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New design of intelligent load shedding algorithm based on critical line overloads to reduce network cascading failure risks

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Abstract: This paper presents a new algorithm for intelligent load shedding based on critical line overloads. This method can increase the efficiency for determining critical lines and sensitive loads. Hence, when critical lines expose an overload, the system will run an intelligent load shedding, which considerably curtails the sensitive loads of critical transmission lines. This can fully reduce the harmful risks of power system cascading failures that impose extensive losses to the economy of a country. For testing the accuracy and applicability of this technique, the IEEE 39-bus test system is applied as a standard case study.

Key words: Cascading failures, intelligent load shedding, critical line over-load, sensitivity analysis

1. Introduction

Power system load shedding can be executed using various types of techniques, but the main advantage of the method proposed in this paper is that it can detect the need for network load shedding by applying system variables, such as the voltage and frequency, based on the network failure events (generator or line outages). This is relevant for local as well as integrated power system networks.

One of the best known methods of load shedding is voltage load shedding. When an extreme failure event occurs in a network, voltage load shedding can be applied as an economical method for preventing voltage collapse in order to maximize the power system's loadability. In this technique, different bus voltages are considered as overloads or voltage collapse indices [1].

A second common load shedding technique is frequency load shedding. Imbalanced active power in a system leads to frequency changes. Therefore, any type of active overload or generation reduction in a system will show itself as a frequency change. Additionally, the frequencies of all of the network nodes in the overload times are almost the same. Hence, any frequency variation will spread through the network directly [2]. Thus, it is an appropriate idea to apply a frequency index for overload detection. In this load shedding method, conventional [3] and innovational techniques, such as midadaptive [4] and adaptive [5–10] techniques, are considered thoroughly. What have been lacking in previous studies are the optimal location of the loads (in load shedding studies) and the generating unit's control design, which this paper considers.

In addition to the frequency value, new techniques have been applied for frequency-based load shedding. New load shedding schemes use frequency derivatives in addition to the frequency values [11]. Another modern

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load shedding technique, which has been employed in advanced networks, is intelligent load shedding. This technique operates based on network parameters such as transmission line flows, system topology, and computer network management systems [12]. Recently, most of the applied load shedding techniques in networks have followed a series of standards that are commonly based on conventional techniques. In accordance with these standards/protocols, when a critical frequency occurs, a specified percentage of the system's overall load will be curtailed in a determined delay. Loads have been classified as urgent, semiurgent, and unnecessary in load shedding [13]. This paper is not primarily interested in the optimal placement of the load for load shedding, which is based on the intensity of the fault and the situation of it. Some papers have applied centralized load shedding approaches [14–17], but most of them have not considered combinatorial faults and cascading failures. Thus, this paper proposes a new load shedding algorithm that considers these events in power systems. The other argument, which is worthy of study in load shedding methods, is finding the optimal place for the load shedding proportional to the fault type and the fault occurrence location. The authors in [18] have considered this problem based on the V-Q margins of the buses. They have used under frequency load shedding (UFLS) for determining the optimal loads for the load shedding. Therefore, the sensitivity analysis is applied here in order to assess this problem more thoroughly.

Three new load shedding techniques have been presented in [19] based on adaptive combinational load shedding methods for power system stability. In a power system disturbance, the deviation of the frequency and voltage quantities are related to each other. Hence, it is more logical to consider combinational load shedding methods, which are dependent on both frequency and voltage, instead of designing 2 independent under-frequency and under-voltage load shed schemes. In the proposed combinational methods, load shedding decisions are based on the combination of measured frequency and voltage at relay locations. In these methods, load shedding is selected as a function of the disturbance location, either directly or indirectly. Since the load shedding decision is made locally based on local measured quantities, no communication link is required for implementing these methods. It should be noted that this paper is not focused on selecting the most economical location for the load shedding amounts. The objective is to rescue the system during severe combinational events.

The proposed method in [20] employed the Monte Carlo approach to evaluate the impact of the step size variations and nonresponding turbine-governor systems on the UFLS scheme performances. This approach was applied using 2 isolated Spanish power systems of different sizes. The step size variations and nonresponding turbine-governor systems have been modeled by different probable density functions, and their impacts on the UFLS schemes of 2 power systems have been analyzed and compared. The shed load at each stage for the under-frequency relay (81L) has been determined in [21]. The genetic algorithm (GA) has been employed to minimize the shed load and maximize the lowest swing frequency. Penalty functions and chromosomes with various lengths are utilized in the GA to determine the optimal shed loads at all of the stages. The uncertainty in the bus loads has been modeled by a fuzzy set. A stand-alone power system with diesel and wind-power generators has been considered to demonstrate the applicability of the method.

Notwithstanding previous efforts, this paper provides a new efficient approach based on the effects of critical loads and generators on a line, which is more capable of producing blackouts. Another advantage of this approach is with regards to the system's protective devices, such as the distance relays of the transmission lines for intelligent optimal load shedding. Additionally, feasible algorithm operation is investigated at various load levels. These factors have made the algorithms more accurate and applicable.

A new intelligent load shedding algorithm, which this paper presents, is based on critical line overloads. For this reason, 2 fundamental algorithms are proposed. The main difference between these 2 new algorithms is their technique for reaching adequate detections regarding critical line overloads. In the first algorithm, the detected line flow of a constant set-point called the critical flow is the basis for determining critical line overloads. In the second algorithm, detection is based on zone-3 activities of the distance relay.

