Turkish Journal of Electrical Engineering & Computer Sciences

http://journals.tubitak.gov.tr/elektrik/

Research Article

Turk J Elec Eng & Comp Sci
(2016) 24: 3309 – 3320

doi:10.3906/elk-1411-182

A robust undervoltage load shedding scheme against voltage instability

Iman KAFFASHAN*, **Seyed Mohammad Taghi MIRALI MORTEZAEE**, **Turaj AMRAEE**
Faculty of Electrical Engineering, K. N. Toosi University of Technology, Tehran, Iran

Received: 26.11.2014 • **Accepted/Published Online:** 07.04.2015 • **Final Version:** 15.04.2016

Abstract: Undervoltage load shedding (UVLS) is an effective measure for restoring voltage stability as a last resort in emergency conditions. In this paper, a UVLS scheme is proposed considering the uncertainties of load and line parameters. The loading margin is considered as the voltage stability index. The proposed scheme determines the optimal load shedding pattern subject to technical constraints. The info-gap decision theory uncertainty modeling technique is utilized to find a robust and cost-effective pattern of load shedding. The proposed scheme is formulated as a nonlinear programming problem, which is solved using the sequential quadratic programming technique. The performance of the proposed scheme is verified for the IEEE-14 bus and IEEE-118 bus test systems.

Key words: Voltage stability, undervoltage load shedding, uncertainty modeling, information gap decision theory

1. Introduction

Due to economic reasons, nowadays power systems are operated close to their stability limits. One of the most important stability phenomena is voltage stability. Any power system must be operated with an acceptable margin of voltage stability in both normal and contingent situations [1,2]. After occurrence of a severe contingency (e.g., double line outage), the reactive power consumption of the power system is increased, and the stability margin is then decreased. In this situation, normal and emergency controls must be triggered to stop the voltage decline. In the case of inability of normal control actions (e.g., reactive shunt switching) to prevent voltage instability, it is required to execute some remedial emergency actions [2,3]. The last-resort remedy is load shedding. In any undervoltage load shedding (UVLS) scheme, it is necessary to determine the location and amount of load shedding. Voltage stability criteria are considered as critical constraints in UVLS schemes [1,2]. All previously proposed UVLS schemes could be classified based on the type of utilized voltage stability index. The conventional UVLS scheme is formulated as an optimal power flow (OPF) problem to minimize the load shedding amount by considering operational and stability constraints [4]. In [5], a UVLS scheme was proposed to minimize load shedding considering load flow equations, while the security constraints of the network were neglected. A risk-based method to design a UVLS scheme was proposed in [6]. According to this method, the load bus with the highest risk of voltage instability is selected as the first candidate to execute load shedding. In [7], a UVLS scheme was developed to provide a predefined voltage stability margin via an OPF formulation. A dynamic adaptive UVLS scheme was proposed in [8] using model predictive control. An efficient computational methodology was described in [9] using the sequential Monte Carlo simulation approach for comparing alternative strategies and artificial neural networks to determine directly the parameters of

*Correspondence: imankaffashan@gmail.com

protection strategy. In [10], the developed methodology minimizes the load cuts through the relaxation of the minimum limits of voltage and maximum limits of active power flows through the transformers. In [11,12] a combinational load shedding algorithm was proposed to enhance the voltage and frequency stabilities. In [13] a novel analytical sensitivity index was proposed to determine the optimal load shedding locations to avoid voltage instability. The effect of forced outage rates of transmission equipment on system loadability was studied in [14]. In [15], the impact of load shedding as a corrective action through simulation of the system dynamic response to a disturbance was demonstrated. Optimal locations and amounts of load shedding in a deterministic UVLS scheme were determined in [16].

It is noted that in all the previously proposed schemes, the uncertainties of load and line parameters have been ignored. The line parameters' uncertainty is due to variation of shunt and series impedance of each transmission line during its lifetime. Without considering the uncertainties, the amount of load shed could be underestimated or overestimated according to the uncertainty's severity. Therefore, it is necessary to make robust and cost-effective decisions under different types of uncertainties. A conservative load shedding pattern may lead to an unnecessary excessive load shedding while a minimum cost pattern of load shedding may increase the risk of voltage instability. In this paper, the UVLS scheme is modified to consider uncertainties of load and line parameters with a predefined voltage stability margin. The proposed algorithm finds the minimum load shedding pattern to obtain the predefined voltage stability margin while satisfying operational constraints. The information gap decision theory (IGDT) technique is utilized to model the uncertainties of input parameters in the UVLS scheme. The results show the effectiveness and robustness of the proposed UVLS scheme.

This paper is organized as follows. In Section 2, the mathematical modeling of the deterministic (i.e. conventional) UVLS scheme is presented. The formulation of the uncertainty-based UVLS scheme using IGDT theory is described in Section 3. Section 4 presents the simulation results. Finally, the conclusion of this paper is given in Section 5.

