, relay protection and circuit breaker failures, and combines it with dynamic simulations.

A system may initially be strong, in terms of low impedance and stability, and the $N-1$ security restricted by post-fault thermal ratings. Nevertheless, after one or several contingencies, the system may be weakened to a state where dynamic instability rather than thermal overloading is the dominating phenomenon related to further contingencies. As a result, the system may experience a loss of stability, leading inevitably to a blackout.

Blackout phenomenon can be analyzed as a process with separate phases, as described in [23] and [24]. In [23], the cascade is divided in two phases: a slow cascade (ruled by thermal transients), and a fast cascade (where the system is considered unstable), and in [24], the slow and fast phases are considered to be separated by a triggering event.

This paper focuses on the transition point when the system becomes unstable and on the dominating phenomena before and after that point. In the analysis of blackouts, it is important to clearly identify the dominating phenomenon of each phase of the process. The paper emphasizes the importance of identifying the point where the dynamic stability becomes critical. This instance indicates the "point-of no-return" of a disturbance, after which the collapse process accelerates drastically and manual remedial actions are too slow to limit the propagation of the disturbance. The examples of occurred disturbances presented in this paper shows that there are cases where a power system may face collapse after only two or three contingencies. Therefore, the authors propose that post-fault dynamics should be included in the reliability assessment of cascading failures, to properly assess the systems' vulnerability against multiple contingencies.

The structure of the paper is the following: Part II describes the theoretical background, describing the relation between power system properties and transfer capacity limitations. Part III presents a description of a blackout as a process and based on this, Part IV proposes vulnerability indicators. Part V presents examples of occurred disturbances and applies the proposed indicators to the examples. Finally, part VI provides discussion and VII

E. Hillberg is with the Norwegian University of Science and Technology, Trondheim, Norway (e-mail: emil.hillberg@ntnu.no).

J. Lamponen and L. Haarla are with Aalto University School of Electrical Engineering, Espoo, Finland (e-mail: jarno.lamponen@aalto.fi and liisa.haarla@aalto.fi).

R. Hirvonen is with Fingrid Oyj, Helsinki, Finland (e-mail: ritva.hirvonen@fingrid.fi).

draws conclusions.

II. Power systems during disturbances

In this section, we describe the basic attributes and expressions related to power system operational security and transfer capacity.

A. Setting limits to transfer capacity

Power systems differ in their response to a disturbance. Similar events may have highly different consequences, depending on grid topology, power flows, generation and load related characteristics.

The first requirement for an $N-1$ operated system is that the oscillations that occur during the transition from the pre-fault to post-fault state are damped and that there is no transient (angle or voltage) instability. If the transition to the post-fault state is stable, it is meaningful to study the stability and (thermal) adequacy of the post-fault operating state. In this paper, depending on the limiting phenomenon for the maximum transfer capacity, systems are referred to as *thermally* or *stability limited*.

For thermally limited systems, the dynamics connected with the consequences of dimensioning faults are not critical. The maximum transfer capacity given to the market depends therefore on the adequacy of the post-fault state, which can be specified by steady state analysis of the post-fault state. In steady state analysis, transfer capacity limits are defined through power flow contingency calculations, neglecting the duration of short-circuits and the stability of the transition to the post-fault state.

If the stability during the transition from the pre-fault to post-fault state is the limiting phenomenon, the dynamics of the transition period should not be neglected when specifying the maximum transfer capacity. In this case, dynamic simulations are required.

B. Thermal limitations on power transfer

The effects of exceeding the thermal limitations depend on previous loading and thermal time constants of the components, the settings of overload protection, and the clearance to vegetation. The time constants of a thermal overloading of lines, and other components, usually provide sufficient time for manual actions to recover the system to a normal state.

C. Stability limitations on power transfer

In a system where stability sets the limits for transfer capacities, power flows are, logically, below the thermal limits. In such systems, even after several lines have tripped, the remaining lines can typically carry the power without becoming thermally overloaded. The stability limits are sensitive to the changes in grid topology and dynamic behavior of generation and load in the system. In practice, the stability limits are defined through off-line simulations using dynamic power system models. Because of the complexity to accurately determine stability limits, and because of the persistent load variations and other changes in the system, there is a need for safety margins to ensure reliable operation. Therefore, operational limits are established conservatively.

