Reducing the Risk of Cascading Failures via Transmission Switching

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Abstract—After decades of research, cascading blackouts remain one of the unresolved challenges in the bulk power systems. A new perspective for measuring the susceptibility of the system to cascading failures is clearly needed. The newly developed concept of system stress metrics may be able to provide new insight into this problem. The method employs power engineering and graph theory to analyze the network structure and electrical properties of the system, with metrics that measure stress as the susceptibility to cascading failures. In this paper, we investigate the effectiveness of transmission switching in reducing the risk of cascading failures, measured in system stress metrics. A case study, analyzing different metrics on IEEE 118-bus test system, is presented. The results show that transmission switching can be used as a preventive as well as corrective mechanism to reduce the system’s susceptibility to cascading failures. Contrary to the conventional operation wisdom that switching lines out of service jeopardizes reliability, our results suggest the opposite; system operators can use transmission switching, when the system is under stress, as a tool to reduce the risk of cascading failures.

Index Terms—Cascading failures, corrective switching, line outage distribution factors, network theory, power system security, preventive operation, stress metrics, transmission switching.

I. INTRODUCTION

There is an extensive body of academic and industry literature on analyzing cascading blackouts, seeking ways to eliminate them or at least reduce their frequency and size, and improve the speed of recovery [1]. Most of the blackouts have been subject to investigations and postmortem analyses [1]. The largest blackout in the North American grid, the Northeast blackout of 2003, was studied for over a year. The results of this extensive analysis was published in an illuminating three-volume report [2]. This report also provides useful insight into a number of earlier cascading failure events [1]. The North American Electric Reliability Corporation (NERC) was established by the US-Canadian power industry after the 1965 blackout to improve reliability, notably by producing criteria and collecting data. Preventing cascading blackouts has always been central to the objectives of these criteria [3]. In 1974, state estimation was introduced in power systems, so that system operators have more accurate inputs to real-time procedures for increasing reliability. In the context of cascading failures, the purpose of state estimation was more to make data availability reliable rather than improving the data accuracy [4]. Prior to that, a state model was developed in which necessary considerations for the design of a total control system for reliability improvement of the the generation and transmission systems were incorporated. In this model, the control system was made of automatic functions, human participation, and an information system [5]. Much labor has been invested in a host of efforts to solve the blackout problem. Recently, network theory has been applied to blackouts and other problems in power systems, but blackouts continue; the problem has not been solved [1].

A. Cascading Failures

Cascading failures in large systems can be due to at least one of the following reasons: [1]

1) Failure of protection system and control devices;
2) Failure of processes and procedures;
3) Overly stressed loading conditions;

Among these failure causes, the possibilities of forestalling the first two (i.e., “control and protective devices” and “policies and procedures”) or even testing for these failures are astronomical and individual events are improbable. We simply lack models that would reflect the effects of these two on the system. In other words, we cannot model protection and control system failures, and failures in processes and procedures into our bulk electric system model. However, history shows that cascading also depends critically on how the system is loaded, which can be described by the system stress metrics [1], [6]. This trend can be clearly observed in 2011 Western Interconnection post blackout study, shown in Fig. 1. The figure shows the system stress for four different loading conditions, with three stress metrics. Arizona and Southern California are most stressed during the peak in the summer, as the system is heavily loaded. The system is usually not nearly as stressed during spring and winter peaks. The Southwest blackout of 2011 occurred on September 8 at around 3:38 PM PDT. This time is not usually regarded as a peak hour; however, as shown in Fig. 1, stress metrics reveal that the system was indeed atypically stressed prior to the blackout. The blackout was initiated by a technician mistake, who switched a 500 kV line between APS’s Hassayampa and North Gila substations in Arizona [7]. This blackouts could have been avoided if stress had been identified and reduced in the vulnerable and critical parts of the system [8].

A set of new tools including metrics of stress or susceptibility to cascading failures has been developed and discussed in [1], [6]. They have been built on two very different theoretic bases to develop methods that planners and operators can use to spot stressed operating states and regions, and to plan and operate the system securely. The tool has been successfully
implemented on Peru System, Eastern Interconnection, and Western Interconnection to explore the susceptibility of the system to cascading failures [9]. In every instance of cascading blackouts, the stress metrics were able to show unusual system stress before the event [9].