In order to implement the presented algorithms, a preliminary plan is explained according to determinations of blackout scenarios and network cascading failures. A set of cascading failures that occur after an initial failure event lead to a slight or total collapse/blackout called a blackout scenario. Each blackout scenario consists of failure events, such as line outages, transformer outages, and generator outages. On the other hand, sets of failures (line, transformer, and generator outages) that automatically occur in sequences after the initial failure event (because of network weaknesses and network limit violations) are called cascading failures.

Preventing lines from facing overloads in a blackout scenario may lead to the prevention of power system cascading failures and system blackouts. The transmission of power along critical lines depends on network load and generation. Thus, adequate load shedding prevents distance relays of critical lines from operating at a time when the critical lines get overloaded.

In this paper, widespread statistical samples have been analyzed via 7 load levels in the IEEE 39-bus test system to detect critical lines that participate in most blackout scenarios. For all of the existing blackout scenarios (84 scenarios), convenient indices have been determined for the critical line detection. Moreover, loads and generators that have the most impact on the detected line flows have been assessed based on a sensitivity analysis technique. For implementing and simulating the abovementioned algorithms, the DIgSILENT software is applied. In this paper, load shedding is based on transmission line loads. Thus, if a load curtailment occurs in a network (in generation or transmission sections), this technique can respond to it immediately and resolve the immense negative consequences of overloads. For instance, when a generation trip happens, the network frequency will drop, and the frequency relays will operate rapidly. Hence, the presented algorithms have been tested in a network that has simulated frequency, voltage, overcurrent, and distance relays. Furthermore, excitation systems, as well as generator governors of the considered network, have been regulated according to power system standards in order to observe the efficiency of the proposed algorithms in real power systems.

2. Detecting critical lines

Load level is defined as the summation of the loads existing in the network. The IEEE 39-bus test system has a 5764 MW load level. According to the growth of the load consumption in power systems, it is necessary to consider the load growth effects when designing comprehensive protection algorithms. In order to study the effects of the total network's load growth on the proposed algorithm, 7 load steps have been applied to model a uniform load growth. Thus, the system loads have been increased by applying an identical load scaling factor to achieve the system load levels (5955 MW, 6143 MW, 6335 MW, 6524 MW, 6716 MW, and 6905 MW). However, the generation amount will be increased based on the generator's power charts for the power flow convergence. The reason for assuming 7 load levels is to simulate situations in which the transmission lines are faced with overloads. This can happen through increasing the load and the generation to some steps (7 steps in this paper).

Thus, all transmission lines are exposed under a 3-phase short-circuit event at 7 load levels (5764 MW, 5955 MW, 6143 MW, 6335 MW, 6524 MW, 6716 MW, and 6905 MW), and cascading events, which lead to islanding and a complete network collapse, are recorded precisely in the case study. A 3-phase short-circuit fault is considered because it can impose more severe tension on the system than other faults. It should be mentioned that imposing a short circuit on all transmission lines does not necessarily lead the network to a critical mode. Thus, by imposing a short circuit to 7 load steps, only 84 blackout scenarios have been created.

For instance, the result of the 5764 MW load level is given in Table 1, where it is seen that only 8 lines [(16, 19), (16, 21), (21, 22), (26, 27), (26, 28), (26, 29), (28, 29), (2, 3)] are able to create blackouts. Thus, 8 out of 84 blackout scenarios are devoted to the 5764 MW load level. For instance, the outage of line-(928, 29) has 3 cascading events. First, the relay of bus-26, side of line-(26, 29), operates. Next, the relay of bus-26, side of line-(26, 28), operates, and finally generator-38 will shut down. In this cascading failure, frequency relays do not operate, but blackout when the value of 449 MW is being created in an island.

Table 1. Blackout scenarios at the 5764 MW load level.

	Scenario1	Scenario2	Scenario3	Scenario4	Scenario5	Scenario6	Scenario7	Scenario8
Line numbers	19, 16	21, 16	22, 21	27, 26	28, 26	29, 26	28, 29	3, 2
Events numbers (line and generator tripping)	2	1	10	4	2	2	3	6
Load shedding due to frequency relay	0	0	157	0	0	0	0	199
Load shedding due to islanding	624	0	2039	0	449	449	449	609.8
Islanding no.	2	2	5	2	2	2	2	3
Event 1	34	23_24 B24	23_24 B24	3_2 B2	29_26 B26	28_26 B28	29_26 B26	1_2 B2
Event 2	33		3_2 B2	3_2 B3	38	38	28_26 B26	26_27 B27
Event 3			16_19 B19	1_2 B2			38	30
Event 4			17_27 B27	30				37
Event 5			28_26 B28					25_26 B26
Event 6			1_2 B2					38
Event 7			3_4 B4					
Event 8			14_15 B14					
Event 9			34					
Event 10			33					

Based on the different scenarios and studies of the IEEE 39-bus test system, 2 indices are applied for detecting critical transmission lines:

- Presence index (PI): is in most blackout scenarios as a continuum of a cascading failure chain.
- Presence order (PO) index: is the initial failure event among all of the cascading failures.

The PI defines the number of line outages in the different blackout scenarios as a continuum of the cascading failure chain, corresponding to a blackout scenario. The PO index represents the situation of the line outages in a cascading failure chain. For instance, if the outage of a transmission line is an event after the initial disturbance (0), its order will be (1). The PO index can be obtained for a line outage in any load level through a summation of the mentioned line order with blackout scenarios related to the load level. Therefore, if the number of the outage participation of a transmission line is more in the blackout scenarios, the role of this line in creating the cascading failures and blackout expansion will be more. In other words, when the PO value is high, it presents the rate of a line in a critical situation. Both the PI and PO indices are considered in the algorithms of this paper to find optimal solutions. For detecting critical transmission lines, which have more influence on cascading failure expansion, the algorithm selects the lines with a lower PO among the set of lines that have higher PI values.

