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# Methodology for Assessment of the Impact of Smart Transformers on Power System Reliability

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***Abstract*—The smart transformer (ST) has been proposed as an alternative to the traditional low frequency transformer as a means to provide extra control functionality in the smart power system. The ST has merits in terms of reactive power decoupling and voltage decoupling at the primary and secondary side. This provides flexibility for reactive power compensation in the transmission system and demand reduction in the distribution system. Using its ability to control demand through voltage regulation, the ST provides the possibility to reduce demand while keeping the entire load online, which can provide an alternative to load curtailment. Thus, it may provide a means to improve power system reliability. However, no of previous research has investigated these potential system reliability benefits of the ST. The paper presents a methodology which can be used to quantify the system reliability impacts of the use of STs as an interface between the transmission and distribution systems. Using the methodology, the ST impacts on the system reliability are assessed using the IEEE 39-bus system as an example.**

***Keywords—Smart Transformer, Power System Reliability, Load Curtailment, Demand Control, Reactive Power Decouple***

## I. INTRODUCTION

The smart transformer (ST) [1] is a power electronics converter based transformer, which could be uses as a replacement for the traditional low frequency transformer (LFT), but offering active control of voltages and powers. The ST commonly consists of AC-DC rectifier, DC-DC converter and DC-AC inverter [2]. This structure can also provide the DC port to integrate the DC subsystems, i.e., renewable energy sources [3], electric energy storages [4,5] and electric vehicle charger stations [6]. Active control of the ST manages the power flow between the subsystems [7]. This feature improves the system flexibility, especially for a system which is moving towards becoming a fully smart grid.

The port voltages are decoupled from each other. In other words, the primary and secondary voltages are independent. This is the main advantage of the ST compared to the LFT. Particularly, at the secondary side the voltage can be fully controlled in terms of both frequency and amplitude. This feature can be used to better control the active and reactive power demands considering the voltage dependent nature of the system loads [8]. By adjusting the voltage amplitude in response to the change in the grid frequency, the ST has the potential to improve the frequency stability [9,10]. In some under-frequency situations, the ST may be able to keep the entire load online and to obviate the need for load curtailment [9]. In addition, frequency regulation at distribution system side could be used to enable the droop-controlled distributed energy sources to generate extra power by deliberately reducing the frequency. This has been used to reduce the active power which is transferred through the ST to avoid the overcurrent [11]. Application of a 4-leg inverter structure [12] at this side allows for voltage control in each phase independently, which can reduce the common-mode harmonics [13], manage the fault [14,15] and minimize the energy losses in the distribution system [16,17].

On the other hand, the capacitor in the DC ports decouples the reactive power at the primary and secondary side. This enables the ST to provide reactive power support into the grid [18]. Using this ability, the ST is able to improve the voltage stability [19,20]. Particularly, in under-voltage conditions, instead of curtailing the power demand, the ST can inject more reactive power into the grid and help maintain all consumer demand in the distribution system. Although these device-level controls and capabilities have been well researched in previous works, there is still limited research on the quantification of the overall system-level benefits of such capabilities. Some recent studies have developed a static model ST for the use in optimal power flow analysis [21] and applied this model in a power system to show benefits in terms of generation cost [22]. The authors concluded that further studies of a similar nature are required to understand the potential benefits from a system investment and planning perspective. The contribution of this paper is to develop a methodology which provides a basis for quantifying the impact of the ST on system reliability. Here it is considered that the ST is able to enhance the system reliability via its load voltage control capabilities and the voltage sensitivity of the load. Specifically, by adjusting its secondary voltage to reduce load in emergency situations, the ST facilitates the reduction of load curtailments and the reduction of the probability of load shedding. This potential for system reliability improvement has not been analyzed in the literature to date. This work is the first paper to attempt to quantify the power system reliability improvement gained by the application of the ST in power system.