B. Transmission Switching

Transmission switching (TS) refers to changing the topology of the transmission network by opening or closing transmission lines. The concept, which was first introduced in 1968 by the German mathematician Dietrich Braess, is counter-intuitive but a well-known fact that removing edges from a network with selfish routing can decrease the latency incurred by traffic in an equilibrium flow. Since then, a large body of academic literature has been dedicated to study this paradox in infrastructure networks [10]. This concept was first proposed in power system in the 1980s; in the following years, a number of studies adopted transmission switching as a corrective mechanism [11]. Later, the concept of optimal transmission switching was proposed to minimize the operation cost [12].

Recently, this technique has been integrated within different power system operation models, such as security-constrained economic dispatch, security-constrained unit commitment, as well as real-time contingency analysis. TS has been proven to be able to significantly reduce the operational costs and improve the system reliability [12]–[15].

Due to computational complexity, as well as other concerns such as dynamic stability, industry adoption of TS has been very limited. Some system operators use TS as a corrective mechanism for improving voltage profiles and mitigating line overloads [16], [17]. TS is also being employed during planned outages, to make the transition smooth, and also as a post-contingency corrective action [18]. California ISO (CAISO) is reported to perform TS on a seasonal basis and to relieve congestion in the system [14], [19]. PJM has posted a list of potential switching solutions that may reduce or eliminate violations for normal and post-contingency situations [20], [21]. However, these switching actions are not guaranteed to always provide benefit because they are identified offline.

The use of transmission switching has been extensively studied for different purposes in power systems, but no study yet explicitly looked into the impact of transmission switching on reducing the susceptibility of the system to cascading failures.

This paper, first, aims to quantify the system susceptibility to cascading failures in terms of the system’s stress. The paper, then, studies the impacts of transmission switching on reducing the system stress, and thereby lowering the system’s susceptibility to cascading failures. The contributions of this paper can be summarized as follows:

1) Further development of statistical metrics to measure system stress by introducing two new metrics;
2) Examination of the impacts of preventive transmission switching on reducing stress during unusually stressed or poorly forecasted loading conditions;
3) Investigation of the benefits of corrective transmission switching in reducing the system stress, after N-1 contingencies.

The rest of the paper is organized as follows. In Section II, we introduce stress metrics to measure the susceptibility of the system to cascading failures. Section III presents preventive and corrective transmission switching. Section IV demonstrates the effectiveness of the method via simulation studies on IEEE 118-bus test system. Finally, Section V concludes this paper.

II. MEASURE OF STRESS

To measure the stress on the system, elements from network theory and traditional power system analysis have been combined. Consequently, indices are developed, which can describe how a failure would propagate through a system [1].

To calculate the stress metrics, flow violations on all the lines after every potential contingency are needed. Such information is readily available from the contingency analysis tool,
which is a part of energy management systems [13], [22]. Even without access to such information, post-contingency flows can be approximately calculated via line outage distribution factor (LODF), which colloquially are also referred to as DAFAX [1], [6]. These sensitivities can be calculated using conventional power flow software with DC approximation, or using the current-based generalized injection shift factors [23].

An LODF$_{ij}$ of 0.5 indicates that 50% of the pre-outage flow on line $j$ would be added to the flow on line $i$, should line $j$ go out of service. Post-outage flow on line $i$ after the outage of line $j$ is calculated in (1), where $f^0$ indicates the pre-outage flow.

$$f_i \approx f^0_i + \text{LODF}_{ij} \times f^0_j$$

This relationship is approximate, because the power system is only approximately linear. However, the accuracy of (1) is acceptable and power system planners and operators extensively use LODFs in contingency analysis [1]. The experience shows that for real power analysis, which is believed to be the key issue, the nonlinearity is rarely troublesome [1], [24]. It can be argued that nonlinear and dynamic issues, as well as voltage problems, which are not reflected in the linearized LODF, are part of cascading failures. We, of course, agree that such effects occur, for example in the two famous blackouts we described above. However, cascading failures always begin with the linearizable real-power stresses that our model captures.