2. Conventional deterministic UVLS scheme

Conventional UVLS is carried out based on the following mathematical model. In this model, the objective function (OF) is to minimize the cost of load shedding.

$$MinOF = (\sum_{i=1}^{N_L} \omega_i \times \Delta P_{Di}) \tag{1}$$

Subject to:

$$P_{Gi}^0 - P_{Di}^0 + \Delta P_{Di} = |V_i| \times \sum_{j=1}^{N} |V_j| \times (G_{ij} \times \cos(\delta_{ij}) + B_{ij} \times \sin(\delta_{ij})) i \in N \tag{2}$$

$$Q_{Gi}^0 - Q_{Di}^0 + \Delta Q_{Di} = -|V_i| \times \sum_{j=1}^{N} |V_j| \times (G_{ij} \times \sin(\delta_{ij}) - B_{ij} \times \cos(\delta_{ij})) i \in N \tag{3}$$

$$(1+\lambda_{\min})(P_{Gi}^0 - P_{Di}^0 + \Delta P_{Di}) = |V_i^c| \times \sum_{j=1}^{N} \left|V_j^c\right| \times (G_{ij} \times \cos(\delta_{ij}^c) + B_{ij} \times \sin(\delta_{ij}^c)) i \in N \tag{4}$$

$$Q_{Gi}^0 - (1+\lambda_{\min})(Q_{Di}^0 - \Delta Q_{Di}) = -|V_i^c| \times \sum_{j=1}^{N} \left|V_j^c\right| \times (G_{ij} \times \sin(\delta_{ij}^c) - B_{ij} \times \cos(\delta_{ij}^c)) i \in N \tag{5}$$

$$V_i^{\min} \le V_i \le V_i^{\max}, i \in N_L \tag{6}$$

$$V_i^{c\_\min} \le V_i^c \le V_i^{c\_\max}, i \in N_L \tag{7}$$

$$|P_{ij}| \le P_{ij}^{\max}, \forall ij \in \text{ transmission line} \tag{8}$$

$$\left|P_{ij}^c\right| \le P_{ij}^{c\_\max}, \forall ij \in \text{ transmission line} \tag{9}$$

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max}, i \in N_G \tag{10}$$

$$Q_{Gi}^{c\_\min} \le Q_{Gi}^c \le Q_{Gi}^{c\_\max}, i \in N_G \tag{11}$$

$$\Delta P_{Di}^{\min} \le \Delta P_{Di}^{shed} \le \Delta P_{Di}^{\max}, i \in N_L \tag{12}$$

$$\Delta P_{Di} \times Q_{Di}^0 = \Delta Q_{Di} \times P_{Di}^0 \tag{13}$$

Eqs. (2) and (3) and Eqs. (4) and (5) are load-flow equations without and with considering voltage stability margin, respectively. Eqs. (6)–(11) are technical constraints. The minimum and maximum amounts of dispatchable load at each bus are constrained as given in Eq. (12). The power factor is fixed by Eq. (13). The weighting factor (i.e.ω_i) is determined based on the priorities of the load points. Here, for the sake of simplicity, all weighting factors have been considered at the same value.

The overall structure of the conventional UVLS scheme is illustrated in Figure 1. It should be noted that loading margin (λ) as the voltage stability index has a physical meaning for power system operators. At a given operating point, the amount of additional load in a specific pattern of the load increment that would cause a voltage collapse is called the loading margin [7]. The loading margin is calculated by uniform increment of load toward the collapse or bifurcation point. In this paper, the reactive power limits of generators are considered in computing the loading margin. The type of bifurcation in this situation is named the limit-induced bifurcation (LIB). The saddle node bifurcation (SNB) is the type of bifurcation without considering the reactive power limits of generators.

According to the overall structure of the conventional UVLS scheme, the load shedding strategy is executed in the case of violation of voltage stability criteria. In addition, if some of the operation limits such as maximum and minimum limits of reactive power generation are violated, the load shedding scheme could be executed to restore the voltage stability margin.

3. Undervoltage load shedding with uncertainty modeling

Practically, the information about model and input parameters of the UVLS scheme is not complete. One of the main causes of model inaccuracy is the uncertainties of its parameters. In other words, due to the mismatch between the simulation model and the actual physical model, the results of the conventional UVLS scheme may fail to restore the voltage stability margin. In this section, the conventional deterministic UVLS scheme is modified to include uncertainties of load and line parameters.

IGDT is a nonprobabilistic method for quantifying uncertainty [17]. This method needs no information about the probability density function (PDF) or membership function (MF) of input parameters. The main purpose of IGDT is to guide decision-makers to set the decision variables to values that hedge them against the risk of ignoring uncertainties. The IGDT method has 2 major models, including the robustness model and opportunistic model. In its robustness form, the IGDT technique finds the risk-averse strategy for a conservative decision-maker. The robustness function is the greatest level of uncertainty consistent with no failure while the opportunity function is the least level of uncertainty that entails the possibility of sweeping success [18].