The rest of the paper is organized as follows. Section II reviews the ST and formulates its model applied for reliability

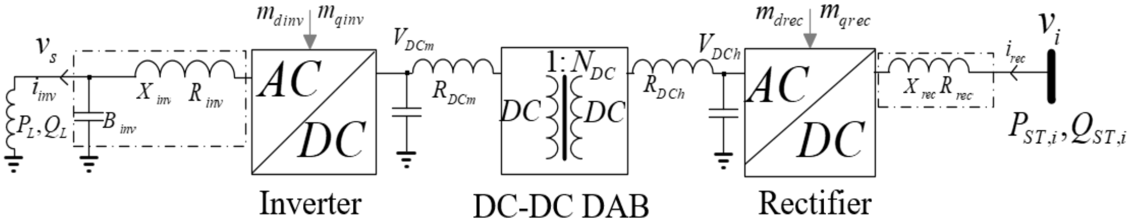


Fig. 1. Smart Transformer Topology

analysis. Section III discusses the reliability analysis technique. Section IV presents the results. Concluding remarks are provided in Section V.

## II. SMART TRANSFORMER

For this work it is assumed that the ST is deployed at the interface between the transmission system and the distribution system. The ST therefore consists of a HVAC-HVDC rectifier, HVDC-MVDC converter and MVDC-MVAC inverter as shown in Fig. 1. The HVAC-HVDC rectifier uses a phase locked loop (PLL) to synchronize to the transmission system and applies outer power, inner current control HVDC voltage constant while also regulating its reactive power to a given setpoint. The HVDC-MVDC DC-DC converter is controlled to maintain the MVDC voltage constant, while the MVDC-MVAC inverter applies outer voltage inner current to determine the MVAC voltage.

### A. *Smart Transformer Active Power Control*

The secondary side MVAC voltage can be independently and fully controlled in terms of both amplitude and frequency. Using this capability, in combination with the voltage sensitivity of the load, the power demand of the load can be controlled within certain limits. The load is commonly assumed to be voltage dependent and can be modelled as (1),

$$P_L = P_{L0}(\frac{V_s}{V_{s0}})^{\alpha} \tag{1}$$

where $P_{L0}$ is the loading at nominal voltage $V_{s0}$, $V_s$ is the ST controlled MVAC voltage, $\alpha$ is the voltage sensitivity. Note, the voltage sensitivity value $\alpha$ can be considered to represent the percentage of power reduction resulting from a 1% voltage reduction. For the different types of load, the load voltage sensitivity is different. For example, the load voltage sensitivity for the residential load is 1.6, for the commercial load is 1.2, and for the industrial load is 0.2. Also, at different times in a day, for the same system, the voltage sensitivity is also different, for example, at night-time it may be around 0.7 while during the day-time it is around 1.7 for typical residential loads [8]. However, standards such as, EN 50160 [23] require that the load voltage should be maintained within $1 \pm 0.1$ *pu*. Considering the voltage drops on the line, the voltage $V_s$ is therefore constrained. At night-time, the loading is light so that the voltage $V_s$ has a larger range, while at day-time, when the loading is high, the voltage $V_s$ has a narrower range. Considering the combination of the voltage sensitivity and the possible voltage range, the daily demand reduction for the residential load has been shown to be in the range of 5-6% [9]. However, the power delivery efficiency of the ST must also be considered, and this is generally lower compared with an LFT. Previous works have indicated that the ST efficiency around 96.75% may be achievable [24]. To account for the ST efficiency, the ST active power being drawn from the transmission system for the reliability analysis is formulated as follows:

$$P_{ST} = P_{L0} * \frac{1 - R}{\eta} \tag{2}$$

where R is the fraction of demand which is controllable due to the voltage sensitivity, and $\eta$ is the ST power delivery efficiency. From (2), it can be seen that the provided fraction is greater than the ST losses; thus, the ST can provide system demand reduction. On this basis, it is considered that the application of the ST in the system has the potential for system reliability improvement through load reduction as an alternative to direct load shedding during emergency situations.