The LODF matrix is not symmetrical. However, for a large network, most of its values are rather small. Small values beyond a threshold can be ignored to generate a sparse matrix. The sparsity can, then, be exploited for enhancement of the computation. In a passive linear network, the value of each LODF is between -1.0 and +1.0. Large positive or negative values of LODF make cascading failure more likely. Tighter coupling is more likely to overload line $i$ and force it out of the service if line $j$ experiences and outage, all else being equal. With an LODF of zero, the outage of line $j$ by itself will not cause an overload or outage of line $i$ [1], [6].

Network theory suggests analyzing a network with metrics. The metrics we describe below are variants of metrics used commonly in network analysis. The stress metrics proposed in [1], [6] reflect the pre-contingency and post-contingency flows. This pre-contingency loading is determined by the demand and the generation dispatch. These values are hypothetical in planning models; however, in operation, the pre-contingency loading is obtained from real-time metering, which is processed by the state estimator [1], [6].

The definition of some of the metrics developed previously, and those proposed in this paper to measure the stress or susceptibility of the bulk electric power systems to cascading blackouts are given below.

A. Vulnerability

Vulnerability deals with the post-outage flow on a monitored line or transformer after the outage of another line or transformer in the system. This is a reasonable measure of stress, because cascading failures always begin with an outage, overloading one or more other line or transformer. Consequently, the protection relays will isolate the newly overloaded lines, which will further weaken the system. Two metrics were proposed in [1], [6] to quantify the vulnerability: the rank and the degree of vulnerability. In addition, we introduce a new metric for indexing the entire system’s vulnerability.

1) **Rank of Vulnerability ($V_{rank}^i$)**: The rank of vulnerability is the maximum absolute value of flow on a line or transformer in per unit of its rating after the outage of another line or transformer. The rank of vulnerability matrix is a $1 \times m_1$ matrix, where $m_1$ is the number of monitored lines and transformers. The $i^{th}$ rank of vulnerability is the maximum post-outage flow on line or transformer $i$ after the outage of all $m_2$ lines and transformers, taken out one at a time, where $m_2$ is the number of lines and transformers, whose outage is monitored. Note that, the $i^{th}$ rank of vulnerability may be greater than, less than, or equal to the pre-contingency flow on the line or transformer [1], [6]. This metric is expressed as a percentage of the post-contingency flow compared to the line/transformer rating.

$$V_{rank}^i = \max \left( \frac{|f_i|}{f_{i\text{ rated}}} \right)$$

2) **Degree of Vulnerability ($V_{degree}^i$)**: The degree of vulnerability is the number of single outages for which a monitored line or transformer will be loaded over some threshold value. The line’s rating is used to compute the degree of vulnerability in this paper. The degree of vulnerability matrix is a $1 \times m_1$ matrix, where $m_1$ is the number of monitored lines and transformers. The $i^{th}$ element of this matrix is the number of lines and transformers, among all the $m_2$ lines and transformers, whose outage leads to a power flow beyond the specified threshold for the $i^{th}$ line or transformer. This metric is calculated and shown in (3).

$$V_{degree}^i = \text{count}_i \left( \frac{|f_i|}{f_{i\text{ rated}}} > \text{Threshold} \right)$$

3) **System Vulnerability Degree ($V_{System}$):** The system vulnerability degree, proposed in this paper, is the number of non-radial monitored branches that will have a vulnerability rank beyond some threshold value. The lines’ ratings were used, here, to compute the number of vulnerability in this study. The system vulnerability degree is a scalar, which is measured as an index for the entire system, rather than a specific line or transformer.

B. Criticality

Criticality measures how the outage of a line or transformer affects other lines and transformers in the system. Rank and degree of criticality are used to define criticality [1], [6], [8]. In addition, this paper introduces a new metric for measuring the entire system’s criticality level.

