Development of a user-defined system protection model against voltage collapse in PSS/E

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Development of a user-defined system protection model against voltage collapse in PSS/E

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Abstract—**This paper investigates the voltage instability problem leading to a voltage collapse and how such scenario can be prevented by the use of a user-defined system protection model in PSS/E. The model continuously monitors in real-time the system as a whole and can initiate a system protection control actions when a prominent voltage collapse is detected based on a voltage stability indicator in parallel with signals from overexcitation limiters (OELs). Two well-known voltage stability indicators have been evaluated, namely the Impedance Stability Index (ISI) and the Transmission Path Stability Index (TPSI). Both indicators has been evaluated in a case study using the Nordic-32 test system. In this case study, two separate contingency scenarios were designed to cause a voltage collapse. It was found that the calculations of the ISI were time consuming and did not indicate the margin to voltage collapse as clearly as the TPSI did. The TPSI and signals from OELs were used as input signals in the system protection model designed to protect the power system. The model was designed to generate the control signals to change Automated Voltage Regulator (AVR) set-points of synchronous generators and initiate load shedding control actions. The functionality of the system protection model was successfully verified when it was able to prevent the voltage collapse scenarios designed in the case study.**

Keywords: **Voltage collapse, Voltage stability indicators, Impedance stability index (ISI), Transmission path stability index (TPSI), PSS/E, System protection model, Automatic voltage regulator (AVR), Load shedding.**

I. INTRODUCTION

A large and highly interconnected power system connected to loads that varies throughout the day and which operates close to its limits during certain periods of time will be defined as a stressed network [1]. When contingencies occur at this stage, voltage instability and in worst case voltage collapse is likely to occur. Protecting the power system from voltage collapse is essential for providing a reliable power transfer and to be able to ensure that precautions are taken when a contingency occurs. A voltage collapse can result in the entire system shutting down, which leads to extensive economic consequences and unsatisfied customers [2]. The vitality in detecting an imminent voltage collapse and taking fast corrective actions to prevent it is of great importance to maintain stability [3]. One way to obtain this is to implement a system protection model based on system stability indicators [4]. These types of models are still in a stage where not as much research is done for an operational implementation in the power system and the efficiency is still being evaluated by means of simulations. In such simulations the model utilizes system protection schemes (SPS) which are initialized to protect the system if there are tendencies to voltage instability [1], [3], [4]. This paper tries to integrate the indicators in a system protection model which can be used by the transmission system operator to evaluate various control actions to prevent a voltage collapse. This is a first step in developing a prototype of the voltage collapse controller which can be used in the TSO's control room. This paper is based on the MSc thesis work at Chalmers by the first two co-authors [5]. The main contributions of the papers are the following:

- Investigation of the uses of two major indicators, including Impedance Stability Index (ISI) and Transmission Path Stability Index (TPSI) for real-time prediction of voltage instability and/or voltage collapse.
- Development of a user-defined system protection model based on voltage stability indicators in PSS/E
- Evaluation of the performance of the model in voltage collapse scenarios.

II. ISI AND TPSI INDICATORS

A. ISI

ISI is based on the maximum power transfer of a circuit. The maximum power transfer occurs when the Thévenin impedance Z_{Thv} equals the load impedance Z_{Load} as presented in [6]-[8]. The power dissipated by the load has its maximum value when $Z_{Thv} = Z_{Load}$ or in other words, when the voltage drop over Z_{Thv} is equal to the voltage drop over the Z_{Load}. This also implies that the maximum power transfer and therefore the voltage instability critical point is reached when:

$$ISI = |Z_{Thv}| / |Z_{Load}| = 1 \qquad (1)$$

If the ISI is less than one, the voltage at the bus is stable. If instead greater or equal to one, the voltage profile is unstable. A value of 0.8 has been discussed to be a good indicator value for alarm [4, 8].

B. TPSI

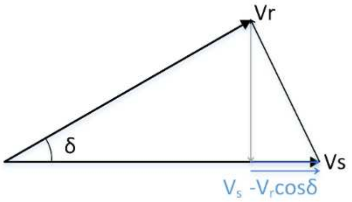

Fig. 1. Voltage drop $V_s - V_r\cos\delta$ between sending end and receiving end projected on the sending end bus voltage phasor Vs.