### B. *Smart Transformer Reactive Power*

Because of its structure, the ST provides reactive power isolation between ports. Unlike the LFT, which normally absorbs the reactive power from the transmission system, the ST can be controlled to inject the reactive power to the transmission system in order to support the local voltage, in a manner similar to a STATCOM. However, the reactive and active power share the same rectifier converter, and therefore to avoid overload of the converter, the reactive power compensation must be constrained as (3), where $S_{STm}$ is the rated ST capacity. Thus, the reactive power from the ST to the transmission system must lie within the range given by (4).

$$Q_{STm} = \sqrt{S_{STm}^2 - P_{ST}^2} \tag{3}$$

$$-Q_{STm} \leq Q_{ST} \leq Q_{STm} \tag{4}$$

From (4), it can be seen that instead of reactive power load curtailment, for example in voltage dip situation, the ST provides an extra freedom on reactive power compensation. Especially, in light load situation with small $P_{ST}$, the reactive power compensation ability is significant from (3). Therefore, the application of the ST in the system has potential on the system reliability improvement.

## III. RELIABILITY

Power system reliability [25] is defined as the ability of the power system to keep supplying the load, considering the generation and transmission capacity, considering the fact that the system components have a certain probability of failure. This section reviews the power system reliability indices and introduces the evaluation methods used in the case study in this paper.

### A. Component Reliability Model

In the reliability studies of this paper, the system components, i.e., generators and transmission lines, are modelled using classical two-state reliability model with up and down states as shown in Fig. 2 [26]. The availability $A$ and unavailability $U$ of component $j$ can be formulated using its failure rate $\lambda_j$ and repair rate $\mu_j$ as follows.

$$A_j = \frac{\mu_j}{\lambda_j + \mu_j} \tag{5}$$

$$U_j = \frac{\lambda_j}{\lambda_j + \mu_j} \tag{6}$$

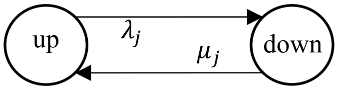


Fig. 2. Component two-state reliability model

### B. System Reliability Parameters and Indices

Assuming there are $N$ independent components in the power system with $M$ failed components, the state probability $p_i$ for the scenario $i$ can be computed using (7).

$$p_i = \prod_{j=M+1}^{N} A_j \prod_{j=1}^{M} U_j \tag{7}$$

The expected energy for the load active power $EE_P$ and reactive $EE_Q$are defined as (8) and (9). The expected active and reactive demand not supplied, i.e., $EENS_P$ and $EENS_Q$, due to the active power and reactive power shortages, are calculated using (10) and (11), respectively. Where $NC$ is the number of the scenarios, $D_{Pi}$ and $D_{Qi}$ are the active and reactive loading for the scenario $i$; $LC_{Pi}$ and $LC_{Qi}$ are the active and reactive load curtailments due to the real and reactive power shortage for the scenario $i$.

$$EE_P = \sum_{i=1}^{NC} D_{Pi} \times p_i \tag{8}$$

$$EE_Q = \sum_{i=1}^{NC} D_{Qi} \times p_i \tag{9}$$

$$EENS_P = \sum_{i=1}^{NC} LC_{Pi} \times p_i \tag{10}$$

$$EENS_Q = \sum_{i=1}^{NC} LC_{Qi} \times p_i \tag{11}$$

### C. Reliability Evaluation Technique

In order to evaluate the system reliability, first a set of scenarios is generated to model the uncertainties associated with the load fluctuations. Based on the historical data available on the active and reactive power consumption and using the forecast techniques, the statistical moments of and correlation between these uncertain parameters are first found. For instance, the average forecast power consumptions are the first row moments, and variance and skewness are the second and third order central moments. The maximum order of statistical moments is set to make a compromise between the accuracy and computational burden. The forecast outputs usually comprise the expected active and reactive power consumptions, standard deviations and correlation between these parameters. Under such setup, these data can be used to approximate a joint probability distribution function (PDF) based on normal distribution assumption. With more accurate techniques, statistical moments of the higher orders can also be predicted. The procedure of generating a set of scenarios that best comply with the forecasted statistical characteristics is presented in this subsection.