As an example, a 5764 MW load level has 8 blackout scenarios and the outage of line-(2, 1) has an impact on the scenarios as a ring of cascading chain failures (highlighted in Table 1). It has been the 6th event in the 3rd scenario, the 1st event in the 8th scenario, and the 3rd event in the 4th scenario. Therefore, the numbers inside of and behind the bracket are 10 (10 = 1 + 3 + 6) and 3, respectively. In order to determine the role and participation factor of each line in the blackout scenarios, the number of outages and the presence order of each line in all of the levels are presented in the last column of Table 2. For instance, Table 2 shows the value of 29 (136) for line (23, 24). This means that the outage of this line has participated 29 times in scenarios with a presence order of 136. Thus, the information in Table 2 has PI (PO) formats.

Table 2. The role of the line outages in the different blackout scenarios according to the PI and PO indices.

Load level	5764	5955	6143	6335	6524	6716	6905	Total
No. of blackout scenarios	8	11	11	13	13	14	14	84
Line outage	PI (PO)							
23-24	2(2)	2(2)	5(30)	6(35)	5(23)	5(24)	4(20)	29(136)
3-2	2(3)	6(10)	5(8)	7(11)	7(11)	9(13)	9(13)	45(69)
16-19	1(3)	3(13)	4(30)	7(50)	6(48)	6(37)	5(25)	32(206)
17-27	1(4)	2(11)	1(4)	3(16)	3(17)	2(10)	2(12)	14(74)
28-26	3(8)	6(32)	8(34)	8(38)	7(29)	8(44)	9(50)	49(235)
1-2	3(10)	6(26)	5(17)	6(28)	6(30)	7(28)	7(27)	40(166)
3-4	1(7)	4(36)	4(40)	8(81)	7(75)	7(73)	7(79)	38(391)
14-15	1(8)	3(31)	1(9)	4(47)	3(34)	5(59)	5(62)	22(250)
29-26	2(2)	4(12)	7(34)	7(37)	6(35)	4(32)	4(18)	34(170)
26-27	1(2)	3(7)	4(9)	6(21)	7(35)	8(35)	8(36)	37(145)
25-26	1(5)	3(36)	1(6)	1(17)	1(14)	6(52)	6(55)	19(185)
18-17	0(0)	3(24)	1(5)	2(22)	2(22)	2(17)	4(41)	14(131)
9-8	0(0)	2(16)	2(20)	2(23)	4(40)	3(17)	4(34)	17(150)
16-15	0(0)	3(21)	3(20)	3(20)	3(19)	5(37)	5(46)	22(163)
22-21	0(0)	1(1)	0(0)	1(1)	1(1)	1(1)	1(1)	5(5)
16-17	0(0)	1(7)	0(0)	0(0)	0(0)	1(12)	4(46)	6(65)
6-11	0(0)	1(11)	2(20)	1(19)	1(17)	0(0)	1(15)	6(82)
5-4	0(0)	0(0)	1(9)	0(0)	0(0)	0(0)	0(0)	1(9)
16-21	0(0)	0(0)	3(21)	3(21)	2(17)	3(23)	2(12)	13(94)
16-24	0(0)	0(0)	1(11)	1(10)	2(27)	4(41)	6(53)	14(142)
18-3	0(0)	0(0)	0(0)	1(6)	2(13)	2(16)	1(7)	6(42)
21-19	0(0)	0(0)	0(0)	1(8)	1(8)	0(0)	1(10)	3(26)
25-2	0(0)	0(0)	0(0)	0(0)	1(18)	0(0)	0(0)	1(18)
39-1	0(0)	0(0)	0(0)	0(0)	0(0)	1(9)	1(10)	2(19)

According to Table 2, transmission lines (2, 3), (26, 28), (2, 1), and (4, 3), with PI values of 45, 49, 40, and 38, are the most effect transmission lines for systems in cascading failure mode. As mentioned before, critical lines have maximum PI but minimum PO values. Hence, among these 4 mentioned lines, only lines (2, 3) and (2, 1), with PO values of 69 and 166, are considered as the critical lines of the IEEE 39-bus test system.

3. Detecting critical loads

Critical loads are loads that have the most influence on the critical transmission line flow reduction by curtailing them. In addition to load shedding, generation rescheduling should be employed in order to regulate the balance between the load and the generation sides. Therefore, an adequate algorithm has to find generators with the most influence on critical transmission line flows. After determining the critical lines, mutual loads and generators should be selected. For these reasons, a sensitivity analysis technique is used. The sensitivity factors of the transmission line flows toward the load and generation buses can be obtained by applying load flow equations.

The value of θ can be obtained through Eq. (1). Next, this value is placed in Eq. (2):

$$P = A.\theta, \tag{1}$$

$$F = B.\theta, \tag{2}$$

where P is the injected power to the bus's matrix, F is the transmission line flow matrix, θ is the voltage angle of the buses, A is the linear Jacobian matrix for active power with a (n – 1) × (n – 1) dimension, B is the admittance matrix of lines with m × (n – 1), n is the number of buses, and m is the number of lines.

$$\theta = A^{-1}P \tag{3}$$

$$F = BA^{-1}P = CP \tag{4}$$

$$F = CP \tag{5}$$

The matrix *Cm × (n – 1)* presents the relation between the active line flows and the active injected power to the buses. The sensitivity of line-k towards the injected power to the buses can be calculated based on Eq. (5):

$$F_k = \sum_{i=1}^{n} C_{ki} P_i, \tag{6}$$

$$\Delta F_k = \sum C_{ki} \Delta P_i. \tag{7}$$

For determining the sensitivity of the transmission line (DF) related to bus-K towards the load changes of bus-i, C_{Ki} has been applied in the C matrix. For assessing this sensitivity in relation to the generator power changes of bus-j, C_{Kj} has been used. The critical buses corresponding to the critical transmission lines of (2, 1) and (2, 3) can be found through Eq. (8) to Eq. (14).