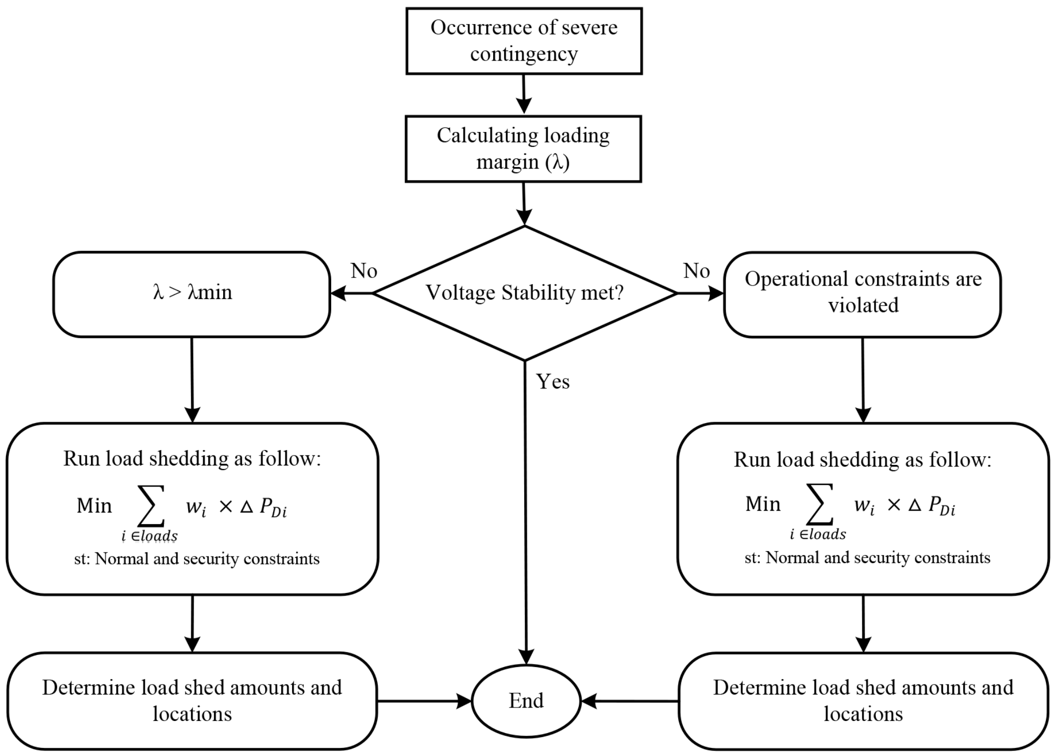

Figure 1. Flowchart of the conventional load shedding.

In this paper, the robust form of IGDT theory is used to model the uncertainties of load and line parameters. Robustness can be defined as a maximum interval on the uncertainty parameter in which all the constraints have been met [19]. In other words, the feasible worst case has been considered for the uncertainty parameter during the most available error.

The uncertainty of input parameters in the IGDT method is usually defined using the envelope bound model as follows [19,20]:

$$X \in U(\alpha, \overline{X}) \tag{14}$$

$$U(\alpha, \overline{X}) = \left| \frac{X - \overline{X}}{\overline{X}} \right| \leq \alpha \tag{15}$$

where α is the uncertainty level of parameter X, $\overline{X}$ is the predicted value of X, and $U(\alpha, \overline{X})$ is the set of all values of X whose deviation from $\overline{X}$ will never be more than $\alpha\overline{X}$ [13].

Indeed, the robust model is used to make robust decisions against severe uncertainties of input parameters. For better clarification, consider a typical optimization function as follows:

$$\begin{aligned} &y = \min f(X, d) \\ &H(X, d) = 0 \\ &G(X, d) \geq 0 \end{aligned} \tag{16}$$

where the function f describes the system model, X is the vector of input uncertain parameters (which are subject to severe uncertainty), d is the vector of decision variables, and y is the output variable. H and G

are the sets of equality and inequality constraints, respectively. The robust model of the IGDT context could be defined as follows. The OF should be always less than a prespecified threshold ℓ_c while the parameter ς is the degree to which the decision-maker tolerates the deterioration of the OF due to forecasting error of input parameter X.

In IGDT, the robustness is defined as the immunity of satisfaction of a predefined constraint. The robustness of a decision d based upon the requirement $\ell_c, \wedge\alpha(d,\ell_c)$, is defined as the maximum value of α at which the decision-maker is sure that the required constraints are always satisfied [17]. The decision-making policy is defined as finding the decision variables, d, that maximize the robustness of the predefined function. A robust form of IGDT for the optimization problem given in Eq. (16) could be expressed as follows.

$$MinOF = f(X,d) \tag{17}$$

Subject to:

$$\wedge\alpha(d,\ell_c) = Max\alpha \tag{18}$$

$$\forall X \in U(\alpha,\overline{X}) \tag{19}$$

$$f(X,d) \leq \ell_c \tag{20}$$

$$\ell_c = (1+\varsigma)\times\overline{y} \tag{21}$$

$$H(X,d) = 0 \tag{22}$$

$$G(X,d) \geq 0 \tag{23}$$

Here, α is the uncertainty level. According to Eqs. (17)–(23), the mathematical expression of load shedding with considering uncertainties of load and line parameters is presented in Eqs. (24)–(31):

$$MinOF{=}(\sum_{i=1}^{N_L}\omega_i \times \Delta P_{Di}) \tag{24}$$

Subject to:

$$\text{Max } \alpha,\beta \tag{25}$$

$$P_{Gi}^0 - P_{Di} + \Delta P_{Di} = |V_i| \times \sum_{j=1}^{N}|V_j| \times (1+\beta)\times(G_{ij}\times\cos(\delta_{ij}) + B_{ij}\times\sin(\delta_{ij}))i \in N \tag{26}$$

$$Q_{Gi}^0 - Q_{Di} + \Delta Q_{Di} = -|V_i| \times \sum_{j=1}^{N}|V_j| \times (1+\beta)\times(G_{ij}\times\sin(\delta_{ij}) - B_{ij}\times\cos(\delta_{ij}))i \in N \tag{27}$$

