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An Adaptive Undervoltage Load Shedding Against Voltage Collapse Based Power Transfer Stability Index

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Abstract – This paper highlights the comparison of a proposed methods named adaptive undervoltage load shedding based PTSI techniques for undervoltage load shedding and two previous methods named Fixed Shed Fixed Delay (FSFD) and Variable Shed Variable Delay (VSVD) for avoiding voltage collapse. There are three main area considerations in load shedding schemes as the amount of load to be shed, the timing of load shedding event, and the location where load shed is to be shed. The proposed method, named as adaptive UVLS based PTSI seem to be most appropriate among the uncoordinated schemes. From the simulation result can be shown the Adaptive UVLS based PTSI give faster response, accurate and very sensitive control for the UVLS control technique. This technique is effectively when calculating the amount to be shed. Therefore, it is possible to bring the voltage to the threshold value in one step. Thus, the adaptive load shedding can effectively reduce the computational time for control strategy.

Keywords : Adaptive load shedding, UVLS, Voltage collapse

1. Introduction

In the deregulated environment and owing to the difficulty of building new transmission and generation facilities, power systems will be operated closer to their stability limits. There are two ways of defence against incidents likely to trigger such instabilities which estimate security margin with respect to credible contingencies; i.e. incidents with a reasonable probability of occurrence, and take appropriate preventive actions to restore sufficient margins when needed and correctively: implement automatic corrective actions, through system protection schemes (SPS), to face the more severe, but less likely incidents [1].

Preventive security criteria usually requires that the system remain stable after any credible contingencies, without the help of corrective action. The main reason is that these actions effect generators and/or loads, which is acceptable only in presence of severe disturbance.

Since long-term voltage instability is triggered mainly by loss generation and or transmission facilities, the contingencies corresponding loss of single equipment are consider in preventive security analysis and more severe disturbances should be counteracted by an SPS [1]. While it must be used in the last resort and to the least extent, automatic load shedding is very effective in this respect. A few under voltage load shedding schemes have been proposed or implemented throughout the world [2-7]. Most of the schemes use close-loop shedding controllers in terms of performance and design computational effort [1]. There are three types of close-loop shedding controller. First two controllers are local by nature are preventively rely on local measurements taken from the system and shed the loads once the observed signal stays below some threshold for some time. The third controller is a step towards a wide area protection, in the sense that other post-disturbance corrective controllers are managed in additional to load shedding.

To be effective counter measure against voltage collapse, the three main area consideration in load shedding schemes as the amount of load to be shed, the timing of load shedding event, and the location where load shed is to be shed [1, 4, 6, 8]. The amount of load to be shed is determined by a concept which is load to be shed has to be optimum. Load shedding less than necessary will obviously not to be effective in arresting voltage collapse. Load shedding too much may result in transitioning the system from an under voltage to an over frequency condition as the resulting system will have more generation than load [6]. The timing of the load to be shedding event is very important. The minimum amount of time allowed before load shedding scheme is triggered is the time taken for the detection of the onset voltage collapse. The maximum amount of time allowed before a load shedding scheme is triggered is the time is taken for all the intervening system components to attempt system recovery. Last important factor is determining the location where load to be shed. In the dynamic simulation some

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researchers are using the optimal power flow methodologies [1, 6, 8]. In this case the load buses are ranked in order of the weakest to the strongest. The weakest bus tends to be most susceptible to voltage collapse given the relatively large reactive power consumption for a small reduction in bus voltage. Therefore, often it is this bus that is the most appropriate candidate for load shedding initially [6].

Most of the methods for load shedding give separate methods for determining the amount of load shedding, time of load to be shed and determine where the load to be shed. An improvement method for dynamic voltage collapse named Power Transfer Stability Index (PTSI) is used for voltage collapse index [9]. This method is using power transfer as indicate for voltage collapse. The PTSI can correctly predict the collapse point of a load bus. The value of PTSI is between 0 and 1. The value zero mean system at that load bus is stable and one indicate voltage collapse at a load bus. The two main important to use as under voltage load shedding consideration as where and how much load to be shed, may be determined together from this index. When the time to be shed determine by using the minimum time allowed, the system component to attempt system recovery. This proposed method may be function both as an indicator, at the same time can be function as a control system from collapse.