1) **Rank of Criticality ($C_{i\text{ rank}}^r$)**: The rank of criticality of a line or transformer $i$ is the maximum absolute value of flow through all other lines and transformers, per unit of their capacity, after the outage of line or transformer $i$. The rank of criticality matrix is a $1 \times m_2$ matrix, where $m_2$ is the number
of lines and transformers whose outage is monitored. The $i^{th}$ rank of criticality is the maximum absolute value of all the post-outage flows divided by the ratings of the $m_1$ monitored lines and transformers, after the outage of line or transformer $i$ [8]. This metric is expressed as a percentage of the rating of the monitored lines or transformers, as shown in (4).

$$C_{i}^{rank} = \max_k \left( \left| \frac{f_k}{f_{rated}} \right| \right)$$ (4)

2) Degree of Criticality ($C_{i}^{degree}$): The degree of criticality of a line or transformer $i$ is the number of monitored lines and transformers that will be loaded above some threshold after the outage of line or transformer $i$. The nominal rating of the lines was used, here, for calculating the degree of criticality, similar to the degree of vulnerability. However, any desirable threshold can be selected by the operator, and the method does not limit this choice. The degree of criticality matrix is also a $1 \times m_2$ matrix, where $m_2$ is the number of lines and transformers whose outage is monitored. The $i^{th}$ degree of criticality is the number of lines and transformers among all the $m_1$ monitored lines and transformers whose flows will exceed the threshold after the outage of the $i^{th}$ line or transformer. This metric can be calculated as shown in (5).

$$C_{i}^{degree} = \text{count}_{i} \left( \left| \frac{f_k}{f_{rated}} > \text{Threshold}_k \right| \right)$$ (5)

3) System Criticality Degree ($C_{\text{System}}$): The system criticality degree is the number of non-radial contingencies that will result in a criticality rank beyond some threshold value. Nominal line ratings were used to compute the number of criticality in this study. Similar to the system vulnerability degree, system criticality degree is also a scalar, which is measured for the entire system.

III. TRANSMISSION SWITCHING

The electric transmission network is built redundant, in order to ensure mandatory reliability standards, which require protection against worst case scenarios. Due to the existence of loop flows in this redundant meshed network, transmission switching may lead to improved economic efficiency and reliability [14]. This phenomenon is widely acknowledged; however, finding appropriate switching candidates within the available computational time for power system operation remains to be a challenge.

Although transmission switching has many applications, it can be solely performed to enhance the system reliability [18], [21], [22], [25]. Reliability-motivated switching is perhaps the first application of transmission switching that is used by the industry [20]. References [18], [21], [22] employ transmission switching to reduce the post-contingency network violations. The method proposed in this paper also aims to enhance reliability, but rather than post-contingency violation reduction, we focus on reducing the system stress, which is measured via the metrics, introduced in Section II.

As mentioned before, transmission switching is considered to be a computationally challenging problem. A recent method, which achieved tractability for reliability-motivated switching, handled this challenge by only allowing a very limited set of switches. However, rather than searching within the vicinity of contingency or violation, we employ the LODF matrix to choose the most effective switching candidates. The potential candidates can be selected by looking at the column of the overloaded line corresponding to a contingency. A high negative LODF value is one of the indications of the potential line for switching. Thus, LODF matrix will provide us with a smart and fast method to select the switching candidates.

Switching is generally classified into two categories, depending on its timeline: preventive and corrective transmission switching. We consider both of these categories in the next two subsections, in the context of system stress reduction.

A. Preventive Transmission Switching

A preventive action in power system operation is taken to avoid the adverse consequences of a potential disturbance. The disturbance may never happen, but the preventive action will protect the system against it, should it actually occur. In this paper, we use preventive transmission switching to reduce the system’s susceptibility to cascading failures. History shows that cascading failures depend critically on how the system is loaded, which can be described by the system stress metrics. Post-blackout investigations show that in most cases the system was atypically stressed before the blackout [1]. Had the stress of the system been taken care of, the blackout could have been prevented. This can be seen in [8], where the stress on San Diego area was analyzed over different seasons of the year and found that on September 8, 2011, and before the blackout that happened later on the same day, the system was atypically stressed. The blackout could have been avoided through appropriate preventive actions that reduce the system stress.