First, multivariate generalized Gram-Charlier series [27] is used to find a multi-variable joint PDF for uncertain parameters. A set of scenarios is then generated by producing random samples for uncertain parameters. At this step the probability of generating a sample within a specific area in the hyperplane representing the state space is proportional to the probability associated with this area. This probability is found using the aforementioned joint PDF.

After generating these random scenarios, in order to reduce the computational burden, the number of these scenarios should be reduced without compromising the model accuracy. The probabilities of the scenarios should also be found. A linear programming-based (LP-based) moment matching technique is used to accomplish both goals. The idea is to find a set of probabilities for the initial scenarios that best comply with the statistical moments of and correlation between the uncertain parameters. The details of this technique can be found in [28]. After solving this optimization problem, the scenarios with probabilities less than a predefined value (here $0.01/N_s$) are eliminated. $N_s$ is the number of initial scenarios. These scenarios are combined with the components' outage scenarios to form the final set of scenarios. Finally, with $\pi_m$ and $N_m$, as the probability of scenario $m$ and number of final scenarios (index by $m$), the expected energy not supplied can be calculated using (10,11).

### D. Load Shedding Calclulations

In this paper, the optimal load shedding problem is formulated as an Optimal Power Flow (OPF) problem. Each load curtailment is modeled as a pseudo generator with very high production cost, and minimum and maximum producible active power equal to zero and total active power demand of the regarding load. The formulation of the AC OPF problem was provided in [29]. The first modification required with respect to the model provided in [29], is inclusion of the aforementioned pseudo generators. Constraint (2) is also considered in order to include the effects of STs on active power demand reduction.

## IV. CASE STUDY

We use IEEE 39-bus system (Fig. 2) to illustrate the effects of STs on the system reliability. Matpower on Matlab is used in order to solve the OPF problems with minimum generator cost as the objective. The total generation capacity of the system is 7367 MW and the total transmission line capacity is

33780 MW. The line flow limits, generator capacity constraints and bus voltage limits are provided in [30]. The load is assumed to be residential load for all buses. The scenarios used to model the uncertain nature of the system will be discussed in subsection A. In order to force the load curtailment, the line capacity for all lines is reduced to 70% of the original value and set as the base case. The ST is used to replace the original constant PQ load to the ST-controlled load (2-4), where R=6% and $\eta = 96.75\%$. The rating of the ST is set equally to the maximum load conditions at the connected bus. Here, we investigate the effect of the ST penetration level on the system reliability in subsection B and the effects of network capacity and different ST penetration levels of reliability improvement in subsection C. The load curtailment for each load in different ST penetration levels is presented in subsection D.