Stability phenomena may be fast and instability may occur only seconds after a triggering incident causing a system collapse. All stability phenomena, rotor angle, voltage and frequency stability, are involved in the dynamic behavior of the power system during and after a contingency.

Voltage instability may arise as a long-term phenomenon, which can develop during several minutes, depending on the time constants of load recovery, tap changer controls, and other devices. This implies a possibility to implement manual remedial actions to prevent the system from a long-term voltage collapse. However, since the time constants of such phenomena are highly related to the system operation it is difficult to distinguish in advance the exact available time for the implementation of manual actions.

D. Interpretations of N – 1 criterion

Even though the $N-1$ criterion is widely used, there are different interpretations of its usage. Usually, this criterion is interpreted as including the loss of any single element, such as a line, generator, transformer, or busbar. However, the criterion may also include common cause failures, such as the loss of multiple lines, generating units or HVDC links. Furthermore, the interpretation may depend on the probability of the contingency. Some transmission system operators may apply an $N-X$ criterion, with $X > 1$, in order to meet the acceptable security level.

III. Blackout process

A. Sequence of events of large disturbances

Large disturbances are often the result of successive or simultaneous failures occurring until the system becomes unstable, resulting in a blackout, [1, p. 1.99] and [15, p. 16]. In the beginning of the disturbance, contingencies move the system to an alert or emergency operating state[1]. Further contingencies increase overloading and finally excite instability, causing additional line and generator trips. Actions by equipment protection (overloading and distance relays) may further excite instability.

The time frame of the sequence of events varies significantly. Depending on whether the system is initially thermally or dynamically limited, the total time frame of the sequence will be measured in hours, minutes or even seconds.

If the system is initially thermally limited, the time frame is likely to be minutes or even hours. If remedial actions are insufficient, the system will at some stage become unstable. A system which is stability limited will experience instability immediately when the limits are breached.

The point at which instability occurs is a distinct transition to the next *phase* of the blackout process. Until this point, the deterioration process is mainly governed by the *thermal* overloading of components, and from this point to the final collapse, the process is dominated by *instability*. These two distinct phases are identified as typical parts of a blackout cascading process in [23], [24].

B. Thermally governed phase

Thermal overloading leading to consecutive line disconnections gradually reduces the system security. The process can be slow or fast, depending on the time

[1] In alert and emergency states, the system is not secure against further contingencies [25], [26].

difference between the failures. The time between consecutive line trips can be long enough for manual actions. The goal of the remedial actions is to reduce the power flow on the overloaded lines. If lines are heavily overloaded, relays may trip them almost immediately and the cascading may accelerate dramatically.

This kind of cascade can only occur in a system where the power flow does not exceed stability limits, and transitions to the next post-fault state are stable. Therefore, this phase of the disturbance can be analyzed through simulation of the post-fault state using steady-state power flow calculation tools.

It is worth noting that faults, which do not cause instability if occurring separately, may cause instability if occurring almost simultaneously. Similarly, if the fault duration is extended, the system may lose its stability.

C. Transition to the unstable phase

If the system faces one contingency after another, after a sufficient number of faults and component trips, the system becomes unstable and finally collapses. A possible sequence of events is, for example, that the power flow from tripped lines transfers to the remaining lines increasing the reactive power consumption, which reduces the voltage. Reactive power sources, such as synchronous generators, finally reach their limits and the voltage collapses. Low voltages reduce the electrical power transmitted in the grid. If the generators are unable to feed their mechanical power to the grid, they accelerate and finally lose their synchronism. Generators can also lose the synchronism transiently, when the grid is weakened and the system still faces a fault. The specific details of the instability vary from case to case, [1] and [15].

D. Unstable phase

The last phase of a blackout process is dominated by instability phenomenon, characterized by the rapid disconnections of transmission lines and generators. The time frame in this phase can be very short, therefore automatic control actions are needed to prevent uncoordinated system separation and a system collapse.

In this phase, the dominating phenomenon is instability and cascading trips are the consequence of unstable conditions. Therefore, when analyzing this phase, it is relevant to analyze instability rather than cascading trips because instability causes the cascading trips, not vice versa.