When load shedding is activated, it is important to minimise consumer disruption through proper design of the load shedding arrangements. Current practice in most load to shed load when certain setting limit level are breached. As the objective of the load shedding, it is necessary to shed load as fast as possible to threshold level of voltage to avoid any overload shedding upon the current load situation. An adaptive load shedding scheme is proposed to do that. This method is based on PTSI, which is using the updated values of system apparent power load parameter information in addition to the usual measurement of voltage, and to bring the voltage to threshold voltage.

The thirty nine-bus test system is used for carrying out the simulation for dynamic voltage collapse. The details of the machines, governors, exciters, and induction motors are given. The results of the time domain simulations carried out using the Power System Analysis Toolbox (PSAT) simulation program are then presented.

2. Protection Against Voltage Collapse

Two Protection consider in this study rely on a measured signal which is typically the average voltage V over several transmission or load buses in the load area concern. Previously, two controller types have been developed for load shedding upon detection of a significant drop of the average voltage. First controller is called Fixed Step Fixed Delay (FSFD) [1], second controller is called Variable Step Variable Delay (VSVD) [4], and a new method is developed by detected power transfer to the load bus, it called Power Transfer Stability Index [9]. Three above Methods will be described as follow:

2.1 Derivation of Power Transfer Stability Index

Power Transfer Stability Index (PTSI) is actually an indicator for detection of voltage stability. Because of the characteristic this index, thus PTSI can be developed as an adaptive UVLS control technique. The PTSI is calculated by knowing information of total load power, voltage, and impedance at Thevenin bus and phase angle between Thevenin and load bus [9]. The value of PTSI will fall between 0 and 1. When PTSI value reaches 1, it indicates that a voltage collapse has occurred.The proposed power transfer stability index (PTSI) is derived by first considering a simple two-bus Thevenin equivalent system, where one of the buses is a slack bus connected to a load bus. It can be shown at Fig. 1.

According to reference [9] the PTSI can be calculated as equation (1).

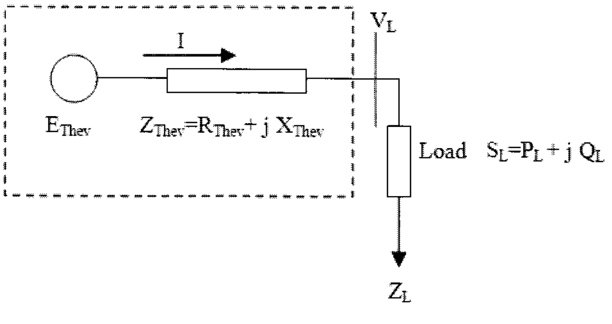

Fig. 1. Simple two-bus Thevenin equivalent system

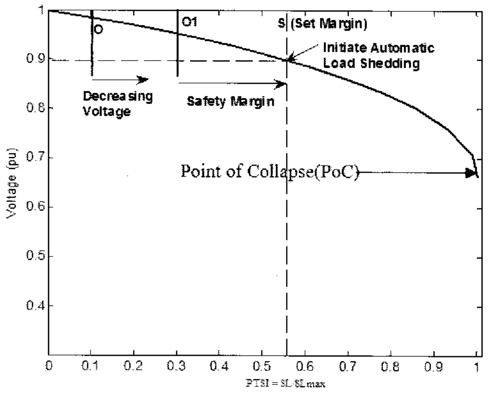

Fig. 2. Characteristic PTSI - Voltage

$$PTSI = \frac{S_L}{S_{L\max}} = \frac{2S_L Z_{Thev}\left(1+\cos(\beta-\alpha)\right)}{E_{Thev}^2} \quad (1)$$

where,

S_L is Load power at a bus
β phase angle of Thevenin bus
Z_{Thev} is impedance Thevenin connected at bus
α phase angle of Load bus
E_{Thev} is voltage Thevenin at bus

2.2 Undervoltage Load Shedding using PTSI

The Power Transfer Stability Index (PTSI) is index for dynamic voltage collapse. This index is for measuring level of stability by calculation ratio of actual apparent power to the maximum apparent power from a load bus. From equation (1) with increasing load at a bus, the voltage will declines gradually until reach PTSI = 1 or $S_L/S_{L\,max} = 1$. This point is called point of collapse (PoC). For the prediction of incipient voltage instability, the load bus power is continuously monitored.

The concept of adaptive control for undervoltage load shedding can be explained from the PTSI-Voltage characteristic. Fig. 2 shows the characteristic PTSI-Voltage at a load bus.