$$DF_{Ki} = C_{ki} = \frac{\Delta P_K}{\Delta P_{Li}}, \tag{8}$$

$$DF_{Kj} = C_{kj} = \frac{\Delta P_K}{\Delta P_{Gj}}, \tag{9}$$

$$\Delta P_K = DF_{Ki}.\Delta P_{Li}, \tag{10}$$

$$\Delta P_K = DF_{Kj}.\Delta P_{Gj}, \tag{11}$$

$$\Delta P_K = DF_{Ki}.\Delta P_{Li} + DF_{Kj}.\Delta P_{Gj}, \tag{12}$$

$$\left\{ \begin{array}{l} \Delta P_{Kij} = (DF_{Ki} - DF_{Kj})\Delta P_{Li} \\ \Delta P_{Kij} = (DF_{Kj} - DF_{Ki})\Delta P_{Gj} \end{array} \right. , \tag{13}$$

$$\left\{ \begin{array}{l} DF_{Kij} = DF_{Ki} - DF_{Kj} \\ DF_{Kij} = DF_{Kj} - DF_{Ki} \end{array} \right. . \tag{14}$$

Here, DF_{Kij} is the flow sensitivity of line-K towards the changes of the load in bus-i and the generation in bus-j.

Table 3 presents a sensitivity analysis for line-(2, 3). The load and generation, which have the maximum sensitivity on critical lines, consider critical load and critical generation.

Table 3. Sensitivity matrix of line- (2, 3) related to the injected powers of the buses.

Load bus	Generator bus no.	30	31	32	33	34	35	36	37	38	39
	C_{kj}	0	0.631	0.644	0.635	0.635	0.635	0.635	0.074	0.353	0.313
3	0.798	0.798	0.167	0.154	0.163	0.163	0.163	0.163	0.724	0.445	0.485
4	0.681	0.681	0.05	0.037	0.046	0.046	0.046	0.046	0.607	0.329	0.368
7	0.613	0.613	–0.018	–0.031	–0.022	–0.022	–0.022	–0.022	0.539	0.26	0.299
8	0.603	0.603	–0.028	–0.04	–0.032	–0.032	–0.032	–0.032	0.529	0.251	0.29
12	0.644	0.644	0.012	0	0.009	0.009	0.009	0.009	0.57	0.291	0.331
15	0.642	0.642	0.011	–0.002	0.007	0.007	0.007	0.007	0.568	0.29	0.329
16	0.635	0.635	0.004	–0.009	0	0	0	0	0.561	0.283	0.322
18	0.693	0.693	0.062	0.049	0.058	0.058	0.058	0.058	0.619	0.341	0.38
20	0.635	0.635	0.004	–0.009	0	0	0	0	0.561	0.283	0.322
21	0.635	0.635	0.004	–0.009	0	0	0	0	0.561	0.283	0.322
23	0.635	0.635	0.004	–0.009	0	0	0	0	0.561	0.283	0.322
24	0.635	0.635	0.004	–0.009	0	0	0	0	0.561	0.283	0.322
25	0.074	0.074	–0.558	–0.57	–0.561	–0.561	–0.561	–0.561	0	–0.279	–0.239
26	0.353	0.353	–0.279	–0.291	–0.283	–0.283	–0.283	–0.283	0.279	0	0.039
27	0.479	0.479	–0.152	–0.164	–0.156	–0.156	–0.156	–0.156	0.405	0.127	0.166
28	0.353	0.353	–0.279	–0.291	–0.283	–0.283	–0.283	–0.283	0.279	0	0.039
29	0.353	0.353	–0.279	–0.291	–0.283	–0.283	–0.283	–0.283	0.279	0	0.039
31	0.631	0.631	0	–0.012	–0.004	–0.004	–0.004	–0.004	0.557	0.279	0.318
39	0.313	0.313	–0.318	–0.331	–0.322	–0.322	–0.322	–0.322	0.239	–0.039	0

In this case, load-3 and generator-30, with a sensitivity value of 0.798, are the load and generation with a maximum effect on line-(2, 3). Load-18 and generator-30 (sensitivity: 0.693), load-4 and generator-30 (sensitivity: 0.681), and load-12 and generator-30 (sensitivity: 0.644) are the effective loads and generations for line-(2, 3). The C_{ki} and C_{kj} values, which are calculated from the C matrix, are shown in Table 3 (for instance, $C_{ki} = 0.798$ for bus-3, $C_{kj} = 0.631$ for bus-31). The values inside of Table 3 are $DF_{kij}s$, which are calculated from Eq. (14). They represent the sensitivity of line-k to the load variations of bus-i and the generation of bus-j. As an example, the sensitivity value for line-(2, 3) to the load variation of bus-3 and the generation of bus-31 is equal to 0.167. Hence, the load and generation sets (30, 3), (30, 18), (30, 4), and (30, 12) are critical load and generator sets, iteratively, which are employed in the load shedding algorithm of line-(2, 3). Load and generation sets (7, 37), (8, 37), and (37, 39) are critical loads and generators for the backup load shedding algorithm of line-(2, 1). This information is presented in Tables 4 and 5.

Table 4. Sensitivity of the mutual load and critical generation related to the critical line-(2, 3).