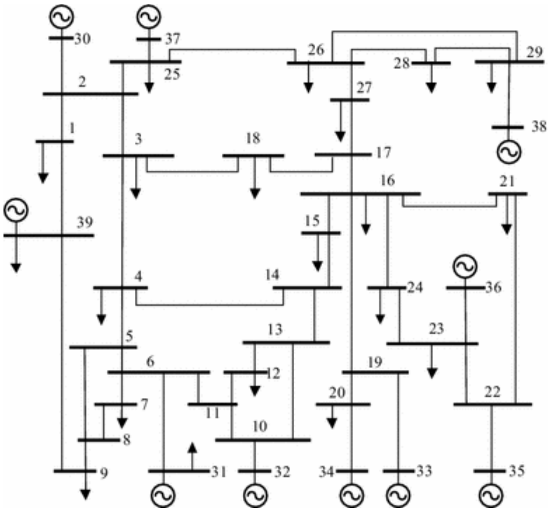


Fig. 2. New England IEEE 39-bus system

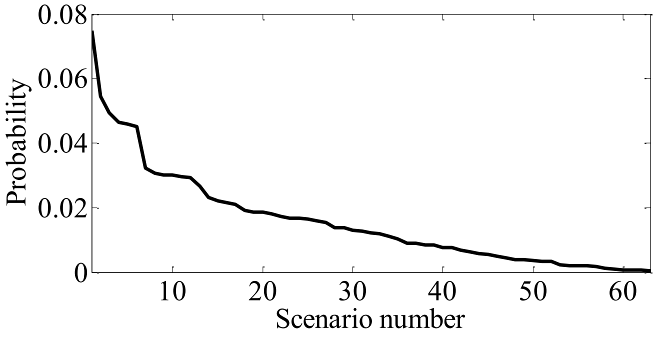


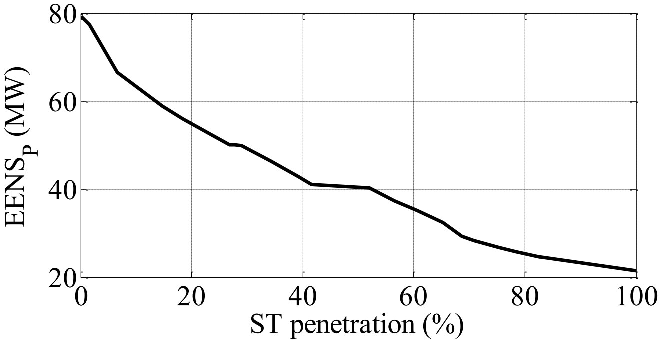
Fig. 3. Probability for each scenario

### A. Scenarios

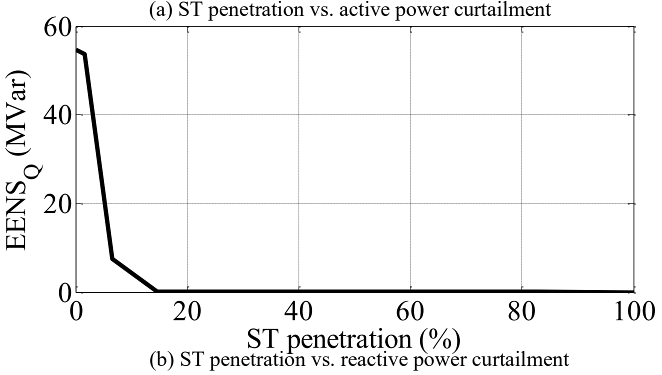
In order to generate the scenarios to analyse the system reliability, the mean values for active and reactive power consumption are considered to be equal to the values specified for this standard test system in [30]. A standard deviation of 5 percent is assumed for each uncertain parameter. The correlation between the active and reactive power consumption at a certain bus $m$ ($D_{Pm}$ and $D_{Qm}$) is assumed to be 65%. The correlations between ($D_{Pm}$ and $D_{Pm}$), ($D_{Pm}$ and $D_{Qn}$) and ($D_{Qm}$ and $D_{Qn}$) are considered to be 50, 30 and 35%, respectively. Using the method presented in subsection IIIA, first 2000 scenarios are generated. Then the proposed method in order to find the probabilities is applied. The number of scenarios for which the occurrence probability is higher than 0 is 63 in these studies. The probabilities of these scenarios are presented in Fig. 3 after sorting these scenarios according to their probabilities.

### B. Case 1: ST Penetration

In this case, we gradually replace the original constant PQ load by the ST controlled load bus-by-bus, starting from bus 1 to bus 39 (corresponding to 0% to 100% penetration level for STs). Fig. 4 presents the load curtailment in this process.