IV. $N-K$ VULNERABILITY INDICATIONS

An $N-k$ contingency analysis could be used to define the secure transfer capacity up to the $N-k$ contingency level, taking into account both stability and thermal limitations. Fig. 1 presents an example of transfer capacity limited by voltage stability (a), angle stability (b), and thermal characteristics (c). For each contingency level, the lowest limit (thermal, angle stability, or voltage stability) dictates the secure transfer capacity. In the figure, the order of the limiting constraint changes from thermal to angle stability limit, for the $N-1$ and $N-k$ contingency levels respectively. The voltage stability is not critical in this example in any contingency level.

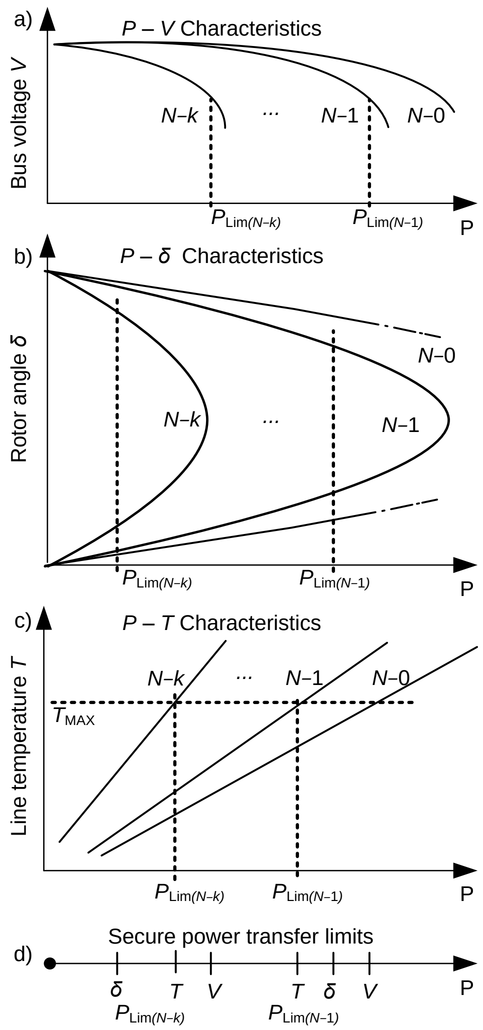

Fig. 1. Limitations of secure power transfer (P) by a) voltage stability (V), b) rotor angle stability (δ), and c) thermal characteristics (T). The lowest limit for the $N-1$ and $N-k$ contingency levels ($P_{\mathrm{Lim}(N-1)}$, $P_{\mathrm{Lim}(N-k)}$) defines the transfer capacity and the limiting phenomenon, described in d).

The stability limits could be defined through $N-k$ contingency analyses, and could be utilized to define the indicators for the $N-k$ security of the system.

A useful vulnerability indicator would be the margin between the (actual) power flow and the maximum power flow limited by the stability limit. This indicator, denoted I_{N-j}, is calculated for each contingency level j as:

$$I_{N-j} = P_{N-j}^{\mathrm{stab}} - P_0, \quad (1)$$

where P_{N-j}^{stab} is the stability limit of the $N-j$ contingency level and P_0 is the actual power flow. This power flow margin can thus be a measure of the $N-j$ stability margin of a thermally limited system. Fig. 2 presents an example of the utilization of this indicator.

Another way to analyze the vulnerability of a specific operating scenario is to determine different sets of successive contingencies that would directly cause instability or initiate a rapid thermal cascade that would quickly lead to instability. The systems vulnerability could thus be assessed using the indicator, k_{min}, defined as:

$$k_{\mathrm{min}} = \min\,(s_1, s_2, \ldots, s_n), \quad (2)$$

where s_i is a set of contingencies leading to an unstable state at the specific operating scenario. The indicator describes the minimal number of contingencies after which instability occurs.

When determining the value of $k_{\min}$, one approach is to study contingencies related to critical (congested) transmission corridors. If defining critical corridors is not self-evident, there are contingency reduction techniques, described in e.g. [22], that can be used to reduce the number of considered contingencies.

Both suggested indicators are useful for power systems operated according to the $N-1$ criterion, for which extreme contingencies, more severe than $N-1$, can be a threat to the integrity of the system.