TPSI is described by the voltage magnitude of which maximum power transfer occur and can be described according to (2):

$$TPSI = V_s/2 - (V_s - V_r\cos(\delta)) \quad (2)$$

which when equals zero, indicates the maximum power transfer operation point or the stability/instability boundary at the knee of the PV-curve [4], [8]. This indicator is, as in the case of the ISI, based upon that the maximum power transfer occurs when the voltage drop over the line equals the load voltage.

The voltage drop over the line $V_s - V_r\cos(\delta)$ can be illustrated with phasors as in Fig. 1, where Vs and V_r is the sending and receiving end voltage with the angle difference δ for a two-bus system. The TPSI does not however, use the Thévenin equivalent, as compared to the ISI, but only the voltage at the sending end, receiving end and the voltage angle difference for a two-bus system [8]. The voltage and angle measurement needs to be synchronized.

For the two-bus system, the indicator can easily be calculated using (2). For larger systems, however, all paths need to be taken into account. The weakest path will then determine the margin to a voltage collapse. This is due to the fact that if one transmission path moves past the maximum transmission point, it will put higher stress on the other transmission paths. Each transmission path can be seen as a radial network with the bus furthest away from the generating bus being the bus which is most exposed to voltage instability. In addition, the effect of each bus along the path needs to be considered as they can contribute to keeping the path stable. An active power transmission path is defined as a sequence of buses with decreasing voltage angle between each bus, in essence the direction of active power flow [4], [8].

III. NORDIC-32 CASE STUDY

This section contains two different base cases where contingency scenarios occur. For each case the designed scenarios lead to a full voltage collapse in the Nordic32 test system [9]. The indicators were evaluated in both cases together with the voltage characteristics at the most critical buses. The base cases presented here contain the underlying sequence of events leading to a voltage collapse which is going to be prevented by implementing the system protection model which will be presented in next the chapter. Further, the test system contains dynamic models resulting in a more realistic simulation outcome of phenomena occurring in the power system. The Nordic32 test system is visualized in Fig. 2.

A. Case 1

The first case study was designed in such a way that distance relays were utilized which led to a sequence of events that resulted in a voltage collapse for the modified Nordic32 test system. A three phase to ground fault was introduced at the line between bus 4032 - 4044 and the succeeding events can be seen in Table 1. The impact of these events can be seen in Fig. 3. which show the behavior of the two indicators and Fig. 4. show the voltage profiles at the buses 1042, 1043, 4042, and 4047 which were most affected by the contingency.

The fault occurred at 20 s and after 2.5 simulation cycles (50 ms) the distance relay from bus 4032 to 4044 tripped the line. Between these two time instances the three-phase fault gave rise to transient behavior of the voltage which decreased after the line was tripped and after which a somewhat more stable operating point was found. However, OLTC actions between 20.6 - 52 s lead to the activations of the OELs at the generator buses 1043, 4031 and 4042. The intention of the OLTC actions at this stage was to increase the voltage in the 130 kV grid, which is the weakest. An increase of this voltage will force the voltage in the 400 kV grid to decrease the flow of reactive power will change, leading to the OEL activation. The activation of the OEL at bus 1043 at 52 s resulted in that the voltage at bus 1043 falls below the under-voltage limit of 0.85 pu, and after a time delay of 20 s the generator at 1043 was tripped at 72.6 s. The tripping gave rise to further OLTC actions and OEL activations at generator buses 4047 and 1042, at 104 and 177 s respectively, and the system was further weakened. Finally, at 270 s the generator at bus 4042 was tripped due to under voltage and the system collapses.