(a) ST penetration vs. active power curtailment



(b) ST penetration vs. reactive power curtailment

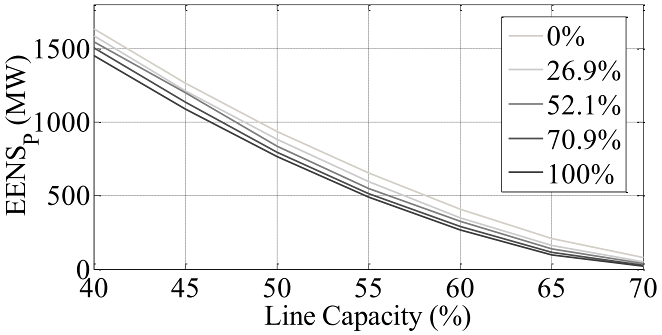
Fig. 4. Case 1: the effect of ST penetration on the system reliability

It can be seen from Fig. 4 that the increase in the ST penetration level can reduce the amount of the total load shedding in the system. This is because the ST can purposely reduce the load demand to 97.2% based on (2). On the other hand, the ST at the transmission system side can inject the reactive power and at the low voltage side can independently supply the reactive power of the load, so that there is no reactive power load curtailment needed as long as the number of STs in the system is sufficient. Therefore, the increase of the ST penetration level indeed improves the system reliability.

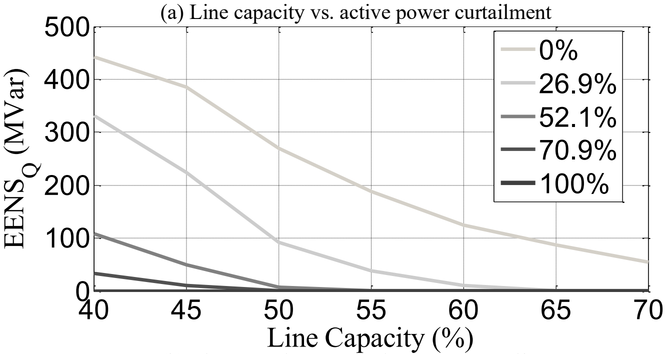
### C. Case 2: transmission system upgrade

In this subsection, we investigate the benefits of the ST on the transmission system upgrade. Instead of increasing the demand by generating a new set of scenarios, we keep the same scenarios but reduce the total line capacity from 70% to 40%. Fig. 5 presents the load curtailment in this process.

The line capacity reduction, of course, reduces the power system reliability with higher expected load curtailment. The increase in the ST penetration level can help reduce this negative influence. For example, at expected 500 MW active power load curtailment, the line capacity for no ST case can reduce to 58% while with 100% ST case, it can be further reduced to 55%. This means the inclusion of the ST in the system can help us defer the investment on upgrading the transmission system while maintaining the same system reliability. On the other hand, the ST has a significant positive influence on the reactive power load curtailment which also alleviate high investments on upgrading the transmission system.



(a) Line capacity vs. active power curtailment



(b) Line capacity vs. reactive power curtailment

Fig. 4. Case 2: the effect of ST penetration on the system upgrade.

The line capacity reduction, of course, reduces the power system reliability with higher expected load curtailment. The increase in the ST penetration level can help reduce this negative influence. For example, at expected 500 MW active power load curtailment, the line capacity for no ST case can reduce to 58% while with 100% ST case, it can be further reduced to 55%. This means the inclusion of the ST in the system can help us defer the investment on upgrading the transmission system while maintaining the same system reliability. On the other hand, the ST has a significant positive influence on the reactive power load curtailment which also alleviate high investments on upgrading the transmission system.

### D. *Case 3: Load curtailment at each bus*

This subsection gives the detail of how the ST reduces the load curtailment at each bus. We consider the cases with 0%, 52.1% and 100% for ST penetration levels and 50% network capacity. Table I records the results as well as the expected loading at each bus.

It can be seen from Table I that in the most buses, the application of ST can help reduce the load curtailment. However, in some buses, for example bus 3 and bus 18, the active power demand is almost fully curtailed, whatever if ST is implemented or not. This is because the OPF determines these buses as those with highest energy price. This indicates that the application of ST in some buses may not enhance the system reliability as the loads in these buses have to be fully disconnected during the emergency states. This can also be verified in Fig. 4 (a), where the regarding curve sometimes becomes flat, for instance around the value of 50% for ST penetration level.