$$(1+\lambda_{\min})\times(P_{Gi}^0 - P_{Di} + \Delta P_{Di}) = |V_i^c| \times \sum_{j=1}^{N}\left|V_j^c\right| \times (1+\beta)\times(G_{ij}\times\cos(\delta_{ij}^c) + B_{ij}\times\sin(\delta_{ij}^c)) \tag{28}$$

$$Q_{Gi}^0 - (1+\lambda_{\min})\times(Q_{Di} - \Delta Q_{Di}) = -|V_i^c| \times \sum_{j=1}^{N}\left|V_j^c\right| \times (1+\beta)\times(G_{ij}\times\sin(\delta_{ij}^c) - B_{ij}\times\cos(\delta_{ij}^c)) \tag{29}$$

$$P_{Di} = P_{Di}^0 \times (1+\alpha) \tag{30}$$

$$Q_{Di} = Q_{Di}^0 \times (1+\alpha) \tag{31}$$

Additionally, Eqs. (6)–(13) are included as mentioned in Section 2. The aim of this OF is to minimize the emergent load shedding with considering uncertainties of load and line parameters.

4. Simulation results

In this section, the proposed UVLS scheme is implemented in 2 medium and large-scale test systems, including the IEEE 14-bus and IEEE 118-bus test systems, to verify the computational efficiency and optimality of the suggested IGDT-based UVLS scheme. The proposed scheme is formulated as a nonlinear programming (NLP) problem, which is solved using the sequential quadratic programming (SQP) technique. The proposed method acts based on the steady-state model of the power system. Therefore, the problem is not computationally intensive and this procedure can be used for practical applications where load shedding decisions must be made rapidly to avoid cascading failures. The network data for generators, loads, and transmission lines can be found in [7]. For 2 test systems under normal configuration (i.e. no contingency), all the voltage magnitudes and the reactive power generations are inside their normal limits. In this situation, a disturbance causes the outage of lines 1-2 and 2-5 in the IEEE 14-bus system and lines 5-8 and 17-30 in the IEEE 118-bus test system simultaneously. The reason behind the selection of these contingencies is to increase the electrical distance between load and generation buses to construct a voltage instability condition. It should be noted that load shedding is allowed only for a severe double contingency. The network's configurations are illustrated in Figures 2 and 3.

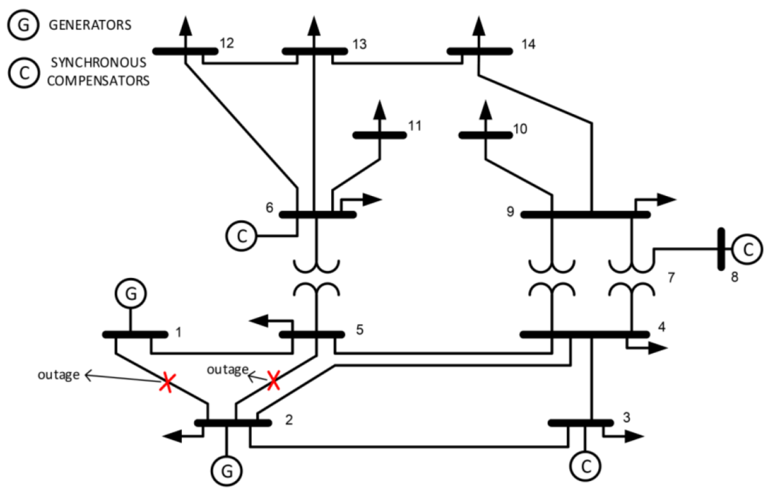

Figure 2. Single-line diagram of IEEE 14-bus test system.

For the IEEE 14-bus test system the 14th bus's P-V curve is illustrated under normal and contingency configuration without (i.e. SNB) and with (i.e. LIB) reactive power generator limits in Figures 4 and 5, respectively. As mentioned before, it has been assumed that a severe contingency, including outage of lines 1-2 and 2-5, occurs simultaneously. It can be seen that the loading margin is reduced from $\lambda_{normal}^{SNB} = 1.443$ to $\lambda_{contingency}^{SNB} = 0.138$ without considering the reactive power limit while the loading margin is reduced from $\lambda_{normal}^{LIB} = 0.077$ to $\lambda_{contingency}^{LIB} = -0.145$. It should be noted that the negative loading margin refers to the disappearance of the operating point after the contingency. The negative margin means that there is no steady-state operating point after the contingency. Therefore, the system moves to the instability point and if there is no control action, available then voltage collapse is inevitable.

The 16th bus's P-V curve for the IEEE 118-bus test system under a normal and severe double contingency including simultaneous outage of lines 5-8 and 17-30 shows that the loading margin is reduced from $\lambda_{normal}^{SNB} = 0.218$ to $\lambda_{contingency}^{SNB} = 0.001$.

