International Journal of Electrical and Computer Engineering (IJECE)
Vol. 12, No. 5, October 2022, pp. 4661~4671
ISSN: 2088-8708, DOI: 10.11591/ijece.v12i5.pp4661-4671

Combinational load shedding using load frequency control and voltage stability indicator

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Article Info

Article history:

Received Dec 19, 2021
Revised May 23, 2022
Accepted Jun 6, 2022

Keywords:

Combinational load shedding
Voltage stability indicator
Load frequency control

ABSTRACT

This paper proposes a load shedding program for evaluating and distributing the minimum load power to be curtailed required to bring the frequency and voltage, after the system was subjected to a heavy disturbance, to the allowable range for each load bus. The quantity of load shedding was estimated to restore the power system's frequency, taking into account the turbine governor's primary control and the generators' reserve power for secondary control. Calculation and review of the load bus's voltage stability indicator (Li) to prioritize the load shedding quantity at these locations. The lower the voltage stability indicator on the load bus, the less load shedding can occur, and vice versa. The frequency and voltage values are still within allowable ranges with this approach, and a significant amount of load shedding can be prevented, resulting in a reduction in customer service interruption. The proposed method's efficacy was demonstrated when it was checked against the IEEE 30 bus 6 generators power system standard simulated in MATLAB environment and it minimize the power to be shed by around 20% of the conventional load shedding schemes.

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1. INTRODUCTION

Modern power systems have narrow stability margins, fewer reserve capacity than ever before. Different types of system instability, such as voltage instability, frequency instability, and a combination of voltage and frequency instabilities, have caused recent system blackouts. Traditional structures involved in ensuring proper control and protection for the network have been ineffective in this situation [1].

When severe disruptions such as big generating failures or important power transmission line outages occur in the system, load shedding is a last-resort and effective strategy to maintain system stability. In power systems, automatic load shedding is generally performed using two separate schemes: under frequency load shedding (UFLS) and under voltage load shedding (UVLS) [2], [3]. One of the primary flaws of traditional schemes is that they do not take into account the interaction of several types of instability in their design, despite the fact that any one type of instability may not take place in its pure form. This is especially right in severely strained networks and for events that cascade [4]. An under-frequency load shedding relays group and another under voltage load shedding relays group make independent determinations and act during such circumstances. In this method, the system performs an uncoordinated and inefficient load shedding procedure. The frequency decay rate is fundamentally slower than the voltage decay rate. As a result, heavily voltage drop at the system load buses lead to a reduction in loading load depend on voltage during fall in frequency for some combinational events [5]. As a result, the amount of frequency fall caused by an imbalance between consumed load and system generation is reduced when the buses voltage of the system is within normal limits. This phenomenon inhibits the frequency of the system from falling under the UFLS relays' settings of frequency. As a result, the quantity of curtailed load by sub UFLS relays is less than what is required. Because of the slowly decline of frequency, delayed load shedding situation may be happened.

Another issue is that when the input voltage of underfrequency load shedding relays drops significantly below the nominal value, they may fail to perform properly [6]. The locations of the loads to be shed under the traditional UFLS scheme, on the other hand, are predetermined and without take the disturbance location into consideration. Because the traditional UFLS algorithm does not always curtail loads in areas where there is a shortfall in reactive or real power, there is always the potential of heavy loadings of tie line and even instability of system voltage after load shedding [7].

Many schemes have been presented in the literature to improve the load shedding algorithms' compatibility. Terzija [8] proposed a method using centralized load shedding algorithms and needing fast communication of the measured parameters of power system. The impact of voltage fluctuations on system loads is taken into account in the system frequency response model in [9], [10]. Abazari and Zahedi [11] works to enhance UFLS and UVLS by considering reactive and active power simultaneously and use load bus location, consumed active power and reactive power as control variables of genetic algorithm (GA). The loads to be shed are chosen in [12] depending on the bus voltages sub-transmission size as well as the buses' static voltage stability margins. Rudez and Mihalic [13] utilized the voltage magnitude of the load buses right after a disturbance to compensate the effect of reduced bus voltages on the system loading and consequently on the measured frequency gradients. Nghia *et al.* [14] propose using of voltage electrical distance to make the priority of distributing the load shed by underfrequency load shedding scheme. Two novel local load-shedding strategies are presented in [15], which take the priority of UFLS to the buses with low-voltage in the system. As it compared with the traditional UFLS scheme, these approaches enhance the security of the power system in the event of major disruptions and provide greater reactive power margins.