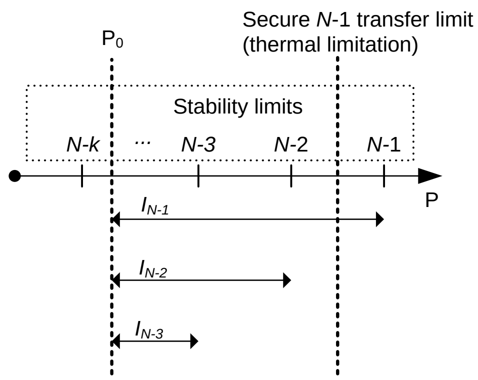

Fig. 2. An example of how the indicator I_{N-j} can be utilized to describe the vulnerability for various contingency levels in a thermally limited power system.

V. Examples of Occurred Disturbances

This section describes the sequence of events of three recent large European disturbances. The analysis of the disturbances relies on published reports of the events. The vulnerability indicators presented in section IV are for cases with sufficient information available.

A. The Italian 2003 blackout

The Italian blackout in 2003 started with the trip of one of the two 380 kV transmission lines between Italy and Switzerland, and ended in a total blackout of Italy. At the beginning of the disturbance, the Italian system was considered to be in a secure operating state even though Italy imported more than scheduled [12, p. 10, 42].

The event started with the trip of a transmission line, caused by an earth fault due to excessive sagging and inadequate vegetation management. An excessive phase angle of 42° across the breaker prevented reclosing of the line [12, p. 28], with the consequence of the thermal overloading of the parallel 380 kV line. After approximately 25 minutes, this thermally overloaded line tripped due to excessive sagging. After a few seconds, the system experienced rotor angle and voltage instability, simultaneously with several line trips due to heavy overloading. This process led to the rapid disconnection of the remaining interconnectors to Italy, [12, p. 4].

The consequences of the first and second line trips differ significantly. After the first trip, loading of other lines increased but since the system remained stable, power transfer before the fault was below stability limits[2]. It took 25 minutes from the first disconnection until the second line was overloaded to such a state that it faced a fault and tripped. After the second 380 kV line trip, the immediate result was the trip of two 220 kV lines and the start of a voltage collapse. The 'point-of-no-return' came with the trip of the second 380 kV line, resulting in instability and uncontrolled system separation. It took only ten seconds from the second line trip until Italy was separated from the Continental European grid.

Without a detailed grid model, the indicator defined in (1) cannot be calculated. According to the disturbance report [12, p. 29], the instability phase started only seconds after the trip of the second 380 kV line. Hence, the minimal number of contingencies leading to instability is assessed[3] to be $k_{\min} = 2$, assuming the pre-fault grid was $N-1$ secure.

With an accurate dynamic simulation model, both indicators could be assessed. Such assessment would provide valuable information for improving the operators' awareness of the vulnerability of the system and for implementing appropriate remedial actions in the decision process.

The sequence of events is described in Table I in the Appendix.

B. Blackout in Sweden and Denmark in 2003

The voltage collapse in the Nordic power system was the result of two successive incidents, together more severe than the dimensioning fault of the system[4]. The disturbance started with an internal failure in a power plant, resulting in the trip of almost 1.2 GW of the generation, [10, p. 12]. The fault was within the $N-1$ dimensioning criterion, and the system remained stable. Five minutes after the first fault, a disconnector failure caused a simultaneous fault of two busbars leading to the disconnection of two generators, two 400 kV transmission lines, and an HVDC link. The total generation loss was now 3 GW [10, p. 13]. These trips led to overload of the power transfer corridor in southern Sweden, followed by a voltage collapse and blackout in parts of Sweden and Denmark.

The total time frame from the initiating event to the blackout was around seven minutes, where the first five minutes was in between the two independent incidents. The affected corridor was limited by voltage stability, and in this disturbance the system was exposed to a fast voltage instability phenomenon and a slow voltage decay, [5, p. 9, 11]. The voltage instability led to system separation, voltage collapse, and a blackout within two minutes after the second incident. According to a system study, the system could have coped with either of the incidents separately even though the second incident was beyond the $N-1$ dimensioning fault [10, p. 37].