Sensitivity	Load bus no.	Generator bus no.
0.79	3	30
0.69	18	30
0.68	4	30
0.64	12	30

Table 5. Sensitivity of the mutual load and critical generation related to the critical line-(2, 1).

Sensitivity	Load bus no.	Generator bus no.
0.22	7	37
0.24	8	37
0.6	39	37

4. First proposed intelligent load shedding algorithm

The critical flow for each transmission line is the amount of power that flows through a specific line [megavolt ampere (MVA)]. If the line flow exceeds this amount, the seen impedance of the distance relays at the beginning of the line will be placed in zone-3 of the relay.

Thus, if the impedance stays in zone-3 for a given time, the distance relay of zone-3 will operate, and the transmission line will be curtailed. The critical flow of each transmission line will be obtained based on its zone-3 distance relay regulations (MVA).

Therefore, the amount of flow for each transmission line is approximately constant and can be determined according to the minimum flow that lets the impedance enter zone-3.

It should be mentioned that different line flows can be directed to zone-3 of the relay, according to different scenarios. Thus, the minimum line flow that enters zone-3 is determined as the critical line flow. When the algorithm detects a critical line flow, it will send signals to both the load and the generator. Changing their values in the same magnitudes and directions can have a maximum influence on the critical line flow. Hence, the flow of the critical line will be decreased by reducing the load and generation. One of the issues that exist with this technique is the critical flow for line-(2, 3). This amount varies in different scenarios. In other words, the flow that activates the zone-3 distance relay varies in different scenarios, but the algorithm assumes that the critical flows in this scenario are the same as those in other scenarios. This can cause other issues, such as improper load shedding in scenarios that do not cause network partial/total blackouts.

In other words, when the minimum flow (which activates zone-3) is considered as a critical flow (along all existing paths) shown in Figure 1, an unnecessary load shedding may occur on other scenarios that have more activation flows. These scenarios are not capable of creating partial or total blackouts. The minimum critical flow for all of the scenarios of line-(2, 3) is equal to 580 MVA. If this value is considered as the operational set-point of the algorithm, it will operate in conditions in which the transmitted flow of the line is more than this set-point value. For instance, if a 3-phase short circuit occurs in line-(4, 3) for a load level of 5764 MW, the flow of line-(2, 3) will reach 585 MVA, but it will not lead to a zone-3 distance relay of line-(2, 3)'s operation. In contrast, a short circuit on line-(4, 3) does not cause blackout scenarios based on Table 1. In this case, unnecessary load shedding will occur according to the presented algorithm.

5. Second proposed intelligent load shedding algorithm

In this algorithm, the activation command of the load shedding is based on the distance relay activation in zone-3. Therefore, the overloads of critical lines can be detected based on an impedance of the distance relay of zone-3 in different scenarios. On the other hand, the distance relay in zone-3 can be activated through a fault in the network. For comparing these 2 situations with each other, the intelligent load shedding algorithm applies the transmission line's active power signal.

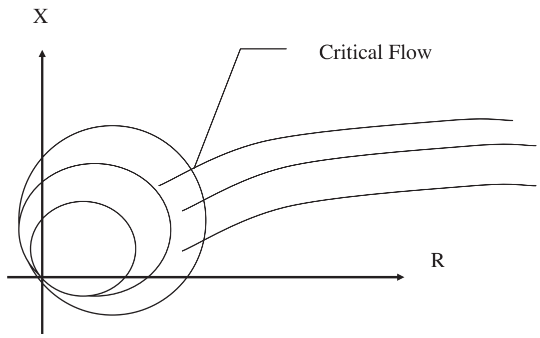


Figure 1. Distance relay characteristics curve.

Hence, the operation of the intelligent load shedding algorithm is based on the distance relay activation in zone-3 and the increasing active power transmission of the critical line from its critical amount. If a fault occurs in the network and the main relays do not operate, the backup protection will be operated through the distance relay in zone-3. In this situation, the intelligent load shedding algorithm cannot operate because the transmitted active power of the critical line is reduced. Considering Figure 2, the algorithm's operation can be regulated based on 2 substantial constraints:

- When the distance relay in zone-3 of the critical line operates.
- When the transmitted active power of the critical line exceeds its critical amount.

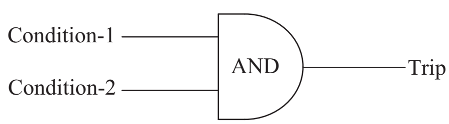


Figure 2. Logical relation between the input signals of the intelligent load shedding algorithm based on the zone-3 operation signal.

The the critical flow of line-(2, 3) is 580 MVA. Hence, its transmitted active power will be 200 MW. If a short-circuit fault occurs in a transmission line of the IEEE 39-bus test system, the distance relay in zone-3 of this line will send a trip command after 100 ms, but if a fault occurs in other parts of network, which activates the distance relay in zone-3 and continues for 700 ms, a trip command will be sent. It should be mentioned that the operating time of the distance relay in zone-3 can be different in networks, such as 400 kV and 230 kV. Moreover, the operating time of the breakers is considerable and should be assessed in any load shedding approach.

Therefore, the intelligent load shedding algorithm can be regulated to curtail the loads and generations between 100 ms and 700 ms in critical buses. By considering different scenarios that factor the operating time of the distance relays in zone-3, along with the tripping time of the breakers in the case study, a 265 ms delay is calculated as an optimum delay for protection from all of the blackout scenarios. If the distance relay in zone-3 operates, it continues operation until 265 ms. When the active power of the critical line exceeds the critical amount, the first step of the load shedding/generation rescheduling will be executed. If the distance relay in zone-3 is still active after 20 ms of the 1st step, the 2nd step of the load shedding/generation rescheduling will be run. This process continues iteratively until the last effective loads reduce the line flows. At this time, the distance relay will be reactivated by the algorithm. Figure 3 illustrates the load shedding algorithm for the 2 presented steps. The remaining load shedding continues with 20 ms delays until the distance relay in zone-3 is deactivated.