The coordinated settings voltage from normal operation for UVLS program range between 0.95- 1.05 p.u. [7]. For load increase or any disturbance to system occurrence, operating point will move from stable area run to limit of safety margin limit ('S'). If the save operating point 'O' is moving and reaches limit of normal operation (threshold level) 'O_1', the dispatcher is alerted and advised to take action. The characteristic is informed that the risk for voltage instability on the load bus by increased due to heavy load and it is notified about safety margin left until instability will occurs. Once the operating point passes the safety margin limit (set margin) 'S', the counter time relay for initiate load shedding action is begin to count. The automatic corrective action has to be taken for load shedding if the operation point is lower than 'S' point for more than certain time delay, to counter attack for voltage collapse. If during certain time delay the voltage is back to more than point 'S' voltage level value, then no load shedding will be activated. The Algorithm to determine how much load to be shed can be calculated as follows.

- Determining the threshold voltage ('O_1') as an objective voltage if load shedding is activating and calculate the PTSI value threshold point. Threshold voltage level is coordinated setting voltage from normal operation for UVLS program. This value guarantees that the controller will not act in a stable situation [1, 7]. Some researches using voltage of 0.95 p.u. as a threshold value [1, 2, 4, 7]. The PTSI value can get from the characteristic PTSI-Voltage by knowing the threshold voltage level at x-axis as showed at Figure 2 until cross the curve and draw the line down until cross the y-axis. The y-axis is PTSI value of a bus. $PTSI_{O1}$ also be calculated from equation (2)

$$PTSI_{O1} = \frac{S_{O1}}{S_{L\max}} \quad \text{at} \quad V=V_{O1} \quad (2)$$

Where,
V is measuring load bus voltage
S_{O1} is load at threshold voltage point
V_{O1} is threshold voltage point
$S_{L\,max}$ is the maximum load at a bus.

- Set the voltage at set margin point/safety margin limit 'S' (V_S) to initialize automatic load shedding. Safety margin limit 'S' is the voltage limit which is use for initialization automatic load shedding. Normally value of Vs is less than V_{O1}.
- Set time delay to activate the load shedding action (T_{LS}).
- If voltage actual (V_{act}) is more than voltage set margin point (V_S) then load shedding is not taken. And if $V_{act} < V_S$, or $PTSI_{act} > PTSI_S$ during $T_{act} > T_{LS}$ then load shedding will activate.

If algorithm 4 is fulfilled, we get the difference value between actual PTSI ($PTSI_{act}$) and PTSI at threshold voltage point ($PTSI_{O1}$). It can be calculated from equation (3)

$$PTSI_{act} - PTSI_{O1} = \frac{S_{act}}{S_{L\max}} - \frac{S_{O1}}{S_{L\max}} \quad (3)$$

where $PTSI_{act}$ is PTSI at actual load bus, and S_{act} is apparent power at a load bus. Modification equation (3), we get

$$\Delta PTSI = \frac{S_{act} - S_{O1}}{S_{L\max}} = \frac{\Delta S}{S_{L\max}} \quad (4)$$

where ΔS is amount overload from ting condition.

To prevent system from voltage collapse, load shedding has to be taken. The amount of load shedding can be calculated by shed load as big as ΔS. This is the minimum amount to bring the system to the setting point. From this, equation (4) modify as,

$$\Delta PTSI = \frac{S_{act} - S_{O1}}{S_{L\max}} = \frac{\Delta S}{S_{L\max}} = \frac{S_{Shed}}{S_{L\max}} \quad (5)$$

$$S_{Shed} = \Delta PTSI \, . \, S_{L\max} \quad (6)$$

where S_{Shed} is amount load to be shedding.

To determine which load bus should be shed; the value of PTSI is calculated at every load buses. Ranking of the load buses based on PTSI is listed descending from higher value to lower value. The higher value of PTSI indicates the weaker load bus. This load bus that has higher value of PTSI is higher priority to be shed. To determine time to activate load shedding, it has to be considered the minimum of time allowed before a load shedding scheme is triggered. The time is considered for all the intervening system components to attempt system recovery. It's purpose to avoiding false alarm at the control part. Most of researchers are using as long as three second minimum time delay where the level of voltage of 0.9 p.u.