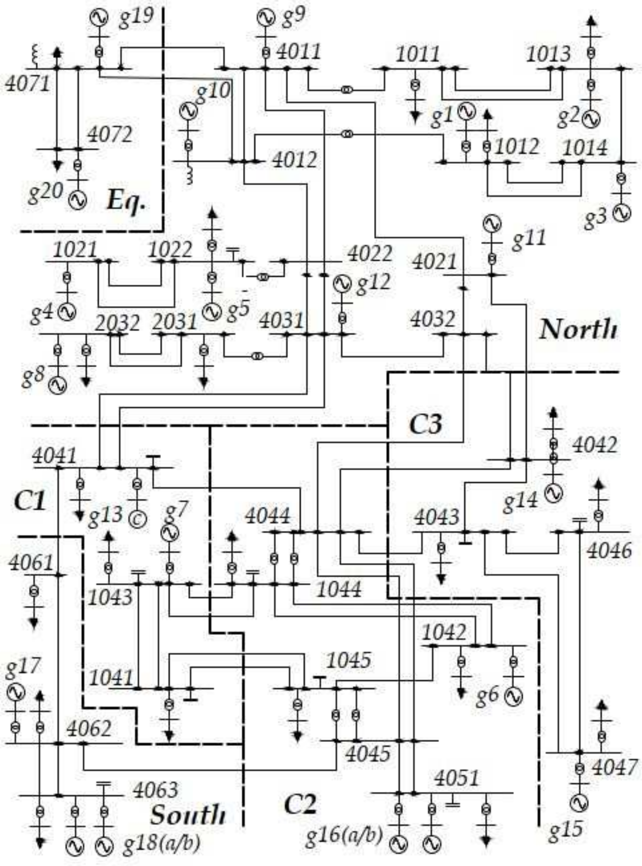

Fig. 2. Single-line diagram of Nordic-32 test system

TABLE I. SEQUENCE OF EVENTS LEADING TO VOLTAGE COLLAPSE IN THE FIRST CASE STUDY OF THE NORDIC 32

Bus number	*Time [s]*	*Time [s]*
4032 - 4044	Fault on line, tripped by distance relay	20
All transformer buses	OLTC actions	20-52
1043, 4031, 4042	OEL activated	48-53
1043	Under voltage tripping of generator	72
All transformer buses	OLTC actions	72-270
4047	OEL activated	104
1042	OEL activated	177
4042	Under voltage tripping of generator	270

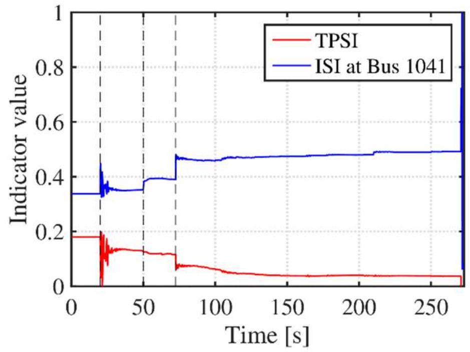

Fig. 3. Indicator values as a function of time of the first case study in the Nordic32 test system

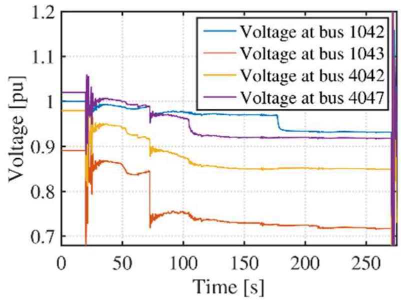

Fig. 4. Voltage characteristics as a function of time of the first case study in the Nordic32 test system

B. *Case 2*

The second case study was designed as a scenario where the events in

TABLE *II* lead to a voltage collapse after an initial loss of generation. The impact of these events on the indicator values can be seen in Fig. 5 and the voltage characteristics of buses 1043, 2032, 4041 and 4042 are shown in Fig. 6. At 20 s the generator at bus 4042 was tripped. The events that followed were activations of the OELs at buses 1022, 1043, 4031 between times 46.61 and 52.44 s. These events initiated OLTC actions at all transformers until 108 s, forcing the OELs at buses 2032, 4021 and 4041 to be activated one by one.

TABLE II. SEQUENCE OF EVENTS LEADING TO VOLTAGE COLLAPSE IN THE SECOND CASE STUDY OF THE NORDIC 32

Bus number	***Time [s]***	***Time [s]***
4042	Generator tripped	20
1022, 1043, 4031	OELs activated	46-52
All transformer buses	OLTC actions	46-108
2032, 4021, 4041	OELs activated	time>108
All transformer buses	OLTC actions	time>108
1043, 4021, 4041	Under voltage tripping of generators	131