Loss of stability occurred as the result of two separate incidents. Defining the second incident as an $N-2$ contingency, the minimal number of contingencies leading to instability is assessed to be $k_{\min} \leq 3$. Without a grid model it is not possible to identify if any $N-2$ combinations would

[2] After the first line tripped the transition to the post-fault state was stable, even though the reconnection of the line was prevented since the voltage angle was above the stability limit.

[3] When calculating the indicator $k_{\min}$, faults in the grid with lower voltage levels can be neglected since it generally has significantly lower transfer capacity and cannot necessarily carry the power after the high voltage grid lines are tripped.

[4] The $N-1$ dimensioning generator trip of the Nordic power system is 1.2 GW. The system is required to return to a secure operation state within 15 minutes [27].

have caused a system collapse.

The sequence of events is described in Table II in the Appendix.

C. Disturbance in Europe in 2006

In 2006, a manual disconnection of two overhead transmission lines in Germany caused a disturbance in the Continental European power system. The disconnection led to the overloading of a parallel line, which eventually tripped and triggered several cascading trips separating the Continental European power system into three asynchronous islands, [13 p. 20]. After the system separation, the proper and swift action of several load shedding schemes, leading to the disconnection of approximately 20 GW load, successfully prevented a blackout of Western Europe, [13, p. 25].

The disturbance report, which describes the consequences reveals that the manual disconnection of two overhead transmission lines transferred the system to an alert, $N-1$ insecure operating state, [13, p. 6]. The following trip of an overloaded line initiated the process of tripping of a number of lines, leading to instability and sectioning of the Continental European power system.

The stability was lost just seconds after the disconnection of the third line ($N-3$). This case clearly shows the importance of proper identification of stability limitations in a thermally limited system. In this case, the manual disconnections transferred the system into a state where a single contingency could initiate a fast process leading to a large disturbance.

Three consecutive incidents led to the islanding of the system, and the minimal number of contingencies leading to instability is assessed to be $k_{min} \leq 3$. Without a grid model it is not possible to identify if any set of double contingencies would have caused islanding or even a collapse.

The sequence of events is described in Table III in the Appendix.

VI. Discussion

Large disturbances are often the result of successive or simultaneous failures that occur until the system reaches an unstable state, resulting in a blackout, [1], [15]. At the beginning of the event the first transition to the post-contingency state is stable. However, at a certain stage, occasionally after just two or three faults, dynamic instability occurs.

Typically, the analyses of cascading failures and blackouts connected to them, are conducted with steady state simulation tools, as described in [18], [19].The steady state simulations provide information on the process only up to the point where the dynamic phenomena start to dominate the system behavior. After this transition point, the steady state analyses do not provide sufficient information, hence relying solely on steady state simulations underestimates the vulnerability of the system. Therefore, in a vulnerability analysis it is important to analyze also the power system dynamic response after each contingency and to recognize the fault combinations that can transfer the system into an unstable state.

The basic assumption in many security studies, such as [28], [29], is that a credible threat of a thermally limited system relates to the cascading failures of thermally overloaded lines. This approach does not provide the whole picture. If the system faces one contingency after another, ignoring the dynamics in the analysis leads to incorrect results and does not reveal significant vulnerabilities of the system. The examples of actual disturbances show that the dynamic instability can start after the trip of as few as two or three lines or generators. Simulating the dynamics connected to credible $N-2$ contingencies would reveal the possible changes of the system response. Even though probability of independent $N-2$ faults may be low, the awareness of the change in the system response would enable the development of proper automatic and manual defense plans. The presented disturbances declare that systems, initially considered thermally limited, finally can collapse due to the loss of stability. This implies that there is a transition point where the system response to a fault changes. Fig. 3 illustrates this, where an initially thermally limited system becomes stability limited after the kth contingency. This means that the transition point from thermal to stability limitation is at the contingency level $N-k$. Even after $N-k$ faults, no problems arise as long as the actual power flow P_0 remains lower than the value defined by the stability limits. In Fig. 3, the loss of stability occurs after $N-(k+1)$ contingencies, implying that the system was in this case in an alert state after $N-k$ faults.