2.3 Fixed Step Fixed Delay (FSFD) [1]

This protection is a close loop protection which takes successive actions, each on the basis of the signal V resulting from the previous actions. In other words, the signal V stemming from the system is fed back to the protection. This closed-loop design is preferred as being more robust with respect to modeling and operating condition uncertainties. It consider a protection based on k rules of the type:

$$\text{If } V < V_i^{\min} \text{ during } d_i \text{ second then shed } \Delta P \text{ MW} \qquad (7)$$

The number k of rules is decided a priori, in practical it is typically equal 2 or 3 step. Each step with different voltage threshold and correspond to a different level of the corresponding delay vary with the voltage threshold. The larger the voltage drop the larger the amount of load to be shed and the shorter is the shedding delay [1]. Note that such a protection operates in closed loop since V is continously measured and the same rule may trigger several successive load shedding in time.

2.4 Variable Step Variable Delay (VSVD) [1, 4]

The second type of controller is kind of generalization of previous one. It relies on unique whose activation delay d and amount of shed load ΔP depend on the time evolution of V [1, 4]. The idea is to set up a controller adjusting its action automatically to the severity of the situation facing: the faster the decrease in V, the shorter d and the larger load to be shed.

Thus, the delay is determinate by following equation:

$$\int_{t_o}^{t_o+d_1}\left(V^{\min} - V\right)dt = C \quad d_{\min}<d<d_{\max} \qquad (8)$$

where t_o is the time at which V become smaller than $V^{\min}$ and C is constant to be optimized at design stage. In the same manner, the load shedding step is given

$$\Delta P = k.I.\Delta V_{avg} \quad \text{with } \Delta P_{\min} < \Delta P < \Delta P_{\max} \qquad (9)$$

where ΔV_{avg} is average voltage drop over the $[t_o \quad t_o+d]$ interval

$$\Delta V_{avg} = \frac{1}{d}\int_{t_o}^{t_o+d_1}\left(V^{\min} - V\right)dt \qquad (10)$$

two variant of this controller have been considered:

i) The Variable Step Fixed Delay (VSFD) controller work with constant delay d and sheds load according equation (10)

ii) In the Fixed Step Variable Delay (FSVD) the delay is adjusted using equation (9) while the shedding step ΔP is constant.

3. Test System

The New England (IEEE 39 bus) power system shown in Fig. 3 is used as the test system. Power System Analysis Toolbox is used in the simulation presented in this paper. The loads were represented as voltage dependencies load model. Reference [10, 14] describes the general consideration of static analysis. For dynamic simulation, the 39 bus test system, which is used in the dynamic simulation, contains a variety of power system component models. The system as shown in figure 3 consists of ten generators connected at buses 30 to 39 in which bus 31 is a slack bus. All generators are equipped with identical automatic voltage regulator (AVR), over excitation limiters (OEL) and turbine governor. The load and line data of the test system for steady state power flow calculation are given in reference [14].

All the ten generators have identical dynamic characteristics using the sixth order synchronous machine model (two axes, with two windings on each axis) for each generator [12]. The AVR and Over Exciter Limiter are used IEEE type 1. Both AVR and over excitation limiter (OEL) regulate the voltage at the synchronous generator terminal by performing both regulating and excitation system stabilizing functions. The AVR defines the primary voltage regulation of the synchronous generator while the OEL provides an additional signal to the reference voltage of AVR [13]. The turbine governor type 1 [12] define the primary frequency regulation of the synchronous generators. In this test system three contingencies as Line outage, Generator outages and Load Increase will implement.

The entire system all connected to identical load characteristic as the voltage dependency load characteristic with $\alpha = 0.8$ and $\beta = 1.5$. The load model represented by the exponential model [11].

$$P = P_0\left(\bar{V}\right)^{\alpha} \text{ and } Q = Q_0\left(\bar{V}\right)^{\beta} \qquad (11)$$

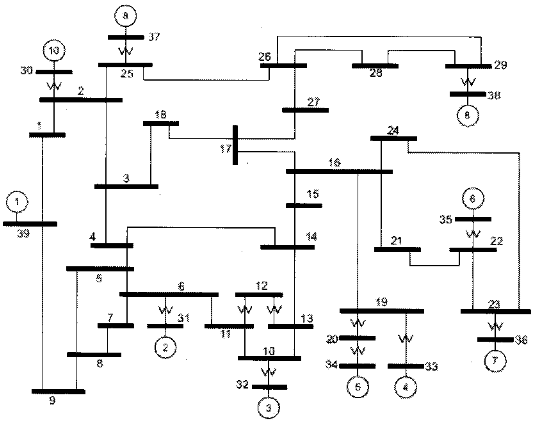

Fig. 3. One-Line diagram of the 39-bus test system

The ULTC is used for controlling the secondary voltage in this simulation system. Its action is represented with time delay and deadbands in which the time delay for ULTC is assumed to be 1 second. The tap ratio considered has a minimum and maximum voltage tap of 0.8 p.u. and 1.2 p.u., respectively, with a step of 0.025 p.u. per tap or 16 steps.