In this paper, depending on the main concepts of proper load shedding program (location and amount of load to be shed from system buses) the minimum amount of load shedding capacity is calculated considering the primary and the secondary generator frequency control. The load to be shed from each load bus is obtained based on its voltage stability indicator (Li). The load with the higher voltage stability indicator (Li) factor will have the priority to shed more capacity and vice versa. This will minimize load to be shed from the system by simple and fast calculation algorithm.

2. METHOD

When there is an unbalance between generation and demand. generating unit disconnection from the electrical system, the frequency and voltage will be reduced. Systems that control the primary and the Secondary adjustments will be implemented to restore the frequency as it is described in subsection 2.1. In case the frequency is still not restored to permissible range, load shedding must be processed to restore frequency to permissible value. The proposed algorithm is applied in two case, the first one if there is a violation in frequency critical limit or combinational violation of voltage and frequency critical limits to calculate the total minimum load to be shed which is necessary to restore the frequency to its acceptable value according to primary and secondary load frequency control as shown in subsection 2.3 and distribute this amount on every load bus by the equation in step 7 of program procedure subsection 2.5 according to its tendency to instability described by the voltage stability indicator (Li) which is calculated as in subsection 2.4 and the second case when only voltage violation of bus voltage level occur then shed a portion of the violated buses load according to its voltage stability indicator (Li) by the equation in step 9 of program procedure. The distributed shedding power at each load buses in the two case is according to this factor, load buses with the largest (Li) will have priority to be shed with the larger amount of shedding power by curtail loads equal to the multiplication of total minimum load to be shed by the portion of its Li to the sum of all load buses Li and vice versa.

2.1. Frequency response of power system

Varying generated power as a respond to change in frequency or frequency stability and the turbine stability ability obtained by the speed control characteristic [16], [17]. speed droop factor is calculated according to (1):

$$R = \Delta f / \Delta PG \tag{1}$$

where, R is the speed droop adjustment factor; Δf is the change in frequency; ΔPG is the change in generation. The relationship between change in power and change in frequency is obtained by (2):

$$\Delta PG = (-1/R).(\Delta f/fn) \quad (2)$$

where fn is the system nominal frequency.

The load in the electricity network is a variant collection of different electrical devices. For resistive loads, such as lighting and heating, the power is independent on frequency. In the case of a motor load, such as a fan and pump, the power changes with frequency causing the motor speed to vary. The equation (3) can express the combined load power [18]:

$$PL = PID + PD \quad (3)$$

where, PL is the combine part of the load. PID is a load part does not depend on frequency change, e.g., heat load, lighting. PD frequency change-dependent load part, e.g., motor, pump. The equation (4) presented the response of the load to the frequency deviation:

$$\Delta PL = \Delta PID + \Delta PD \quad (4)$$

From the Figure 1 when the system frequency is at its nominal value f_0, the required power by the load is the same as the actual consumed power PL_0, when the frequency decays from f_0 to f_1, the actual power used decreases from PL_0 to PL_1.

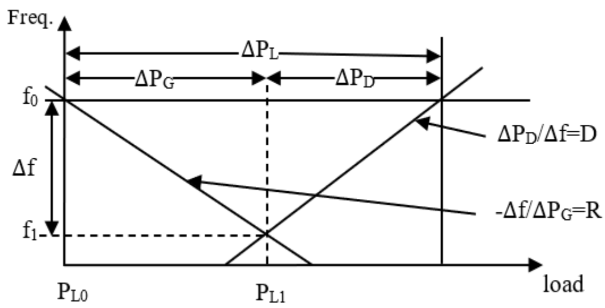

Figure 1. Change in load with frequency change

The equation describes the relationship between fluctuations in load power and variations in frequency is:

$$\Delta PD = -(\Delta f/fn).D \quad (5)$$

where, ΔPD is the load power change with respect to the change in frequency. D is the Damping factor of the system percentage characteristic of load change according to the percentage variation in frequency. Experimentally determined in the power system that D value varies from 1% to 2% and, as an example, for D=1% which represent 1% variation in frequency will cause 1% change in load.