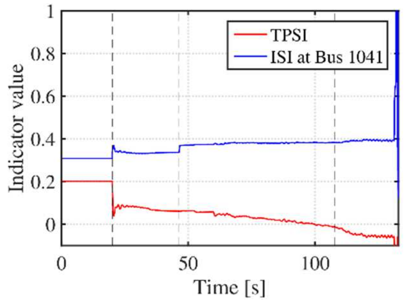

Fig. 5. Indicator values as a function of time of the second case study in the Nordic32 test system

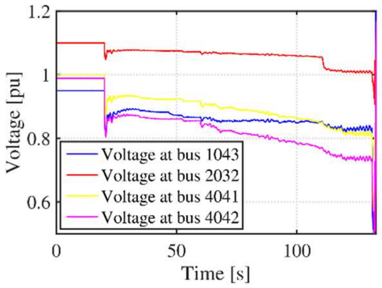

Fig. 6. Voltage characteristics as a function of time of the second case study in the Nordic32 test system

The impact of the OELs does not show very clearly at times greater than 108 s, but the gradually decreasing voltage at this time was a result of this. OLTC actions together with the previous events at times less than 108 s result in that the generators at buses 1043, 4021 and 4041 are tripped due to under voltage which lead to a full system collapse.

For the system protection model described in the next section, only the TPSI was used as an indicator mainly due to the lower time consumption of the calculations as well as that the TPSI performed slightly better when indicating the stability margin compared to the ISI.

IV. PREVENTION OF VOLTAGE COLLAPSE

This chapter describes how the TPSI indicator was implemented in a PSS/E user defined model constituting the system protection model, and how it was used together with OEL and AVR signals to monitor and protect the system from voltage instability and collapse with help of a system protection scheme. The implementation of the model was verified and its performance was also evaluated.

The purpose of the model was to monitor the voltage stability of the system in real-time as well as to be able to take corrective actions to mitigate instability and to prevent voltage collapse. The model was developed by implementing the indicator calculations. After this implementation the SPS by means of controlling synchronous generator AVR set-points and load shedding were implemented.

A. *Model working principle*

The work flow of the model can be seen in Fig. 7 and the steps in this block diagram are performed at each time step.

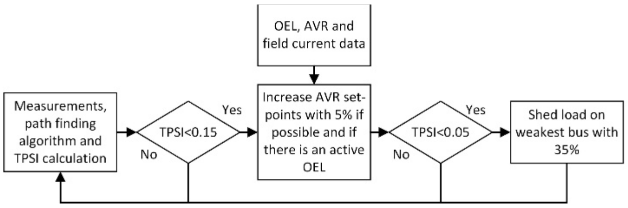

Fig. 7. Block diagram of the system protection model which is run at each simulation time step in PSS/E.

At each time step, synchronized measurements of voltage and angle are performed after which the TPSI are calculated. The system protection scheme uses two types of voltage instability mitigation actions. The first option, which is ranked as the first mitigating action in the SPS, is to increase AVR set-points with a predefined percentage for generators in the network. The second one is load shedding, which is performed if the increase of the AVR set-points is not enough as mitigating action. The increase of AVR set-points are triggered by reduction in a reactive power production from synchronous generators caused by OEL activation and therefore use this signal. This action attempts to balance out the loss of reactive power production. The triggering event for the model to start shed loads is based on the value of the TPSI.

The load shedding criterion was set to when the TPSI reached a value below 0.05, which was decided to be the limit for when the margin to instability is critically low. The choice of limit for load shedding was based on consecutive simulation results which showed that the risk for under voltage tripping of generators increased for TPSI values lower than 0.05. For the simulations presented in this chapter, loads were shed by 35% and the reason behind this is explained later in this chapter. The criterion for increasing AVR set-points was set so that the TPSI needed to be set lower than 0.15 and the increase will occur when the first OEL is activated to compensate for the loss of reactive power.

B. *Evaluation of the system protection model*

The system protection model is designed to prevent voltage instability in two steps, the first step is to increase the AVR set-points for generators capable of increasing reactive power output without the risk of entering the limit of over voltage at the bus. Furthermore, an increase of the AVR set-points is not performed at generators where the OELs are active, nor for generators with field currents above their rated value. If the first step is not sufficient for preventing a voltage collapse the model will shed load at the bus with the lowest TPSI.