4. Results Discussion

To verify the undervoltage load shedding technique, the proposed criterion is tested on 39 bus test system. The test system consist 10 generators are modeled using sixth-order modeled together with a first order excitation and turbine generator type 1. The disturbance considered was the loss of transmission line between bus 5 and 8 (without a fault) at time 1s. The increase load is occurred at bus 20, with 3.14 + 0.515 p.u. MVA at t=20s and with 5.024 + j0.824 p.u. MVA at t=37s. The objective of the UVLS is bringing the voltage to the threshold voltage at 0.95 p.u.

The result of line outage at between bus 5 and 8 causes the load bus voltages to drop, thereby increasing the reactive power demand of the load system. The generator supplies the required amount of reactive power to support the voltage. If the reactive supply is not enough than reactive power demand of the system, the voltage will decrease. It is showed at figure 7, from point A after line outage occur the system will unstable (there is an oscillation) and maintain in same level until 5 second then after that voltage will decrease. This result also happened when the load increase at bus 20. From the Figure 7 showed from point B and C after load increase the voltage will decrease faster and bus will collapse.

Installing a ULTC between bus 30 and 2 is also attempts to restore the voltage as the effect of line outage ULTC is effectively bringing voltage to acceptable level. The ULTC still can help system maintain voltage at acceptable level after the second load increase the load bus is become lower than 0.9 p.u. It is meaning that ULTC and generator reactive power supply support no more effective to support the system voltage. Thus, in this situation load shedding is implementing to countermeasure.

4.1 Result of UVLS by FSFD

Technique of UVLS type FSFD in the system can be shown at figure 4. Figure 4 showed the ULTC can function well to recover voltage at bus 20, in the line outage contingency and first load increase at bus 20. At the second

Table 1. Rank of Load Bus Based PTSI

Bus No	PTSI	Rank	Bus No	PTSI	Rank
20	0.429	1	3	0.181	10
16	0.227	2	4	0.178	11
24	0.223	3	12	0.176	12
15	0.214	4	7	0.172	13
21	0.213	5	8	0.170	14
17	0.210	6	28	0.163	15
27	0.199	7	25	0.154	16
23	0.193	8	29	0.154	17
26	0.182	9			

This technique using rule

5% of load shed at voltage < 0.90 p.u. with 3s delay
5% of load shed at voltage < 0.92 p.u. with 5s delay
5% of load shed at voltage < 0.94 p.u. with 8s delay

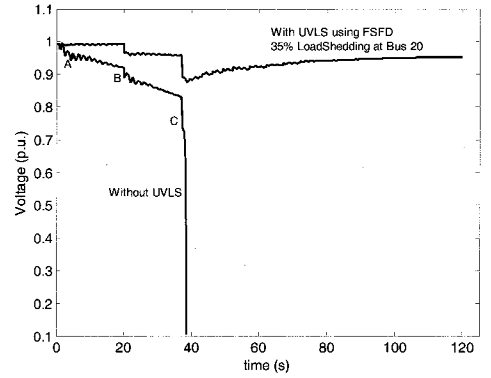

Fig. 4. Technique of UVLS type FSFD Load Shedding at bus 20

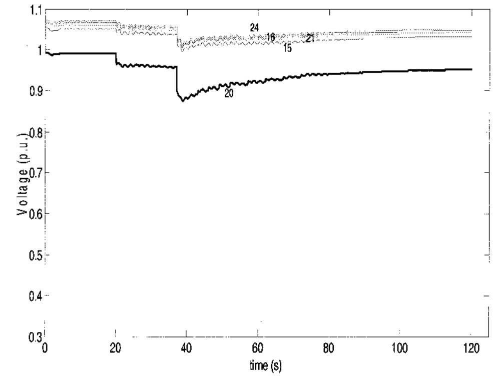

Fig. 5. Voltage profile after load shedding FSFD with 5% shed at 5 weakest buses

load increase, the ULTC is unable to support the voltage. Thus the UVLS is activated. From the UVLS type FSFD rule, the load will increase due to load shedding at bus 20. Bus 20 is the weakest bus due to rank based PTSI. It can be shown at Table 1.