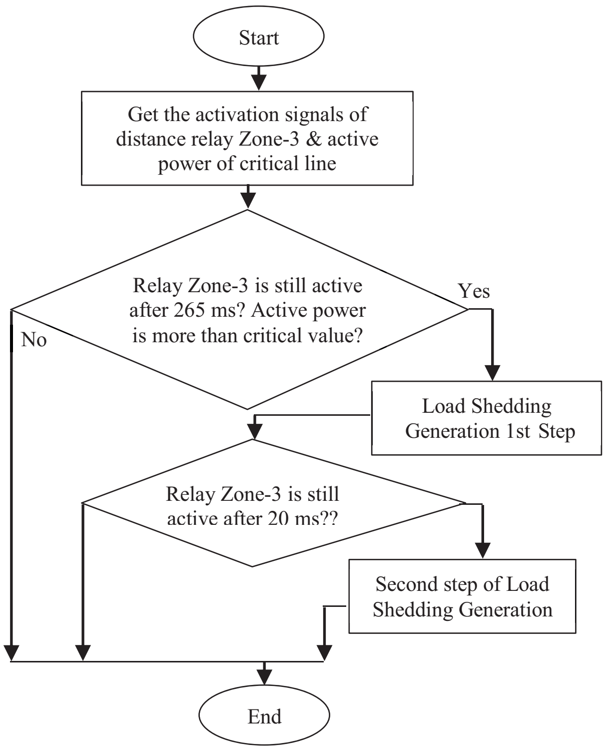


Figure 3. Proposed intelligent load shedding algorithm based on the zone-3 signal of the distance relay.

As continuous load shedding in a network is impossible, the existing loads in the critical buses should be categorized as proper feeders. This can help the load shedding to send a trip signal to a feeder at each load shedding step, to open the related breaker for each feeder. The existing load feeders in the critical buses are categorized based on the critical line flow threshold at the distance relay in zone-3's operating time. In other words, 10% of the determined critical line flow will be reduced at each load shedding step. Table 6 represents the critical load feeder categories.

Table 6. Critical load feeder categories.

Critical load bus no.	3	4	18	12	7	8	39
No. of feeders	4	5	2	2	1	1	10

This algorithm is written in the domain specific language (DSL) programming language in DIgSILENT software, and is simulated as a critical transmission line-(2, 3). The results show that the algorithm performs perfectly in all 84 blackout scenarios, except when a short circuit occurs in line-(2, 3) itself and in line-(27, 26). Thus, for solving the problems of these 2 scenarios, the algorithm is being applied for line-(2, 1) as a backup algorithm.

If a short circuit occurs in line-(2, 3), the transmitted active power will be reduced. Thus, the load shedding algorithm will not operate. If a short circuit occurs in line-(27, 26), the discharged energy in the system will reach a limit that makes it necessary to keep the second critical line from outage, as well as line-(2, 3).

The backup algorithm sends the operating commands based on 3 conditions, and Figure 4 presents their logical relations:

- When the exchanged line-(2, 3)'s power is zero (line-(2, 3)'s relay operates).
- When the exchanged line-(27, 26)'s power is zero (line-(27, 26)'s relay operates).
- When the distance relay in zone-3 of line-(2, 1) operates.

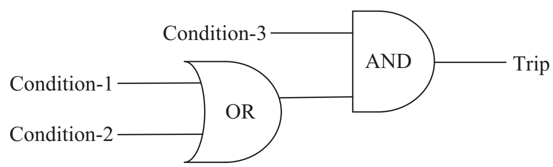


Figure 4. Logical relations between the input signals of the intelligent backup algorithm of line-(2, 1) based on the distance relay of zone-3.

For implementing the proposed algorithm, the operators should apply rapid communication systems, such as the global positioning system, in order to send adequate signals in less than a time cycle. Moreover, by installing the load shedding relays at the beginning of the high voltage distribution feeders, and by designing the generation rescheduling relays as power station control cycles, this algorithm can be employed as an applicable method for decreasing the cascading failures of power systems. Figures 5, 6, and 7 present the cascading failures, total load shedding, and number of islandings with comparison curves in the 7 load levels and 2 states [with/without the proposed intelligent algorithm (IA)].

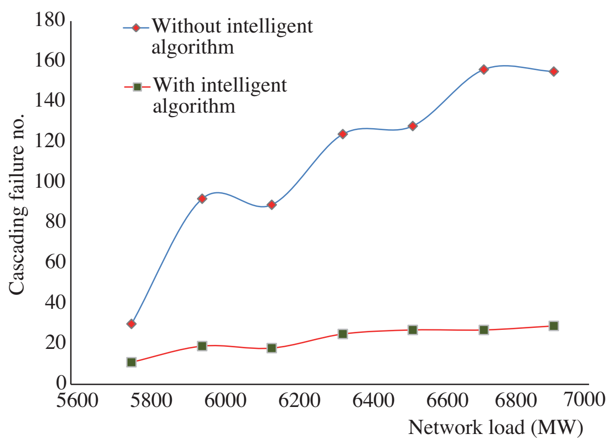


Figure 5. Cascading failure curves in the 7 load levels and system states.