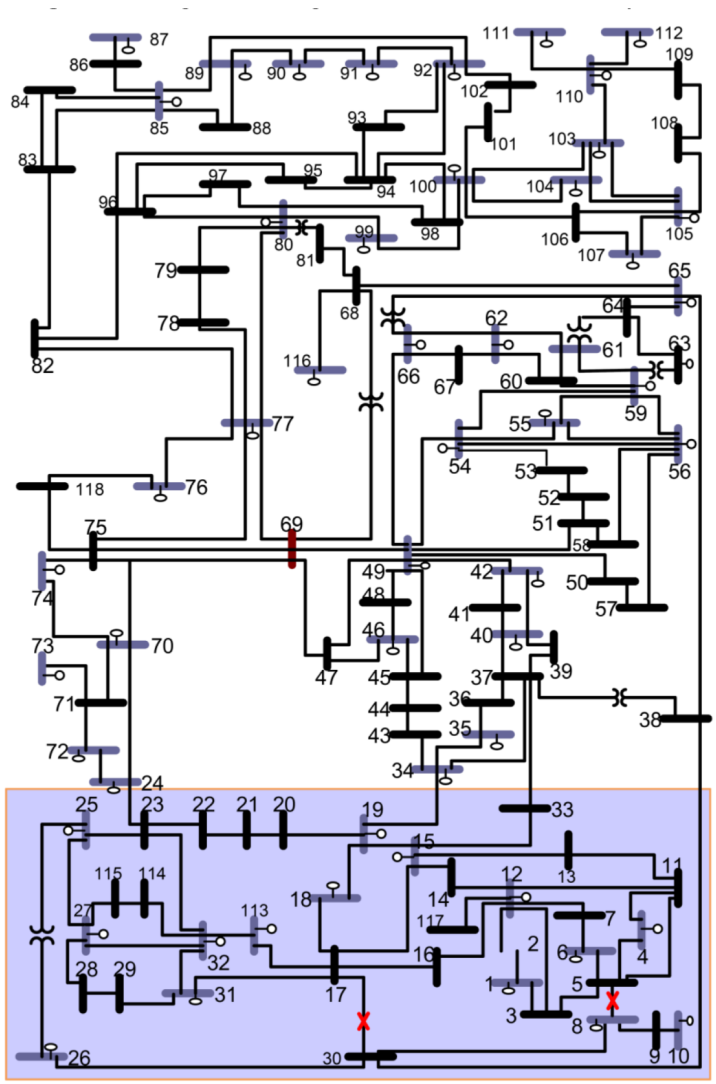

Figure 3. Single-line diagram of IEEE 118-bus test system [21].

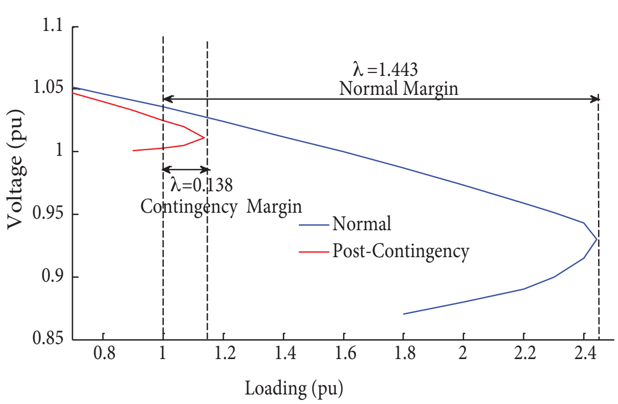

Figure 4. Normal and postcontingency voltage stability margin without considering generator reactive limits (SNB) for the 14th bus of the IEEE 14-bus test system.

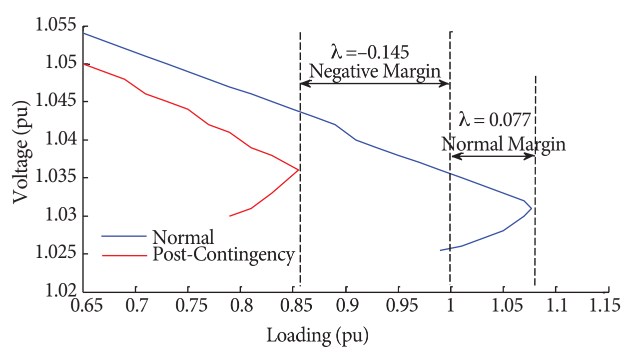

Figure 5. Normal and postcontingency voltage stability margin with considering generator reactive limits (LIB) for the 14th bus of the IEEE 14-bus test system.

The 2 different scenarios, including deterministic conventional UVLS and IGDT-based UVLS schemes, are simulated as given below for both test systems under the mentioned severe contingencies.

4.1. Deterministic conventional UVLS

In this case, the conventional UVLS scheme is simulated over the IEEE 14-bus and the IEEE 118-bus test systems without any uncertainty in load and line parameters. The conventional UVLS scheme is simulated with and without considering voltage magnitudes of the generator's terminal as a control variable. Indeed, the voltage magnitude of the generator's terminal could be changed from $V_{min} = 0.9pu$ to $V_{max} = 1.2pu$ to achieve smaller load shedding. The results of conventional UVLS are illustrated in Figures 6 and 7 for the IEEE 14-bus test system. It can be seen from Figure 6 that the total amount of load shedding is reduced with voltage control significantly. The voltage profile has been shown in Figure 7 for $\lambda^{LIB}_{contingency} = 0.4$.

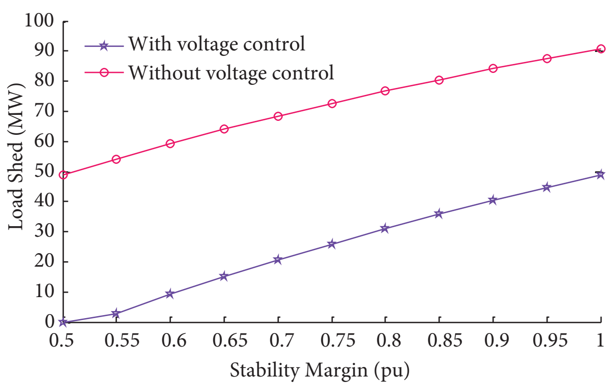

Figure 6. Total amount of load shed with and without considering voltage control for the IEEE 14-bus test system.