TABLE I. BUS LOADING AT 50% LINE CAPACITY SITUATION

| | **Load information** | | **0% ST penetration** | | **52.1% ST penetration** | | **100% ST penetration** | |
|---|---|---|---|---|---|---|---|---|
| **Bus** | $EE_P$ | $EE_Q$ | $EENS_P$ | $EENS_Q$ | $EENS_P$ | $EENS_Q$ | $EENS_P$ | $EENS_Q$ |
| **1** | 78.87 | 44.20 | 0.00 | 0.00 | 0.00 | 0 | 0.00 | 0 |
| **3** | 322.26 | 2.39 | 316.91 | 2.36 | 316.29 | 0 | 321.55 | 0 |
| **4** | 380.67 | 182.19 | 331.44 | 121.97 | 258.09 | 0 | 241.34 | 0 |
| **7** | 178.59 | 82.62 | 10.55 | 3.79 | 10.27 | 0 | 2.33 | 0 |
| **8** | 405.16 | 174.94 | 9.42 | 3.19 | 11.48 | 0 | 2.28 | 0 |
| **9** | 78.66 | -67.66 | 0.00 | -0.00 | 0.00 | 0 | 0.00 | 0 |
| **12** | 102.86 | 87.06 | 6.99 | 72.15 | 1.46 | 0 | 0.56 | 0 |
| **15** | 254.81 | 152.67 | 49.22 | 23.53 | 32.19 | 0 | 16.81 | 0 |
| **16** | 187.25 | 32.46 | 13.19 | 1.29 | 21.58 | 0 | 9.09 | 0 |
| **18** | 158.66 | 29.97 | 155.14 | 29.46 | 157.18 | 0 | 153.46 | 0 |
| **20** | 441.45 | 103.06 | 19.06 | 2.89 | 7.38 | 0 | 2.42 | 0 |
| **21** | 206.65 | 116.19 | 20.80 | 8.73 | 15.40 | 6.46 | 4.09 | 0 |
| **23** | 193.62 | 84.72 | 0.36 | 0.12 | 0.27 | 0.09 | 0.00 | 0 |
| **24** | 208.96 | -93.41 | 0.00 | 0.00 | 0.00 | -0.00 | 9.37 | 0 |
| **25** | 140.53 | 47.28 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0 |
| **26** | 94.73 | 16.70 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0 |
| **27** | 186.09 | 75.92 | 0.00 | 0.00 | 0.18 | 0.05 | 0.00 | 0 |
| **28** | 131.30 | 27.47 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0 |
| **29** | 164.16 | 27.10 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0 |
| **31** | 7.68 | 4.57 | 1.11 | 0.55 | 1.51 | 0.75 | 0.55 | 0 |
| **39** | 736.51 | 248.77 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0 |
| **sum** | 4,659.48 | 1,379.21 | 934.19 | 270.03 | 833.28 | 7.36 | 763.85 | 0 |

On the other hand, the application of ST in some buses leads to load curtailment, such as bus 27 in the case with 52.7% ST penetration level and bus 24 at 100% case. The reason lies in two facts. The first one is that the OPF selects the cheapest load curtailments. The second one is that the reactive power compensation capability of the ST changes the power flow.

## V. CONCLUSION

This paper investigates the effect of STs on power system reliability. The ST can improve the system reliability with lower load curtailments. As the STs' penetration level increases, the expected emergency demand curtailment decreases which in turn further improves the system reliability. Especially, the reactive power isolation capability of the STs has a great impact on reliability improvement according to the results presented in the case studies. On the other hand, the location of the ST has a great influence on the performance of the ST in reliability improvement. In some locations, the application of STs has almost no effect on the total system reliability.

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