In this paper, we propose that preventive transmission switching should be looked at, whenever the system is under atypical stress, beyond a predefined level, in order to reduce the stress on the system. We hypothesize that transmission switching may be able to offer a cheap and fast solution, relieve the system stress, and avoid potential cascading failures. The line can be switched back, once the system stress has been reduced due to change in the loading, if the line provides economic benefits. There are other alternatives that can be implemented as preventive actions, such as generation redispatch. However, transmission switching can be implemented much faster and is often the cheapest option, as it only involves the operation of a circuit breaker. Moreover, it is often the case that during the stressed operating conditions, generation redispatch is depleted and not available anymore to the operator. Fig. 2 shows the proposed algorithm for transmission switching in response to atypical stress on the system. An example of an atypically stressed system was shown in Fig. 1, which led to the Southwest blackout of 2011.
The criticality and vulnerability stress metrics for the IEEE 118 bus test case at 97% of peak loading.

| No. | Line or Transformer | Criticality Rank (%) | Degree | Vulnerability Rank (%) | Degree |
|-----|---------------------|----------------------|--------|------------------------|--------|
| 1   | L_26-30             | 222.94               | 5      | 34.2                   | 0      |
| 2   | L_8-9               | 155.73               | 2      | 32.47                  | 0      |
| 3   | L_25-27             | 128.69               | 1      | 103.38                 | 2      |
| 4   | T_30-17             | 127.94               | 1      | 88.13                  | 0      |
| 5   | T_8-5               | 116.33               | 1      | 60.14                  | 0      |
| 6   | L_65-68             | 107.04               | 1      | 18.56                  | 0      |
| 7   | L_5-11              | 102.22               | 1      | 67.68                  | 0      |
| 8   | L_23-25             | 100.46               | 1      | 114.5                  | 1      |
| 9   | L_15-17             | 80.9                 | 0      | 116.33                 | 1      |
| 10  | L_32-113            | 77.38                | 0      | 222.94                 | 4      |
| 11  | L_23-24             | 77.37                | 0      | 155.78                 | 4      |
| 12  | L_4-5               | 67.68                | 0      | 102.22                 | 1      |

![Flowchart](image)

**B. Corrective Transmission Switching (CTS)**

As transmission switching can be implemented instantaneously, unlike generation redispatch, which is relatively slow, more studies have focused on corrective transmission switching than preventive transmission switching. Corrective transmission switching solutions are only identified beforehand, within the contingency analysis tool, and are ready for implementation [18], [22]. Only after the contingency occurs, does the operator need to implement the solution.

Our interest in this paper is to study how corrective transmission switching can contribute to reducing a post-contingency stress rather than the post-contingency violations. The two are related, but are not the same. This paper examines two hypotheses regarding corrective transmission switching. First, we analyze the post contingency system stress that is imposed on the system by the possibility of an N-1-1 event, for the system that is already in the N-1 state. The second point of interest for us is to monitor the ongoing level of stress in the system, which is measured in terms of the lines that have already exceeded their contingency limits. These overflows should be addressed within a short period of time, defined by the emergency limit’s maximum duration; otherwise, the overloaded lines may trip and initiate a cascading failure. Thus, transmission switching can either be considered corrective, with respect to the current post N-1 state, or preventive, with respect to the possibility of an N-1-1 event.

**IV. Case Studies**

The case studies are conducted on IEEE 118-bus test system. To generate a variety of stress levels, we use different loading conditions at 97%, 105%, 106%, and 110% of the system’s peak load. The nodal loads are uniformly adjusted for all the cases, except for the 106% loaded case, where the demand is increased only on select buses (16% in West End (40) and 105% in S. Tiffin (41)). We, then, run an AC optimal power flow for each loading, to obtain AC feasible base case solutions for the analysis. These solutions are fed to PowerWorld for to assist with calculation of stress metrics and examination of transmission switching impacts.

We assume that all lines have their contingency limits at 120% of the normal limits, which can be used for a limited duration of 4 hours. We further assume the emergency limits to be at 135% of the normal line limits, which can be used up to 15 minutes [26]. We acknowledge that the contingency and emergency limits are not necessarily always scaled uniformly to the normal limits; however, we make this assumption to simplify the analysis presented in this paper. We further acknowledge that such limits may change depending on the weather or loading conditions; again, we have neglected such details to simplify the analysis.

Tables I-IV present the stress analysis with different loading conditions as described earlier. The purpose of these stress tables is to demonstrate how loading with different patterns can affect the system stress metrics. Generally, the stress increases with the loading; however, the 106% loaded case, with non-uniform increase in the nodal loads, is atypically stressed, even beyond the 110% loaded case. This demonstrates that the distribution of the load has a significant impact on the system stress. We pick this atypically stressed case to demonstrate the benefits of preventive transmission switching.