2.2. Frequency primary and secondary control

In reaction to frequency fluctuations, frequency control is an instantaneous frequency adjustment procedure carried out by a large number of generators controlled by a turbine power control unit. Secondary frequency control is achieved by adjusting primary frequency control via the automatic generation controls (AGC's) effect on a number of units that are specifically designed to restore the frequency to its nominal value or otherwise, the frequency-adjusting effects are independent of the governor's response. The primary and secondary frequency control mechanisms are depicted in Figure 2.

The electrical system goes through two stages when there is a power mismatch between the generator and the demand: primary frequency control and secondary frequency control. When this control action is completed but the frequency of the network has not yet restored to its authorized level, load curtailing is used to recover the frequency. This process is described as a last protection to avert a blackout or electrical system failure.

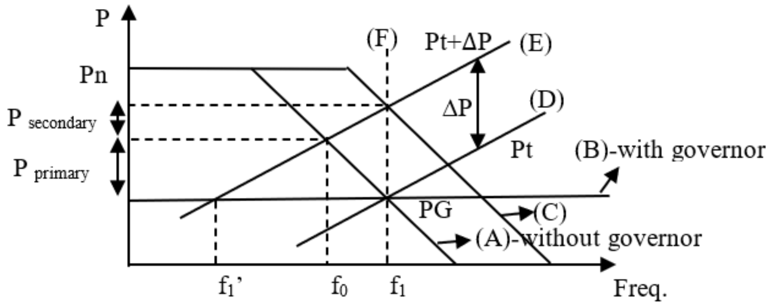

Figure 2. The relationship between frequency deviation and output power deviation

2.3. Calculation of minimum load-shedding

Shedding a minimum amount of load P_{LSmin} ensures restoration of electricity system frequency to the allowable value and helps to reduce the least economic consumer damage. including the primary control and secondary control of the generator, the calculation done in accordance with the actual operation. In a network with n generating units, when a generator shutdown, according to (6) the primary adjustment of the frequency of the remaining (n-1) generator is made with the generated power adjustment [19]:

$$\sum_{i=1}^{n-1} \Delta P_{Primary\ control} = \sum_{i=1}^{n-1} \frac{-1}{Ri} \cdot \frac{\Delta f}{fn} \qquad (6)$$

where, $\Delta P_{Primary}$ control is the i^{th} generator primary control power. ($\Delta f = f1 - fn$) is the frequency attenuation; fn is the nominal frequency of the power system, f1 is the frequency after generator outage.

When the generator outage, the inequality between the source power and consumed power leads to the frequency change, in particular, to be decreased. The reduction in the amount of ΔPD due to variation in the amount of power of the frequency-dependent load as shown in (5).

The equations (7) and (8) show the power balance status:

$$PL - \Delta PD = \sum_{i=1}^{n-1} PGi + \sum_{i=1}^{n-1} \Delta P_{Primary\ control} \qquad (7)$$

$$PL - \sum_{i=1}^{n-1} P\,Gi = -\left(\frac{\Delta f}{f0}\right)\left(D + \sum_{i=1}^{n-1} \frac{1}{Ri}\right) \qquad (8)$$

Set $\beta=[D+\sum_{i=1}^{n-1}\frac{1}{Ri}]^{-1}$ and $\Delta PL = PL\sum_{i=1}^{n-1} PGi$. From (8) infer:

$$\Delta f = -\Delta PL.\beta \qquad (9)$$

Considering secondary control power case, (7) becomes as (10) to represent the new power balance with new frequency:

$$PL - \Delta PD = \sum_{i=1}^{n-1} PGi + \sum_{i=1}^{n-1} \Delta P_{Primary\ control} + \Delta P_{Secondary\ control} \qquad (10)$$

where, $\Delta P_{Secondary\ control}$ (spinning reserve) is the amount of secondary control power released by the generators of the system.

$$\Delta P_{Secondary\ control} = P_{Gm,i} + \Delta P_{Primary\ control,i} \qquad (11)$$

Where $P_{Gm,i}$ is the rated capacity of the i^{th} generator.