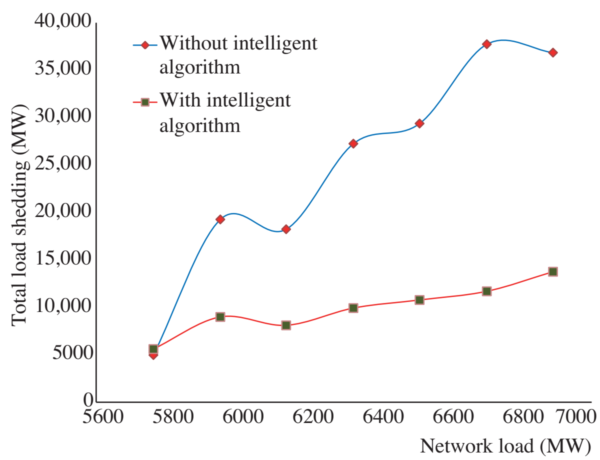


Figure 6. Total load shedding curves in the 7 load levels and system states.

It should be mentioned that this paper used the IEEE 39-bus test system as a case study for checking the accuracy of the proposed algorithm. Therefore, it is possible to implement this algorithm on any electrical power network. There is a further point that deserves some attention here. In order to implement the proposed algorithm on other networks efficiently, the first step is to model the dynamic behaviors of all of the network components, such as the generators, loads, and existing protective schemes, accurately. Due to the enormous volume of system premodeling, which includes the modeling of the automatic voltage regulator, governor, generators, transformer tap-changers, and the distance and frequency relay's protection coordination, this paper has studied only one standard network. Moreover, DigSILENT is used because of its ability to model all of the required parameters dynamically and simultaneously. Other tools do not have DigSILENT's abovementioned specifications. Furthermore, it has more industrial applications than other software tools.

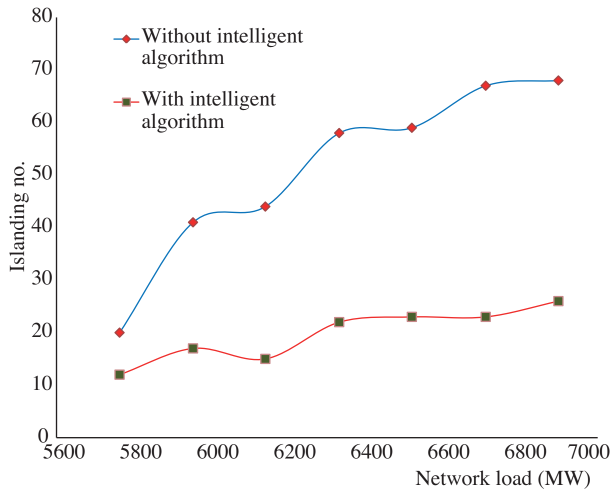


Figure 7. Number of islanding curves in the 7 load levels and system states.

6. Conclusion

Intelligent load shedding algorithms are presented in this paper based on critical line detections and zone-3's distance relay operation of the mentioned lines. Simulating the IEEE 39-bus test system and studying the dynamic behavior of network components, such as generators and protective schemes, has provided an excellent platform for algorithm implementation. The critical lines were determined based on studying possible scenarios in 7 load levels and determining convenient operating factors. Next, the load and generation with the maximum effect on the mentioned lines have been determined with sensitivity analysis. On the zone-3 distance relay threshold, critical load and generation are moved out of the system, and the critical line flow will go out of its relay operating zone. This approach helps the critical lines to remain in the system and prevents system blackouts. As mentioned above, 2 algorithms are presented. In the first algorithm, load shedding is performed when the critical line flow exceeds the critical flow. In this algorithm, the minimum activating flow determines the critical flow, because it is possible to activate the distance relays in zone-3 in different flows of different scenarios. This leads to unnecessary load shedding in some scenarios. For correcting this issue, a second algorithm is presented, which applies a zone-3 distance relay signal directly for the intelligent load shedding.

This paper proposed a new IA for load shedding based on DSL programming in the DIgSILENT software and the applied IEEE 39-bus test system as a case study. The number of cascading failures, the amount of load shedding, and the number of islanding in 2 network states (with/without the proposed second intelligent load shedding algorithm) has been fully studied.

By applying the second algorithm, the cascading failures of the mentioned network can be reduced by 78%; the total network load shedding was near 50.9% and the number of islandings (because of protecting the system's operations) can be reduced to up to 59.3% (Figure 8). Taking into account all of these improvements, it is here concluded that this algorithm can greatly reduce cascading failure along with blackout risks in a power system, as well as increase the system's security.