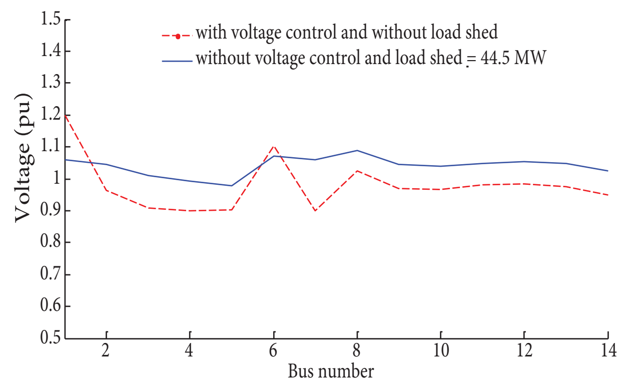

Figure 7. Voltage profile for the IEEE 14-bus test system ($\lambda^{LIB}_{normal} = 0.4$).

The same results are illustrated in Figures 8 and 9 for the IEEE 118-bus test system. It should be noted that all the simulation results are given considering reactive power generator limits.

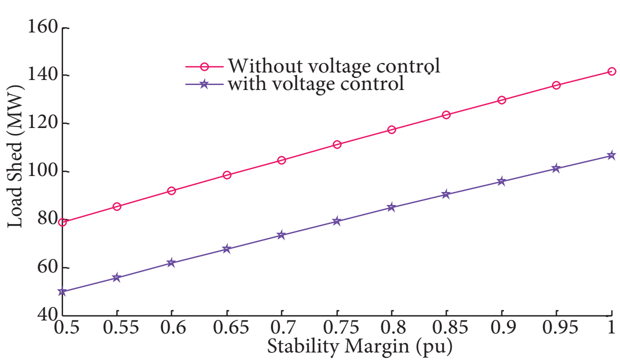

Figure 8. Total amount of load shed with and without considering voltage control for the IEEE 118-bus test system.

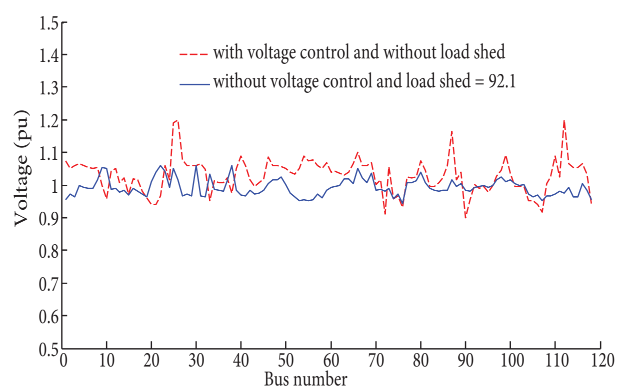

Figure 9. Voltage profile for the IEEE 118-bus test system ($\lambda^{LIB}_{normal} = 0.6$).

4.2. Uncertain IGDT-based UVLS

Practically, the actual values of network parameters (e.g., load, line parameters) are unknown and uncertain. Therefore, it is necessary to consider these uncertainties in an efficient way. In this paper uncertainties of load and line parameters are modeled using the robust IGDT theory for both the IEEE 14-bus and IEEE 118-bus test systems.

The optimal amounts of total load shed for different values of the stability margin without voltage control are given in Table 1 considering 13% uncertainty for load and line parameters. The severe tolerable uncertainty for this network is approximately equal to 13%. In addition to load uncertainty, it can be seen from Table 1 that uncertainty of transmission lines parameters has a significant impact on total load shed and the larger the desired stability margin is, the more load must be shed.

Table 1. Total amount of load shed vs. stability margin without voltage control for the IEEE 14-bus test system.

Stability margin λ_{min} (pu)	Total amount of load shed (MW) with:		
	load uncertainty (α) = 13%	line parameters uncertainty (β) = 13%	simultaneous load and line uncertainty (α, β) = 13%
0	3.3	14.6	31.3
0.05	12.2	14.6	38.6
0.1	20.9	14.6	48
0.15	30.1	14.8	55.8
0.2	39.9	14.8	62.5
0.25	48.3	16.6	68.9
0.3	56	26.8	74.9
0.35	63.2	39	80.5
0.4	69.8	52.2	85.8
0.45	76	64.8	90.8
0.5	81.8	76.8	95.5

In Table 2, total amounts of load shed considering both load and line parameters uncertainties are given for different values of uncertainty level and stability margin without voltage control. As can be seen from Figure 10, by increasing the uncertainty value, the amount of load shed is increased significantly.

Table 2. Total amount of load shed vs. stability margin without voltage control for the IEEE 118-bus test system.