Next to equipping the system with reserved power but until now the frequency of the system has not been recovered to its acceptable limit, then load curtailing is important to restore the system frequency. The following calculation yields the minimal amount of load curtailed power (PLS min):

$$P_{LS\ min} = PL - \Delta PD - \sum_{i=1}^{n-1} PGi - \sum_{i=1}^{n-1} \Delta P_{Primary\ control} - \Delta P_{Secondary\ control} \qquad (12)$$

$$P_{LS\ min} = PL - \sum_{i=1}^{n-1} PGi - \left(\frac{\Delta f}{fn}\right).D + \sum_{i=1}^{n-1} \frac{-1}{Ri}.\frac{\Delta f_{cp}}{fn} - \Delta P_{Secondary\ control} \quad (13)$$

As seen in (12) is abbreviated according to (14):

$$P_{LS\ min} = \Delta PL + (\frac{\Delta f_{cp}}{f0}/\beta) - \Delta P_{Secondary\ control} \quad (14)$$

where Δf_{cp} is the permissible change in frequency=0.5 Hz.

2.4. Voltage stability indicator

From [20] in a power system, the bus current equation stated in matrix form is:

$$I_{bus} = V_{bus}.Y_{bus} \quad (15)$$

Consider an electrical network, where n represents the number of buses and generator buses labelled as 1, 2…. g, and the remaining are load buses labeled g+1…. n.

The partitioned matrix form of (15) is given in (16):

$$\begin{bmatrix} IG \\ IL \end{bmatrix} = \begin{bmatrix} YGG & YGL \\ YLG & YLL \end{bmatrix} \begin{bmatrix} VG \\ VL \end{bmatrix} \quad (16)$$

where IG, IL and VG, VL are the currents and voltages at the generator and load buses. Manipulating and arranging (16) yields (17):

$$\begin{bmatrix} VL \\ IG \end{bmatrix} = \begin{bmatrix} ZLL & FLG \\ KGL & TGG \end{bmatrix} \begin{bmatrix} IL \\ VG \end{bmatrix} \quad (17)$$

where: ZLL=[YLL]-1; FLG=-[YLL] KLG=[YGL ZLL] and TGG=[YGG − YGL ZLL YLG].

For a given system, if the generator bus is i and the load bus is j, then FLG in (17) becomes:

$$F_{ji} = [Y_{jj}] - 1[Y_{ji}] = F_{ji} < \Theta_{ji} = F_{ji}(\cos\Theta_{ji} + j\sin\Theta_{ji}) \quad (18)$$

By using load flow results, acquired for given system loading conditions, the voltage stability indicator (L-index) at bus j is computed using (19) [21], [22]:

$$Li = \left|1 - \frac{\sum_{i\in G} F_{ji} V_i}{V_j}\right| \quad (19)$$

where: i=g+1 ......n, F_{ji} is a complex quantity, V_i and V_j are the complex bus voltages at generator buses and load buses respectively.

2.5. Program procedure and flowchart

The procedure for implementing the program can be described as:

- Step 1 : load input data: voltage angle, initial voltages, the active power, and reactive power of all system buses.
- Step 2 : calculate the bus voltages of the system by Running the load flow program.
- Step 3 : the change in frequency Δf of the system Calculated from the load difference by (9).
- Step 4 : calculate the dynamic stability index for all load bus according to the (19).
- Step 5 : if the system frequency is below the critical frequency (fcret)=49.5 Hz then go to step 6, else if the load buses voltage is below critical voltage (0.95 P. U) then go to step, else No-Load Shedding print results and go to step 12.
- Step 6 : compute the minimum amount of load to be curtailed (P_{LSmin}) by (14).
- Step 7 : compute the load to be curtailed from each load bus by the equation

  $$P_{Dshed} = [\frac{Li}{\sum Li} * P_{Ls\ min}]$$

  where P_{Dshed} is the load to be curtailed from each load bus. P_{Lsmin} is the minimum load to be shed from the hall system.

– Step 8 : compute the load to be shed from the violated voltage level buses by the equation

$$P_{Dshed=}[P_d\text{-}(\frac{Li}{\sum Li}*P_d)]$$

where P_d is the load of the violated load bus.
– Step 9 : calculate new voltage and frequency by running load flow end program. Where (V_{LS}) and (F_{LS}) are the voltages and frequency after load curtailing.
– Step 10 : if the voltages (V_{LS}) and system frequency (F_{LS}) after load curtailing is lower than critical corresponding values, return to step 5, else go to step 10.
– Step 11 : output results.
– Step 12 : end.