Threshold voltage for UVLS is 0.95 p.u. so the load shedding will stop activated when the voltage is reach minimum 0.95 p.u. Fig. 4 showed the UVLS stop activated until 8 steps. Time taken to reach threshold voltage is 100s, when total load shedding is 35% of total load at bus 20. The voltage profile for five weakest buses is showed at Fig. 5.

4.2 Result of UVLS by VSVD

Technique of UVLS type VSVD in the system can be shown at Fig. 6 and Fig. 7. This techniques is using the variable integral rule. Referring to as $R_{integral}$ in the sequel, and based on the time average of the difference between V and a specific threshold V^{min} as showed in equation (10).

The d is time interval consider 3s in this test and the integral extends over the interval $[t_0\ t_0+d]$, where t_0 is the time at which V falls below V^{min}. This time average signal is used to shed a proportional amount of load as show in equation (9). In this case V^{min} has been taken equal 0.95 p.u. while amount of load shedding is vary depend on average voltage drop in every step shed. This can be repeated until maximum load shedding is performed or specific voltage threshold is reached. This loop design may act several time, each action being based on the measured results of the previously taken action and adjusted in amplitude of load shedding to the system response. We can see from the Figure 6 at the beginning, amplitude load to be shed is higher than the next load shedding. When the systems bus voltage is approaching the threshold voltage, the shed is decreased. Fig. 6 showed that the UVLS stop activated to reach threshold voltage is t=105s, when total load shedding is around 35% of total load at bus 20. The voltage profile for five weakest buses is showed at Fig. 7.

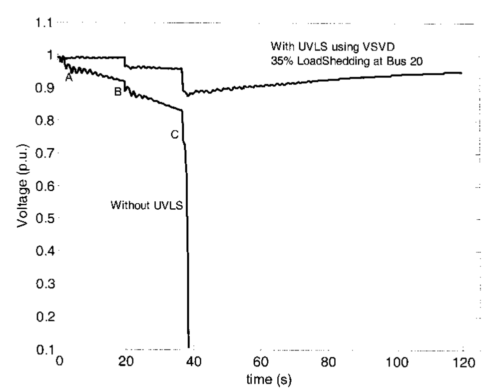

Fig. 6. Voltage profile after UVLS using VSVD at bus 20

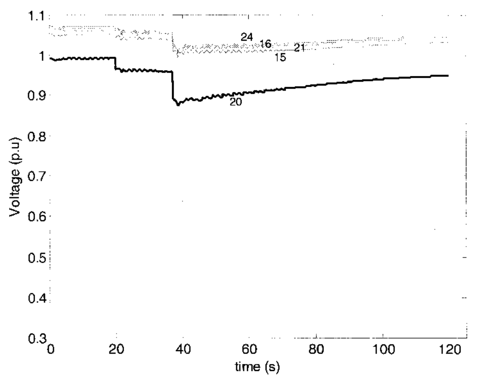

Fig. 7. Voltage profile after UVLS VSVD at 5 weak buses

4.3 Result of UVLS using Adaptive Load Shedding Based PTSI

This technique is based on PTSI, that is providing from in equation (5) and (6). The results can be shown at Figure 11 and 12. Referred to equations (5) and (6), voltage is needed as the objective after load shedding is taken action. The rule of this technique has to be considered as follow. If $V < V_S$ with time delay 3s then shed load at the bus as S_{shed}. V_S in this case is considered 0.9 p.u. and threshold voltage (V_{OI}) is 0.95 p.u. Characteristic PTSI-Voltage at bus 20 can be shown at in Table 2.