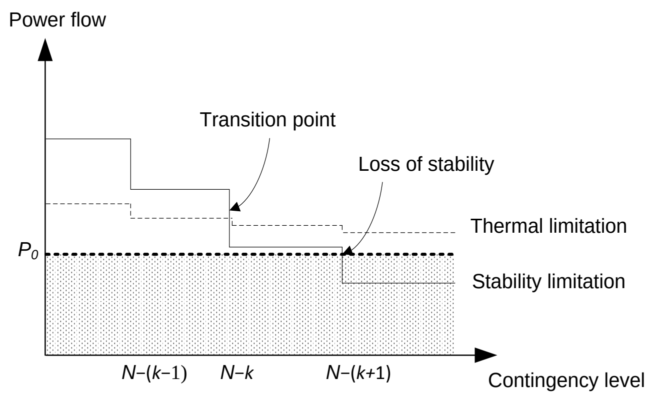

Fig. 3. Illustration of the change in the system response when facing consecutive failures. The transition point (after $N-k$ contingencies) describes where an initially thermally limited system becomes stability limited. The $N-(k+1)$ contingency moves the stability limit below the actual power flow, P_0, and the system becomes unstable.

In order to identify ‘credible threats’ to the system, as well as the vulnerability indicators, the system needs to be analyzed through both power flow of the post-contingency state and time domain dynamic simulations of the transition between the states. Revealing the vulnerabilities of a system requires $N-k$ dynamic contingency analysis since the system may respond totally differently to faults in a weakened state than in the normal state.

Another important aspect in the change of a system response is the available time for remedial actions. At the beginning of the process, when only the thermal limits of overhead lines are violated, there is usually several minutes available for reducing the power flows and preventing further disconnections. If the stability limits are exceeded after the first faults, there may be only a few seconds or less for actions to prevent system collapse.

System monitoring with Phasor Measurement Units (PMU), can be utilized to reveal the dynamic behavior of the power system [30, p. 144]. The PMU measurements, not only from disturbed conditions but also from the normal operation, can help to identify the dynamic interactions in the system.

VII. Conclusion

This paper demonstrates the importance of analyzing multiple contingencies in a vulnerability analysis. The paper proposes two indicators, which could be useful when assessing the vulnerabilities of a power system against multiple contingencies.

In a blackout process, there are two different phases according to the dominating phenomenon: a *thermally governed phase* and an *unstable phase*. If a power system initially is limited by thermal capacity of lines, a cascading process starts as thermally governed. After several faults the system may become unstable.

Awareness of a possible change in the power system response from thermal to instability phenomena after several faults is required for planning and performing the effective and properly timed actions. When the main issue after a fault is the heating of remaining lines, there is typically sufficient time for remedial actions to prevent a blackout. After the system response has changed from thermal to stability phenomena, the system is in a more insecure operating state before the change. Thus, it is important to identify stability limits also in a thermally limited system to develop proper operational actions for preventing blackouts.

A power system limited by stability faces cascading failures directly due to instability after multiple faults, hence the sequence of events before a blackout is fast. To prevent large disturbances in such a system, the system has to be operated with large enough security margins since exceeding stability limits instantly moves the system to an insecure operating state. After an $N-1$ contingency, manual actions are possible but when considering multiple contingencies, often only appropriate automatic remedial actions, if any, can rescue the system from collapse since the dynamic phenomena after the contingencies may be too fast for any manual intervention.

The paper proposes two indicators that can help for identifying the vulnerabilities in a specific operating scenario. One indicator is the margin between the (actual) power flow and the maximum power flow restricted by the stability limit. Another indicator is the minimum number of successive contingencies after which manual actions are no longer effective. Both indicators could give a quantitative measure for threats to the system.

This paper does not consider all possible aspects of large disturbances, the authors rather encourage system operators to increase their awareness about the phenomena connected to multiple contingencies. It is risky to assume that the system response remains the same even after several contingencies. Utilizing this knowledge, appropriate defense plans can be developed to limit the impact of multiple contingencies and prevent large disturbances.