Flowchart of the load curtailing process based on the proposed algorithm is shown in Figure 3. Where: i) F is the system frequency under contingency before load shedding, ii) V is voltage of system buses under contingency before load shedding, iii) Fls is the system frequency after load shedding, and iv) Vls is voltage of system buses after load shedding.

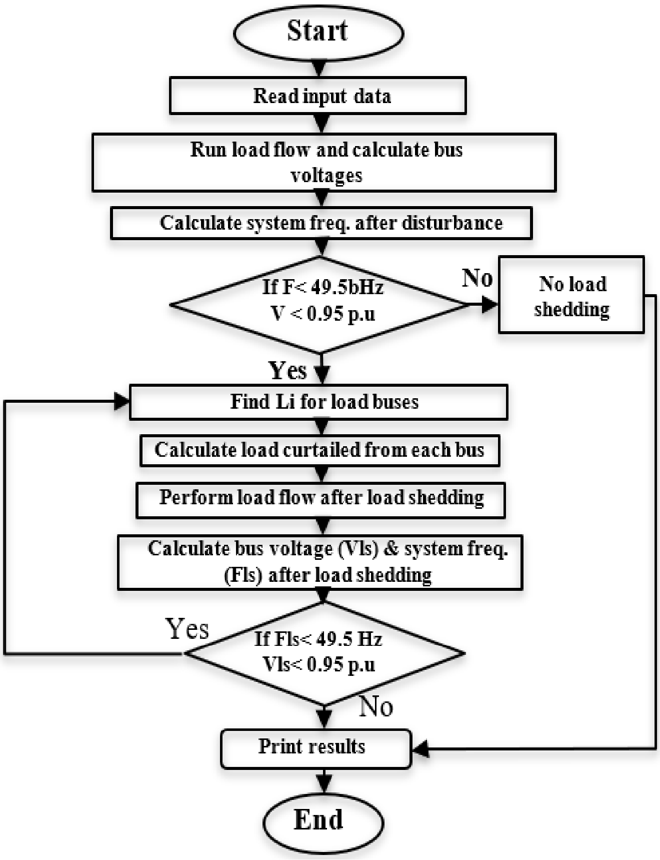

Figure 3. Proposed algorithm flowchart

3. RESULTS AND DISCUSSION

The network shown in the Figure 4 (IEEE 30 bus) is used as a case study. It has 6 generators and 24 load nodes. Six of the generator nodes are PV buses, and one is taken as a slack bus. The system consists of six generators at buses 1, 2, 5, 8, 11, and 13 and four regulating transformers in lines 6-9, 6-10, 4-12 and 27-28. Moreover, buses 10, 24 have reactive power sources. The voltage magnitudes of the PV buses are considered within the range of 0.95 to 1.1 p.u. The tap settings of the regulating transformers are within the range of 0.9 to 1.1 p.u [23]. Generate a code in MATLAB environment to implement the algorithm of the proposed method and simulate the single line diagram by MATLAB/Simulink model to run the load flow analysis on the system and calculate the bus voltage by Newton-Raphson method.