Actual apparent load at a bus can get from measurement data and actual PTSI can be calculated from equation (1). Using this information and considered rule of adaptive load

Table 2. Characteristic PTSI-Voltage at Bus 20

Increase Load at bus 20	Characteristic PTSI Voltage at bus 20	
	Voltage (p.u)	PTSI
0%	0.992	0
20%	0.983	0.037
40%	0.97	0.09
60%	0.95	0.181
80%	0.934	0.222
100%	0.913	0.296

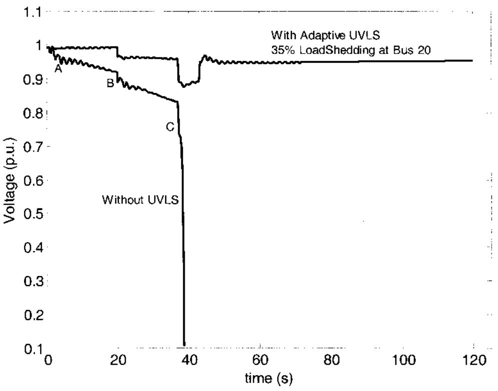

Fig. 8. Voltage profile after UVLS Adaptive load shedding based PTSI

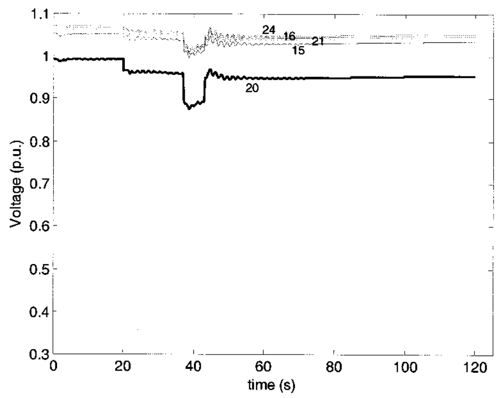

Fig. 9. Voltage profile after adaptive load shedding based PTSI at 5 weakest buses

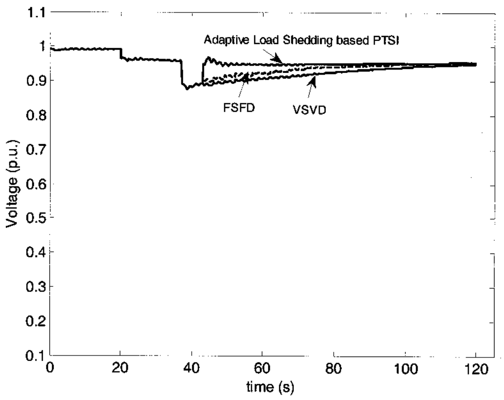

Fig. 10. Comparison response of three UVLS Techniques

shedding, we can get the amount load to be shed. This action is only taken one shoot to bring voltage at a level. And amount load to be shed can be determined without any complex optimization process. This adaptive load shedding technique is give sensitive and fast action to recover voltage at a bus or system. Figures 8 and 9 showed with the time need to bring to the voltage only takes 3s. Total load shedding in this adaptive load shedding is 35% of total load at bus 20. This result showed that total load shedding from three techniques gives the same result. Only time to get threshold voltage is different. The comparison of three technique of undervoltage load shedding showed as Fig. 10. Fig. 13 gives clear image about the comparison of three methods. From this figure we can said that the adaptive load shedding based PTSI gives accurate value comparing to the others. We can see here the disadvantages of the adaptive load shedding based on PTSI is the effect after load shedding action. We can see from fig. 13 that the oscillation occurs is bigger than otherss. This is because of the amount load shedding is bigger, compare to the FSFD and VSVD.

This effect may be reduce by make the adaptive load shedding rule into two step or more, if load shedding is very big. The other problem may be occurred in real time adaptive load shedding is which load has to be shed. This bus can be represented one area, which is consist industrial and residential areas. Thus, the priority area is become more important to be put into account when this technique want to implement.

5. Conclusion

In this paper, two techniques for avoiding voltage collapse are investigated. First is installing ULTC and undervoltage load shedding. Installing ULTC may be help the system for restoring the voltage for the disturbance that effected small effect to the system. For the bigger disturbance when the ULTC no more help, the undervoltage load shedding can be effectively used.

There are three types of undervoltage load shedding controller have been compared in this paper. That is FSFD, VSVD and adaptive load shedding based PTSI. A methodology to optimize their parameters has been described and illustrated on a rather complex example. The propose methods named Adaptive UVLS based PTSI controller seems to be most appropriate among the uncoordinated schemes. From the simulation result can be shown the Adaptive UVLS based PTSI give faster respond accurate, and very sensitive control for the UVLS control technique.

This technique is effectively calculating the amount to be shed. It is possible to bring the voltage to the value in one step time. Therefore, the adaptive load shedding can be effectively reduced the computational time for control strategy.

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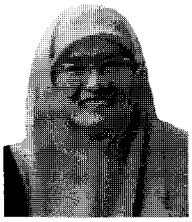

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