VIII. Appendix

Table I
Sequence of events leading to blackout of Italy, 28 September 2003, [12]

Time	Event
03:01:42	The event started with the trip of a transmission line, caused by an earth fault due to excessive sagging and inadequate vegetation management. An excessive phase angle difference across the breaker prohibited reclosing of the line. This fault moved the system to an emergency operating state, with thermal overloading of the 400 kV line and lower voltage lines in the same PTC.
03:25:21	After around 25 minutes, the second line tripped. The cause was thermal overload leading to excessive sagging and a flashover.
03:25:25 – 03:25:34	The system experienced rotor angle and voltage instability, simultaneously with several line trips due to heavy overloading, leading to the disconnection of the remaining transmission lines connected to Italy leaving the Italian system isolated from the rest of the continental European power system.
03:28:00	The high initial imbalance between load and production in Italy, together with instability phenomena, power swings, tripping of generation, and an insufficient load shedding, ultimately resulted in a full blackout of the Italian power system.

Table II
Sequence of events leading to blackout in Sweden and Denmark, 23 September 2003, [5], [10]

Time	Event
12:30	The sequence started with an internal fault in a power plant, disconnecting almost 1.2 GW of generation at the border of a PTC in Southern Sweden. The outage was within the N − 1 dimensioning criterion, and the system remained stable since sufficient spinning reserves were available.
12:35:00	Five minutes after the first fault, a second, independent, fault occurred before the manual secondary reserves were activated. , The fault resulted in the disconnection of almost 1.8 GW generation near the same PTC and two main transmission lines in the PTC. A HVDC connection connected close to the PTC was also lost, which further aggravated the situation.
12:35:00 – 12:35:10	This resulted in a significant frequency decrease and massive oscillations of voltage and reactive power flow, leading to additional transmission line trips bringing the system to the verge of short-term voltage instability within ten seconds.
12:35:10 – 12:35:20	The decreased voltage level led to disconnection of load and an overall load decrease, which had a positive effect and stabilized the frequency at an appropriate level.
12:35:20 – 12:36:40	Insufficient reactive power support south of the PTC led to a slow voltage decrease. After approximately 100 seconds, the last 400 kV transmission lines were disconnected by distance protection, due to the low voltage and high power transfer, islanding the most southern area of the Nordic power system.
12:36:40	The large production deficit in the islanded system, led to a total blackout of southern Sweden and eastern Denmark.

Table III
Sequence of events leading to the disturbance in Europe, 4 November 2006, [13]

Time	Event
21:38 – 21.39	The event started with the manual disconnection of two 380 kV transmission lines in Germany. The disconnection increased the loading of a third 380 kV line close to its protective overload limit.
22:10:11	Manual actions to relieve the highly loaded line were implemented after around 30 minutes, but with adverse effect.
22:10:13 – 22:10:28	The highly loaded line tripped on overloading, triggering fast cascading failure leading to system separation in only 15 seconds.
22:10:28 – 22:49	The Continental European power system operated as three unsynchronized islands for almost 40 minutes before successfully resynchronized.

IX. Acknowledgment

The authors would like to thank Professor K. Uhlen and Adjunct professor G. Kjølle at the Norwegian University of Science and Technology for constructive discussions and comments. E. Hillberg would also like to thank W. Sattinger from Swissgrid for valuable insight in the operation of the Swiss power system.

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XI. Biographies

Emil Hillberg (formerly Johansson) received his M.Sc. degree in electrical engineering at KTH in 2002. Since then he has worked at ABB with HVDC and harmonic filtering and from 2007 at SINTEF Energy Research as a research scientist in the field of dynamics and control of power systems. Mr. Hillberg is currently pursuing a PhD at the Norwegian University of Science and Technology.

Jarno Lamponen received the M.Sc. degree in electrical engineering from Helsinki University of Technology in 2008. He is currently pursuing a PhD degree in the field of power system security at the Aalto University.

Liisa Haarla (formerly Pottonen, M'05) received M.Sc.(Eng) and D.Sc.(Tech) degrees from Helsinki University of Technology (TKK) in 1982 and 2005, respectively. She has worked on power system engineering issues in several utilities. As of 2006, she has been a Professor of Power Transmission Systems at the Aalto University School of Electrical Engineering (previously TKK). Her research interests include power system reliability and oscillation damping.

Ritva Hirvonen (M'95) received M.Sc. (Eng), Lic.Sc. (Tech) and D.Sc. (Tech) degrees from Helsinki University of Technology (TKK) in 1979, 1983 and 1992, respectively. She has worked on power system engineering and energy market issues in private and public utilities. She is currently Development Manager at Finnish TSO (Fingrid Oyj). Her research interests include power system security and electricity markets.