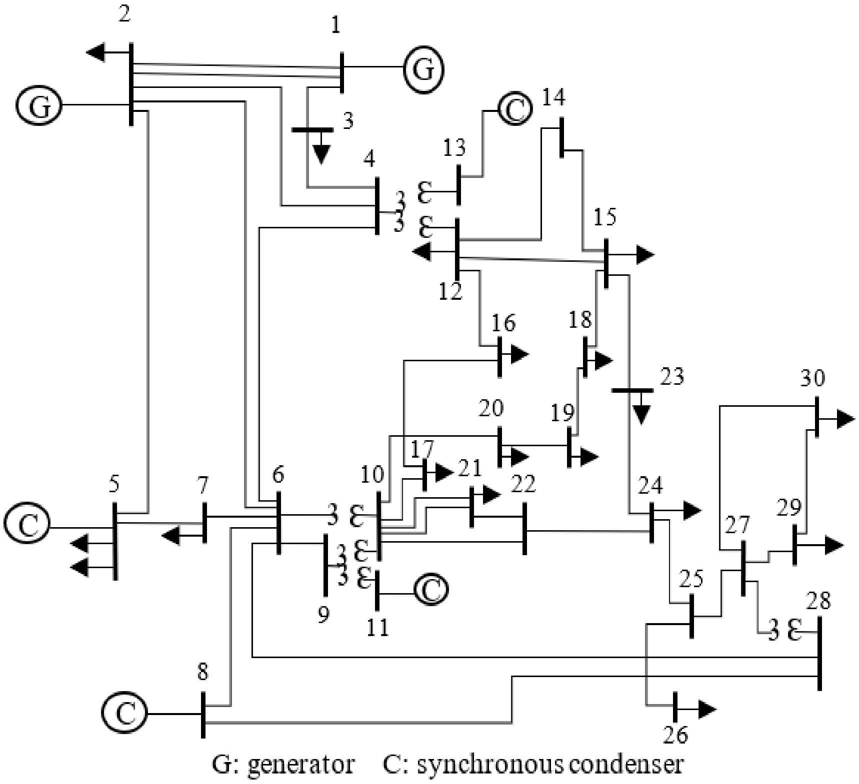

Figure 4. IEEE 30 bus system single line diagram

3.1. Case (1) normal loaded system and remove G1

This case study the effect of removing generation of G1 260.998 MW and compensate the load shortage by G2 and implementing the proposed load shedding algorithm under this situation load flow result of the system under contingency and after load shedding is given in Table 1 which consists of two parts, the first one for the results before load shedding and the other one for the results after load shedding. As it seen from Table 1 at column (3) the voltages of all the buses under contingency condition are within the acceptable range and the voltage stability was not violated but the frequency of the system under which is computed by (9) in subsection 2.3 as: New freq=fn+Δf is equal to (48.973 Hz) and it is under the critical frequency then load shedding algorithm should be implemented to overcome the deficiency of load. By implementing the proposed method, we find that by curtailing minimum load amount computed according to (14) subsection 2.3.

$$P_{LS\ min} = 141.775\ MW$$

Then distribute this amount over all load buses as a function of there (Li) indicator subsection 2.4 according to the equation in step 7 subsection 2.5:

$$P_{Dshed} = \left[\frac{Li}{\sum Li}\right] * P_{LS\ min}$$

This load shedding will brings the frequency to 49.531 Hz which means 1.116% enhancement of frequency and load buses voltage as shown in column (7) of the table by load shedding of 49.97% of the removed generation and by comparing these results with the results of conventional UFLS for the same system and the same contingency from [24] which minimize load shed from 260 to 141.77 MW as in Table 2 comparing with conventional method. From Table 2 it is clear that by removing 141.77 MW with proposed method will enhance the frequency to above the critical level which is less than the curtailed power by the conventional UFLS. By using of voltage recovery concept [20] which calculate the percentage enhancement of the system voltages we find that voltage recovery of the network Vrec=2.9556% and the Figure 5 shows the bus voltage levels before and after load shedding and it's clear that there is no violation in voltage level in this case and show the enhancement of bus voltage level after load shedding.