C. *Case 1*

Starting with the least severe, Case 1, which had a longer time after the fault until the system collapsed. Rerunning the simulation of the same case presented in Section III.A but this time with the system protection model implemented. The result can be seen in Fig. 8. This clearly shows that the model prevents the voltage collapse which previously occurred at approximately 270 seconds. With the corrective actions in the SPS the TPSI value was finally stabilized at around 0.09. Bus voltages were stabilized to values slightly lower than before the fault, which can be seen in Fig. 9.

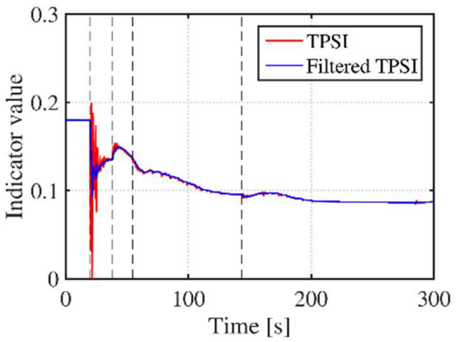

Fig. 8. Indicator values as a function of time of the first case study in the Nordic32 test system with the system protection model implemented.

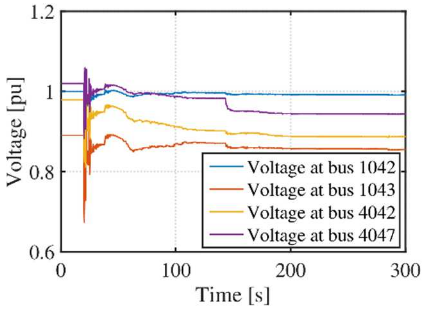

Fig. 9. Voltage characteristics as a function of time with the system protection model implemented me of the first case study in the Nordic32 test system.

Due to the fact that there are no major simulation events after 200 seconds the system can be considered to have reached a new steady state. After this point, no OEL timers are activated as well as only a few OLTC operations. The TPSI threshold for load shedding was 0.05 for this simulation, although it can clearly be seen that TPSI never reaches this value. The increase of AVR set-points is initiated when the TPSI is below 0.15 and when an OEL is activated. The simulation scenario of Case 1 with the system protection model implemented followed a sequence of events which can be seen in Table III.

TABLE III. SEQUENCE OF EVENT FOR CASE 1 WITH THE SYSTEM PROTECTION MODEL

Bus number	***Time [s]***	***Time [s]***
4032 - 4044	Fault on line, tripped by distance relay	20
1022	OEL activated	38
4011, 4012, 4021, 4041, 4051, 4062, 4063	AVR set-point increased with 5%	38
4031	OEL activated	53
4042, 1042	OEL activated	56 - 58
All transformer buses	OLTC actions	60 - 170
4047	OEL activated	143
4062	OEL activated	158

The AVR set-points are increased with 5% for a number of selected buses when the first OEL at bus 1022 is activated after 38 seconds, where the effect on bus voltage and reactive power production at buses 1022 and 4021 can be seen in Fig. 10 and Fig. 11.

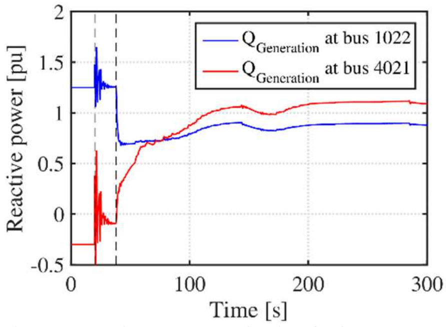

Fig. 10. Reactive power production for bus 1022 and 4021 in Case 1

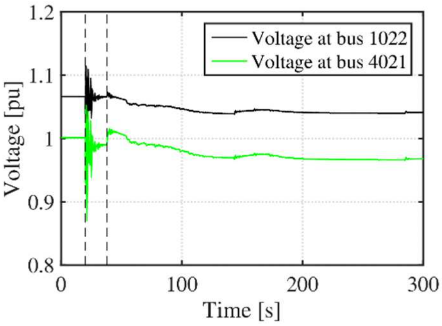

Fig. 11. Voltages for bus 1022 and 4021 in Case 1

The increase resulted in that the two generators at bus 4047 which in Section III.B tripped due to under voltage remained in operation due to the increased bus voltage at 4047 and now only experienced activation of its OEL at 143 seconds. The system experienced an activation of a number of OELs which forces the OEL at the generator at bus 4062 to activate at 158 seconds which previously had its AVR set-point increased at 38 s. This is due to a decrease of reactive power production of the other generators.