Stability margin λ_{min} (pu)	Total amount of load shed (MW) with considering simultaneous load and line uncertainty (α, β)		
	$\alpha = \beta = 5\%$	$\alpha = \beta = 10\%$	$\alpha = \beta = 13\%$
0	160.3	342.6	459.5
0.05	167	348.7	465.3
0.1	173.6	354.9	471
0.15	180.2	361	476.8
0.2	186.8	367.1	482.6
0.25	193.3	373.2	488.5
0.3	199.8	379.4	494.3
0.35	206.3	385.5	500
0.4	212.7	391.6	505.8
0.45	219.1	397.6	511.6
0.5	225.5	403.7	517.4

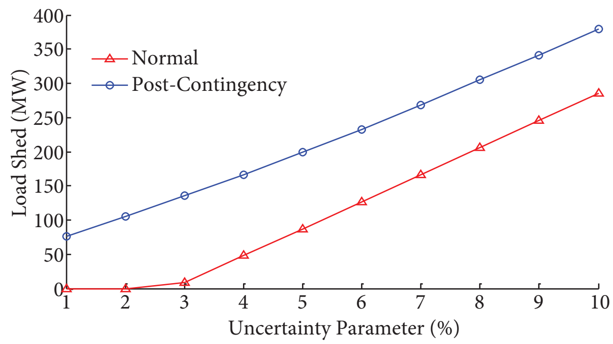

Figure 10. Total amount of load shed with respect to uncertainty parameter for the IEEE 118-bus test system ($\lambda^{LIB}_{normal\&contingency} = 0.5$ and with voltage control).

The total amount of load shed with and without voltage control is given in Table 3 for an uncertainty level of 13% in both load and line parameters ($\alpha = \beta = 13\%$). It can be deduced that the amount of load shedding is reduced significantly by considering voltage control.

Table 3. Total amount of load shed with considering load and line uncertainties for the IEEE 14-bus and IEEE 118-bus test systems.

Stability margin λ_{min} (pu)	Total amount of load shed (MW) with considering simultaneous load and line uncertainty $(\alpha, \beta) = 13\%$			
	Without voltage control $V = V_m$		With voltage control $0.9^{pu} \leq V \leq 1.2^{pu}$	
	14-bus	118-bus	14-bus	118-bus
0.5	95.5	517.4	25.5	494.1
0.6	104.3	528.9	38.5	504.5
0.7	112.2	540.4	50	514.8
0.8	119.2	551.8	60.4	524.9
0.9	125.5	563.1	69.8	534.9
1	131.2	574.3	77.8	544
1.1	136.5	585.5	86.1	554.5
1.2	140.5	596.8	93.2	564.8
1.3	146	607.7	99.8	573.5
1.4	149.8	618.8	105.3	582.8
1.5	154.4	629.6	111.4	592
1.6	157.1	640.2	116.9	602.2
1.7	161.5	651.3	121.3	610.1
1.8	164.8	Infeasible	125.5	619.5
1.9	167.7	Infeasible	129.9	628
2	170.5	Infeasible	133.8	635.9

Moreover, the results of UVLS with and without considering uncertainty have been given in Table 4. For the IEEE 118-bus test system it can be seen that for having a robust load shedding plan it is required to shed more loads.

Finally, as can be seen from Table 5, the proposed UVLS scheme sheds the load at the buses near the contingency area (i.e. as shown in Figure 3).

Table 4. Comparing the deterministic UVLS scheme with the uncertain IGDT-based scheme for the IEEE 14-bus and IEEE 118-bus test systems.

Stability margin λ_{min} (pu)	Total amount of load shed (MW)			
	Without uncertainty (deterministic UVLS)		With considering simultaneous load and line uncertainty = 13% ($\alpha = \beta = 13\%$)	
	14-bus	118-bus	14-bus	118-bus
0.1	0	22.2	48	471
0.2	7.7	37.2	62.5	482.6
0.3	23	51.6	74.9	494.3
0.4	36.8	65.5	85.8	505.8
0.5	48.8	79	95.5	517.4
0.6	59.2	92.1	104.3	528.9
0.7	68.5	104.9	112.2	540.4
0.8	76.7	117.4	119.2	551.8
0.9	84.1	129.6	125.5	563.1
1	90.8	141.7	131.2	574.3

Table 5. Amount of load shed vs. stability margin without voltage control for the IEEE 118-bus test system.

Stability margin λ_{min} (pu)	Amount of load shed (MW) in each bus									
	3	4	6	7	11	13	14	16	18	117
1	0	39	50.4	0	38.1	0.3	0	0	0	13.8
1.2	0	39	52	2.8	47.6	8.5	0	0	0	15.5
1.4	0	39	52	8.5	55.8	16.6	0	0	0	16.9
1.6	0	39	52	12.1	61	24.2	0	6.2	0	17.9
1.8	0	39	52	12	60.8	30.5	6.4	17.3	0.3	17.9
2	0.3	39	52	11.8	60.5	32.2	8.4	19.9	18.5	17.8

5. Conclusions

In this paper, an improved UVLS scheme was proposed to consider the uncertainties of load and line parameters. The proposed scheme models the uncertainty using the IGDT technique. Unlike the other uncertainty modeling techniques, the IGDT-based UVLS scheme does not require information about PDFs of the uncertain parameters. The results illustrate that, besides load uncertainty, the uncertainty of line parameters has a significant impact on load shedding value and the total amount of load shed corresponds with line parameters' uncertainty levels. According to the results, if it is possible to consider the generator voltages as control variables in the proposed UVLS scheme, the amount of load shed is reduced significantly. This algorithm can be used for a variety of network and instability scenarios.

References

[1] Majidi M, Aghamohammadi MR, Manbachi M. New design of intelligent load shedding algorithm based on critical line overloads to reduce network cascading failure risks. Turk J Electr Eng Co 2014; 22: 1395-1409.