**A. Preventive Transmission Switching**

Figure 3 shows the various stress metrics, comparing the stress on IEEE 118-bus case system, in terms of maximum criticality rank, maximum degree, and system degree under different loading conditions. As can be seen, the stress for the case with 106% loading is atypically high. Table V shows the stress on the same case after a preventive switching action is implemented, where 17 Sorenson - 113 Deer Crk line is opened, but the generation dispatch is not changed. A full stress analysis is performed for pre- and post- transmission switching and the stress comparison for this case is shown in Fig. 4. The plot, comparing the number of lines, loaded above both emergency and contingency limits, under different loading patterns including after preventive transmission switching.
Fig. 3. Comparison of the stress on IEEE 118-bus test system in terms of criticality rank, degree, and system degree under different loading conditions.

### TABLE II

| No. | Line or Transformer | Criticality Rank (%) | Criticality Degree | Vulnerability Rank (%) | Vulnerability Degree |
|-----|---------------------|----------------------|--------------------|------------------------|----------------------|
| 1   | L_26-30             | 239.06               | 4                  | 34.2                   | 0                    |
| 2   | L_8-9               | 206.49               | 5                  | 32.46                  | 0                    |
| 3   | L_30-17             | 139.72               | 2                  | 91.57                  | 0                    |
| 4   | L_38-65             | 134.44               | 4                  | 44.16                  | 0                    |
| 5   | L_5-11              | 107.68               | 1                  | 52.17                  | 0                    |
| 6   | L_25-27             | 100.34               | 1                  | 107.52                 | 2                    |
| 7   | L_32-113            | 81.51                | 0                  | 231.31                 | 4                    |
| 8   | L_23-24             | 77.87                | 0                  | 150.16                 | 4                    |
| 9   | L_4-5               | 73.32                | 0                  | 107.52                 | 2                    |

### TABLE III

| No. | Line or Transformer | Criticality Rank (%) | Criticality Degree | Vulnerability Rank (%) | Vulnerability Degree |
|-----|---------------------|----------------------|--------------------|------------------------|----------------------|
| 1   | L_26-30             | 239.06               | 4                  | 34.2                   | 0                    |
| 2   | L_8-9               | 206.49               | 5                  | 32.46                  | 0                    |
| 3   | L_30-17             | 139.72               | 2                  | 91.57                  | 0                    |
| 4   | L_38-65             | 134.44               | 4                  | 44.16                  | 0                    |
| 5   | L_5-11              | 107.68               | 1                  | 52.17                  | 0                    |
| 6   | L_25-27             | 100.34               | 1                  | 107.52                 | 2                    |
| 7   | L_32-113            | 81.51                | 0                  | 231.31                 | 4                    |
| 8   | L_23-24             | 77.87                | 0                  | 150.16                 | 4                    |
| 9   | L_4-5               | 73.32                | 0                  | 107.52                 | 2                    |

### TABLE IV

| No. | Line or Transformer | Criticality Rank (%) | Criticality Degree | Vulnerability Rank (%) | Vulnerability Degree |
|-----|---------------------|----------------------|--------------------|------------------------|----------------------|
| 1   | L_26-30             | 239.06               | 4                  | 34.2                   | 0                    |
| 2   | L_8-9               | 206.49               | 5                  | 32.46                  | 0                    |
| 3   | L_30-17             | 139.72               | 2                  | 91.57                  | 0                    |
| 4   | L_38-65             | 134.44               | 4                  | 44.16                  | 0                    |
| 5   | L_5-11              | 107.68               | 1                  | 52.17                  | 0                    |
| 6   | L_25-27             | 100.34               | 1                  | 107.52                 | 2                    |
| 7   | L_32-113            | 81.51                | 0                  | 231.31                 | 4                    |
| 8   | L_23-24             | 77.87                | 0                  | 150.16                 | 4                    |
| 9   | L_4-5               | 73.32                | 0                  | 107.52                 | 2                    |