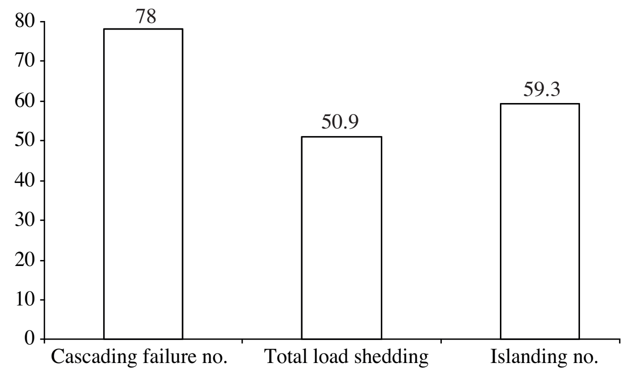


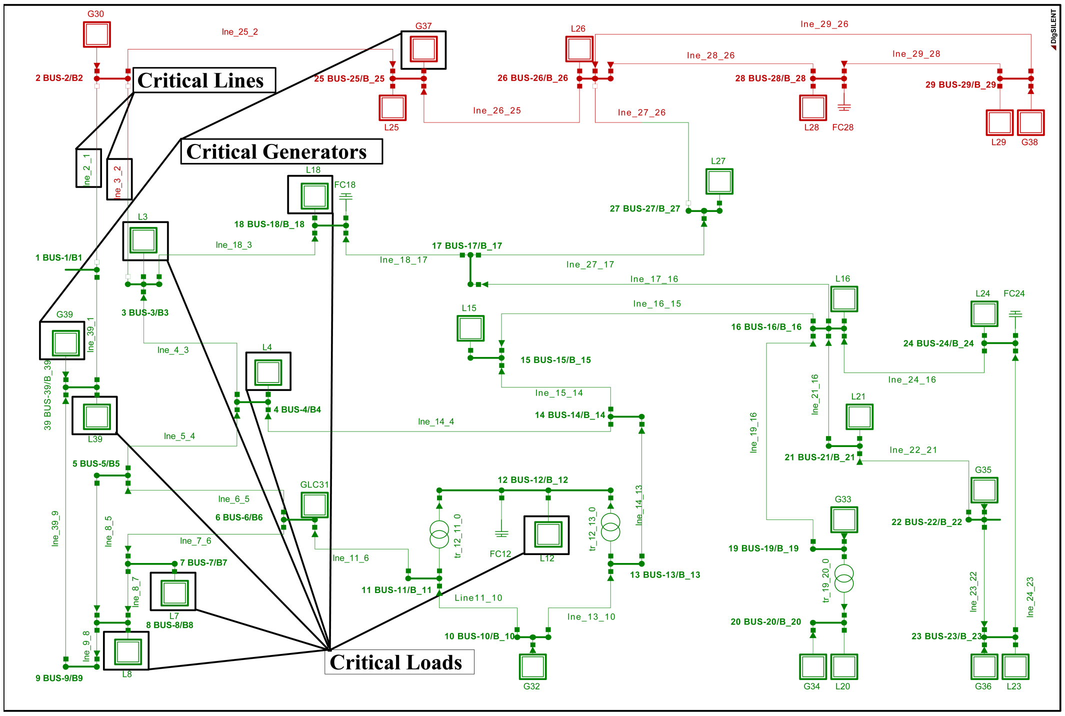
Figure 8. Comparison chart of the proposed intelligent load shedding algorithm performance in the network.

Comparing the methods in [19], which are explained in the introduction section, to the proposed methods in this paper, it is concluded that the proposed methods provide higher levels of active power margin and higher average minimum reactive power margin levels for a system in comparison to the conventional UFLS schemes. These adaptive methods identify the weak areas of the system, follow each event, and prioritize the shedding loads of those areas. Hence, they provide higher reactive power margins in weak system areas. The 3 combinational methods in these techniques have provided the highest average and minimum reactive power margins. Additionally, DigSILENT software has been used in [19].

This paper has studied the effects of the proposed algorithms on blackout paths and the possibility of islanding, which encompasses the dynamic operations of the installed relays, such as the distance, voltage, and frequency relays. The behavior of the whole network in determining critical load and generation locations are fully assessed, but [19] has determined a weak area based on the voltage view first, and then the related loads to that area will be shed based on the load priorities. Thus, the result of the abovementioned research study in [19] is based only on active and reactive power security margins.

Considering the method in [18], which is described in the introduction section, several generator outage events, as well as some combinational events, have been applied for system simulation. The performances of the conventional and proposed adaptive load-shedding schemes have been analyzed according to the major disturbances. These events are classified in 3 groups: generator outage, generator plus transmission line outage, and generator plus transformer outage. Determining the amount of load shedding for the system's stability has been discussed in 2 cases: conventional load shedding and the proposed algorithm [18]. Both [18] and [19] have used assumed faults for testing their algorithms, but in real system conditions, blackout paths are created because of the iterative operations of protective relays, which determine cascading failures. This important factor is considered in this paper's proposed approach, which is unique in comparison to the previously offered methods [18,19].

Appendix 1. Linear diagram of the IEEE 39-bus test system.



Appendix 2. Final results of the proposed smart algorithm.

No.	Load level		Cascading failures after the initial failure event	Emergency load shedding by the voltage/frequency relays (MW)	Load shedding based on IA (MW)	Load shedding based on the blackouts (MW)	Total load shedding (MW)	No. of islands
1	5764	Without the IA	30	356	-	4619.8	4975.8	20
		With the IA	11 (36%)	0	3634.57	1971	5605.57 (112%)	12 (60%)
2	5955	Without the IA	92	2361	-	16906.9	19267.9	41
		With the IA	19 (20.6%)	30.34	6687.47	2271.69	8989.5 (46.6%)	17 (41.5%)
3	6143	Without the IA	89	3071	-	15164.03	18235.03	44
		With the IA	18 (20.2%)	31.31	5492.93	2581.45	8105.69 (44%)	15 (34%)
4	6335	Without the IA	124	3025	-	24228.42	27253.42	58
		With the IA	25 (20.2%)	32.29	6731.5	3161.44	9925.22 (36.4%)	22 (37.9%)
5	6524	Without the IA	128	4714	-	24664.12	29378.12	59
		With the IA	27 (21%)	61.74	7082.61	3632.18	10776.53 (36.7%)	23 (39%)
6	6716	Without the IA	156	5522	0	32214.01	37736.01	67
		With the IA	27 (17.3%)	34.23	7920.94	3737.8	11693.02 (31%)	23 (34.3%)
7	6905	Without the IA	155	5010	-	31837.92	36847.92	68
		With the IA	29 (18.7%)	34.1	10299.59	3419.94	13753.63 (37.3%)	26 (38.2%)

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