The bus voltage at bus 1043 for the new steady state after 200 s were only 0.87 pu making the generator prone to a under voltage trip if additional faults would occur. This is however to be compared with the base case in Section III.B, where the generator at 1043 was tripped due to under voltage 50 seconds after the fault. The system is operating in a weakened state and more mitigating actions could possibly be performed to increase the margin to instability. The immediate collapse is however prevented due to the increase of AVR set-points and no load shedding was needed for this case.

D. Case 2

Case 2 which was initialized by a tripped generator at bus 4042 was more severe with a shorter time course until collapse compared to Case 1. For this case, an increase of AVR set-points did not prove to be enough to prevent the collapse and load shedding had to be utilized. After this action the system margin to voltage instability was increased and when the system had stabilized it had a TPSI value at around 0.09 which can be seen in Fig. 12. The full sequence of events can be seen in TABLE IV. The voltages for the more exposed buses of the network are kept at a lower level compared to before the fault which can be seen in Fig. 13. This is mostly due to the loss of reactive power production at bus 4042 where the generator is tripped. This bus is a critical part of the network and can be seen as a node where a high-power transfer from the northern area to the southern and central area of the Nordic32 takes place.

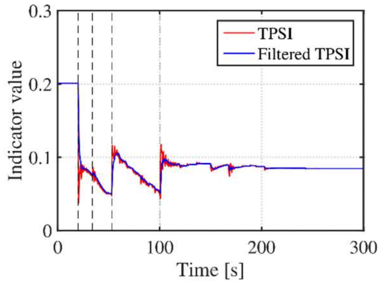

Fig. 12. Indicator values as a function of time of the second case study in the Nordic32 test system with the system protection model implemented

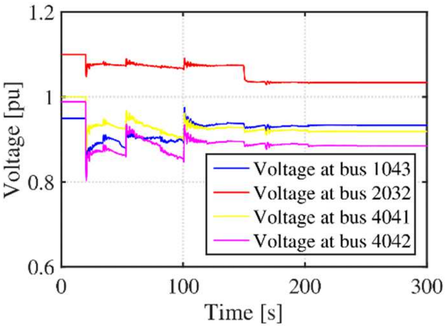

Fig. 13. Voltage characteristics as a function of time with the system protection model implemented me of the second case study in the Nordic-32 system.

The increase by 5 % of the AVR set-point when the first OEL is activated at bus 1022 after 34 seconds was not enough to save the system and had to be supplemented by load sheds of 35 % at bus 42 and 46 after 53 and 100 seconds, until the systems stability margin can be maintained. The shedding occurs at two different buses due to that the weakest bus according to the TPSI is changed after the first load shed, where the effect on voltage and apparent power for these buses can be seen in Fig. 14.

TABLE IV. SEQUENCE OF EVENT FOR CASE 2 WITH THE SYSTEM PROTECTION MODEL

Bus number	***Time [s]***	***Time [s]***
4042	Generator tripped, 630 MW 350 MVAr	20
1022	OEL activated	34
4011, 4012, 4051, 4063	AVR set-point increased by 5%	34
4031	OEL activated	52
42	Load shed by 35 % 172 MVA	53
4021	AVR set-point increased by 5%	55
All transformer buses	OLTC actions	time>60
4047	OELs activated	81
46	Load shed by 35 % 254 MVA	100
2032, 4011	OELs activated	150-166