### TABLE V

| No. | Line or Transformer | Criticality Rank (%) | Criticality Degree | Vulnerability Rank (%) | Vulnerability Degree |
|-----|---------------------|----------------------|--------------------|------------------------|----------------------|
| 1   | L_8-9               | 206.49               | 5                  | 32.46                  | 0                    |
| 2   | L_25-27             | 139.72               | 2                  | 91.57                  | 0                    |
| 3   | L_38-65             | 134.44               | 4                  | 44.16                  | 0                    |
| 4   | L_5-11              | 107.68               | 1                  | 52.17                  | 0                    |
| 5   | L_25-27             | 100.34               | 1                  | 107.52                 | 2                    |
| 6   | L_32-113            | 81.51                | 0                  | 231.31                 | 4                    |
| 7   | L_23-24             | 77.87                | 0                  | 150.16                 | 4                    |
| 8   | L_4-5               | 73.32                | 0                  | 107.52                 | 2                    |

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**HE CRITICALITY AND VULNERABILITY STRESS METRICS FOR THE IEEE 118 BUS TEST CASE AT 105% OF PEAK LOADING.**

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**HE CRITICALITY AND VULNERABILITY STRESS METRICS FOR THE IEEE 118 BUS TEST CASE AT 110% OF PEAK LOADING.**

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**HE CRITICALITY AND VULNERABILITY STRESS METRICS FOR THE IEEE 118 BUS TEST CASE AFTER THE IMPLEMENTATION OF A SINGLE PREVENTIVE SWITCHING ACTION (17 SORENSEN - 113 DEER CRK).**
is shown in Fig. [5] The results of different stress metrics parameters is tabulated in Table [VI]. The results clearly show that a single transmission switching action can substantially reduce the system stress, and avoid a potential cascading failure event.

![Graph showing stress measurements](image)

**Fig. 4.** The stress comparison of pre and post transmission switching for the 106% loaded IEEE 118 bus test case. The rank and degree in this chart represent the single highest value for the system.

![Graph showing number of lines](image)

**Fig. 5.** The plot compares the number of lines, violating both emergency and contingency limits under different loading conditions, including the post preventive transmission switching.

### B. Corrective Transmission Switching

One of the highly critical non-radial contingencies, identified by PowerWorld Simulator, is 8 Olive - 5 Olive transformer. For this contingency, the stress on the system is such that at least one of the in-service lines exceeds the contingency limit, and therefore, the operator has about 15 minutes to address this issue or another line will be tripped. The algorithm developed in this paper suggests switching of 15 FtWayne - 17 Sorenson line, as a corrective action, to reduce the system stress to an acceptable level.

![Graph comparing stress](image)

**Fig. 6** compares the stress on system in terms of criticality rank and degree under different loading conditions for the base case, contingency (8 Olive - 5 Olive transformer), and corrective transmission switching of 15 FtWayne - 17 Sorenson line for the IEEE 118-bus test case. The results confirm the effectiveness of corrective transmission switching in reducing the post-contingency system stress, close to the normal operation levels.

### V. Conclusion

System stress metrics are recently developed to provide insight into the susceptibility of the system to cascading failures. The metrics include measures of the criticality of contingencies and vulnerability of the transmission elements to overloads after contingencies. Building upon those metrics, this paper introduced two new metrics to measure the system’s criticality and vulnerability. All of these metrics can be quickly calculated via the outputs of the contingency analysis tool, or through LODFs. Furthermore, the paper investigated the possibility of employing transmission switching, both as a preventive and corrective measure, to reduce the system stress. In order to achieve computational tractability for the transmission switching algorithm, LODF sensitivities were used to generate a rather small subset of quality switching candidates. Those candidates were then, tested for effectiveness, until an effective solution was found or the list was depleted. The simulation studies on IEEE 118-bus system confirmed the effectiveness of the method. A single transmission switching action was able to substantially reduce the system stress to the normal levels. This implies that system operators should look at transmission switching as an effective tool to prevent cascading failures, when the system is atypically stressed. Other alternative actions, such as generation redispatch, are substantially more expensive and may also not be available when the system is highly stressed.
Fig. 6. Comparison of system stress in terms of criticality rank and degree under different loading conditions for the base case, contingency case (outage of 8 Olive - 5 Olive Transformer), and post corrective transmission switching of 15 Ft. Wayne - 17 Sorenson.

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