[2] Laghari JA, Mokhlis H, Bakar AHA, Hasmaini M. Application of computational intelligence techniques for load shedding in power systems: a review. Energ Convers Manage 2013; 75: 130-140.

[3] Rabiee A, Vanouni M, Parniani M. Optimal reactive power dispatch for improving voltage stability margin using a local voltage stability index. Energ Convers Manage 2012; 59: 66-73.

[4] Popovic DS, Levi VA, Gorecan ZA. Coordination of emergency secondary voltage control and load shedding to prevent voltage instability. IEE Proc-C 1997; 144: 293-300.

[5] Granville S, Mello JCO, Melo ACG. Application of interior point methods to power flow unsolvability. IEEE T Power Syst 1996; 11: 1096-1103.

[6] Jianfeng D, Shuangxi Z, Zongxiang L. A new risk indices based under voltage load shedding scheme. In: IEEE Transmission Distribution Conference and Exhibition; 2005; Dalian, China. pp. 1–5.

[7] Amraee T, Ranjbar AM, Mozafari B, Sadati N. An enhanced under-voltage load-shedding scheme to provide voltage stability. Electr Pow Syst Res 2007; 77: 1038-1046.

[8] Amraee T, Ranjbar AM, Feuillet R. Adaptive under-voltage load shedding scheme using model predictive control. Electr Pow Syst Res 2011; 81: 1507-1513.

[9] Thalassinakis EJ, Dialynas EN, Agoris D. Method combining ANNs and Monte Carlo simulation for the selection of the load shedding protection strategies in autonomous power systems. IEEE T Power Syst 2006; 21: 1574-1582.

[10] Fernandes TSP, Lenzi JR, Mikilita MA. Load shedding strategies using optimal load flow with relaxation of restrictions. IEEE T Power Syst 2008; 23: 712-718.

[11] Saffarian A, Sanaye-Pasand M. Enhancement of power system stability using adaptive combinational load shedding methods. IEEE T Power Syst 2011; 26: 1010-1020.

[12] Tang J, Liu J, Ponci F, Monti A. Adaptive load shedding based on combined frequency and voltage stability assessment using synchrophasor measurements. IEEE T Power Syst 2013; 28: 2035-2047.

[13] Mou X, Li W, Sun T, Rong S, Sun Y. An analytical sensitivity index for load shedding to avoid voltage instability. In: IEEE Power and Energy Society General Meeting; 21–25 July 2013; Vancouver, Canada. pp. 1-5.

[14] Berg GJ, Sharaf TA. System loadability and load shedding. Electr Pow Syst Res 1994; 28: 165-170.

[15] Parker CJ, Morrison IF, Sutanto D. Simulation of load shedding as a corrective action against voltage collapse. Electr Pow Syst Res 1998; 46: 235-241.

[16] El-Sadek MZ, Mahmoud GA, Dessouky MM, Rashed WI. Optimum load shedding for avoiding steady-state voltage instability. Electr Pow Syst Res 1999; 50: 119-123.

[17] Ben-Haim Y. Info-Gap Decision Theory. 2nd ed. San Diego, CA, USA: Academic Press, 2006.

[18] Hipel KW, Ben-Haim Y. Decision making in an uncertain world: information-gap modeling in water resources management. IEEE T Syst Man Cy C 1999; 29: 506-517.

[19] Soroudi A, Ehsan M. IGDT based robust decision making tool for DNOS in load procurement under severe uncertainty. IEEE T Smart Grid 2013; 4: 886-895.

[20] Khairuddin A, Ahmed S, Mustafa M, Zin A, Ahmad H. A novel method for ATC computations in a large-scale power system. IEEE T Power Syst 2004; 19: 1150-1158.

[21] Amraee T, Ranjbar AM, Feuillet R, Mozafari B. System protection scheme for mitigation of cascaded voltage collapses. IET Gener Transm Dis 2009; 3: 242-256.

Nomenclature

Indices

N	Set of all buses
N_L	Set of load buses
N_G	Set of voltage controlled nodes
"c"	Index referring to the collapse point
"o"	Index referring to the initial state

Variables

$V_i\angle\delta_i$	Voltage phasor at bus i
$V^{\min/\max}$	Lower/upper limits of voltage magnitude
G_{ij}	Conductance between buses i, j
B_{ij}	Susceptance between buses i, j
δ_{ij}	Difference of voltage angle at buses i, j
ω_i	Weighting factor for load shedding of bus i
P_{Gi}/Q_{Gi}	Active/reactive power production at bus$i$
P_{Di}/Q_{Di}	Active/reactive power demand at bus$i$
P_{ij}	Active power flow between buses i, j
$P_{ij}^{\max}$	Upper limit of active power flow between buses i, j
$Q_{Gi}^{\min/\max}$	Lower/upper limits of reactive power production at bus$i$
ΔP_{Di}	Active load shedding at bus i
ΔQ_{Di}	Reactive load shedding at bus i
$\lambda_{\min}$	Minimum loading margin
α	Load uncertainty level
β	Line parameters' uncertainty level
$\overline{X}$	Predicted value of X
$\overline{y}$	Predicted value of y

Parameters

X	Uncertain parameter
ℓ_c	A prespecified threshold of objective function
ς	The degree that tolerates the deterioration of objective function