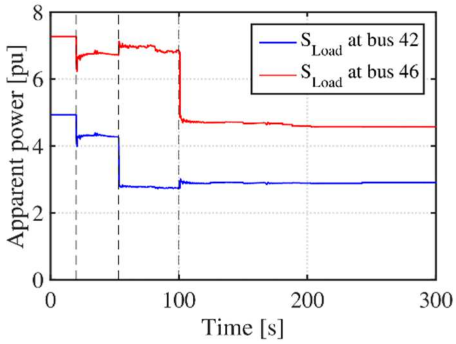

Fig. 14. Apparent load power for bus 42 and bus 46 in Case 2

The percentage value to shed loads with was based on consecutive simulations where different percentages were tested and evaluated. A too low percentage increased the number of times loads had to be shed to avoid a collapse. As well as that a low percentage in the end resulted in a higher accumulated load shed. A high percentage could efficiently prevent instability and collapse, however, this also resulted in an extensive amount of load shed at only one bus. If load shedding instead occurs at a couple of buses in the system when needed, then the improvement of the overall system stability proved to be better. For this reason, 35% was found to be a balanced amount due to that the load shedding was divided between two buses as well as that the total amount of load shed was kept at a low level compared to the overall load of the system. When and where the load shedding occurs are entirely based on the value of the TPSI.

Further increasing the AVR set-point could result in a overvoltage at certain buses in the northern part of the network and could instead resulted in negative results. The activation of OELs at 52 and 81 s for generators at buses 4031 and 4047 respectively cause a major loss of reactive power production resulting in a loss of voltage control. Since these generators stand for the major reactive power production in the transfer area, the generator at bus 4011 also reaches its field current limit resulting in OEL activation at 166 seconds. The collapse is prevented through the increase of AVR set-points together with the shedding of load at the two occasions. One can however argue that the load shedding is at a minimal level due to that OELs are still active when system enter its new steady state. It is also important to mention that minimal shedding of load is desired due to that the main purpose of a power system is to supply power to the customers. In other words, load shedding can be seen as a last resort for maintaining system stability. In addition to this, the total load shed did not equal the generation lost by tripping of the generator at bus 4042.

V. DISCUSSIONS

The system protection model designed in this paper has proved its ability to prevent a voltage collapse in the two cases investigated. The first case responded well to an increase of the AVR set-point and the second case to load shedding. The immediate effect of an increasing AVR set-point was that it could prevent under voltage tripping of generators, thus maintaining a higher generation of power to supply the grid. Since the shunt compensation in the Nordic32 test system is fixed with the reactive production proportional to the square of the voltage, an increase in voltage at buses with shunt compensation further strengthens the effect of increasing the AVR set-points. However, the set-point increase has to be done carefully in order for the increase to not result in an overvoltage for buses with already high voltage in areas with high power production. Furthermore, a large increase of the AVR set-point of a generator could increase the field current above the field current limit, especially if nearby generators experiences activation of their OELs.

The load shedding is an effective method to restore stability and for increasing the margin to instability. It is however important to note that it is used mainly as the last option as well as keeping the load shedding at a minimal amount. It is also worth noting that these actions are short term and used in emergency situations. While indicators such as the TPSI and the ISI can be used to determine the margin to voltage stability, it is important to add that stability indicators do not show all weaknesses in a system. Other important signals to consider are, for example signals from OELs, timers for undervoltage tripping, OLTC actions etc. which have to be used in combination with voltage stability indicators in order to monitor all events in a network. A combination of multiple stability indicators and input signals mentioned above will help to increase the credibility of a system protection model and make it more robust. As an example, in case of an undervoltage trip, a system can quickly become significantly weakened and experience instability at buses if more indicators are utilized indicating the same event the probability to take the right mitigating actions are increased. This is however a balance, since using a model with many inputs requires a complex solution with longer computational times.

VI. CONCLUSIONS

This paper focused on developing a system protection model and evaluating how such model can use voltage stability indicators together with signals from OELs as inputs to monitor the voltage stability of the system. Depending on the value of the two input signals the model will initialize and utilize SPSs to prevent a voltage collapse.

Implementing and evaluating the behavior of the two indicators in the Nordic32 test system showed that the use of ISI in the system protection model would require large computational power. Also, it has been seen that the ISI was not as accurate as the TPSI in indicating the margin to voltage collapse. The system protection model was developed and implemented in PSS/E with the TPSI and OEL signals as inputs. The model was designed to initialize a SPS consisting of increasing AVR set-points of generators if an OEL is activated at the same time as the value of the TPSI is below 0.15 and to shed load when the TPSI fell below 0.05.

Two base cases leading to a voltage collapse were designed for the Nordic32. The model and associated SPS prevented the voltage collapse in both cases, for the first case an increase of AVR set-points was enough to prevent voltage collapse and in the second case both increase of AVR set-point and load shedding was utilized to save the system from collapse.

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