Table 1. Results of load flow analyses before and after load shedding

No	Li	Voltage mag	Load MW	Gen.MW	Li	V mag	Load MW	Gen. MW
1	0.000	1.060	0.000	0.000	0.000	1.060	0.000	0.000
2	0.083	1.043	21.700	161.700	0.031	1.043	18.410	145.582
3	0.079	1.022	2.400	0.000	0.031	1.032	0.000	0.000
4	0.188	1.013	7.600	0.000	0.065	1.025	0.165	0.000
5	0.192	1.010	94.200	0.000	0.073	1.010	86.618	0.000
6	0.270	1.012	0.000	0.000	0.154	1.021	0.000	0.000
7	0.224	1.003	22.800	0.000	0.087	1.010	13.945	0.000
8	0.260	1.010	30.000	0.000	0.123	1.010	19.736	0.000
9	0.296	1.051	0.000	0.000	0.120	1.059	0.000	0.000
10	0.321	1.045	5.800	0.000	0.087	1.055	0.000	0.000
11	0.000	1.082	0.000	0.000	0.000	1.082	0.000	0.000
12	0.374	1.057	11.200	0.000	0.092	1.064	0.000	0.000
13	0.000	1.071	0.000	0.000	0.000	1.071	0.000	0.000
14	0.333	1.042	6.200	0.000	0.082	1.058	0.000	0.000
15	0.354	1.038	8.200	0.000	0.083	1.055	0.000	0.000
16	0.348	1.045	3.500	0.000	0.080	1.056	0.000	0.000
17	0.362	1.039	9.000	0.000	0.083	1.052	0.000	0.000
18	0.371	1.028	3.200	0.000	0.085	1.050	0.000	0.000
19	0.358	1.026	9.500	0.000	0.086	1.048	0.000	0.000
20	0.362	1.030	2.200	0.000	0.089	1.050	0.000	0.000
21	0.373	1.032	17.500	0.000	0.086	1.047	2.752	0.000
22	0.377	1.033	0.000	0.000	0.088	1.048	0.000	0.000
23	0.380	1.027	3.200	0.000	0.089	1.049	0.000	0.000
24	0.361	1.022	8.700	0.000	0.091	1.044	0.000	0.000
25	0.345	1.019	0.000	0.000	0.090	1.039	0.000	0.000
26	0.353	1.002	3.500	0.000	0.086	1.030	0.000	0.000
27	0.347	1.026	0.000	0.000	0.090	1.040	0.000	0.000
28	0.319	1.011	0.000	0.000	0.075	1.021	0.000	0.000
29	0.356	1.006	2.400	0.000	0.097	1.034	0.000	0.000
30	0.328	0.995	10.600	0.000	0.095	1.032	0.000	0.000
	Total		283.400	161.700	Total		141.62	145.582
	Freq.	48.973 Hz			Freq.	49.5 Hz		

Table 2. Compression with previous work

	Remove G1	Freq. before LS	Freq. after LS	Load shed
Proposed method	286 MW	48.973 Hz	49.53 Hz	141.77 MW
Reference [24]	260.928 MW	48.175	49.95	260.11 MW

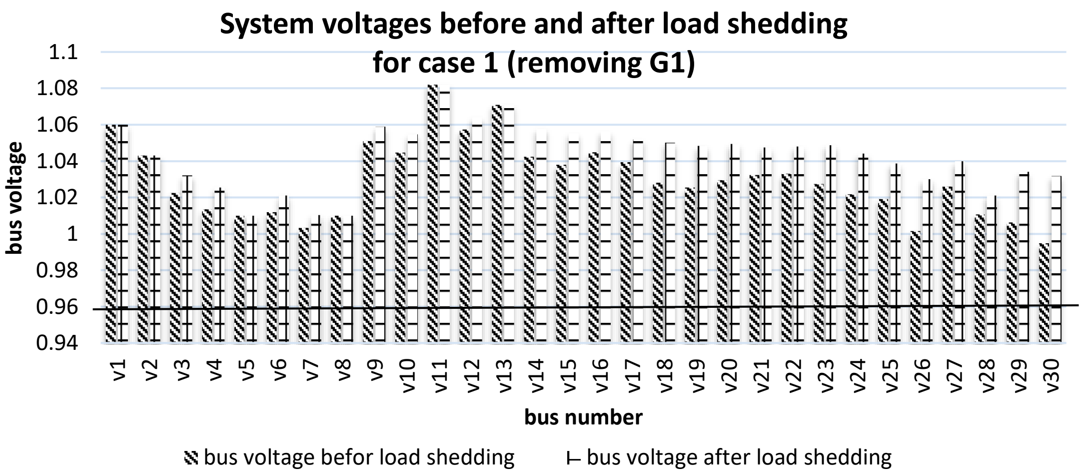

Figure 5. Bus voltage levels before and after load shedding

3.2. Case (2) remove two lines between bus 22, 24 and line between bus 25, 26 from loaded system

The removal of the line between bus 22, 24 and line between bus 25, 26 not cause system freq. reduction under critical level because there is no imbalance between generation and demand, but it violates the bus voltages of the buses 24, 25, 26, and 30 as it shown in Figure 6. The results of load flow analyses for the system shows that bus voltages of buses 23, 24, 25, and 30 under the critical voltage (0.95) as it clear in Figure 6 and after load shedding of 14.5241 MW from load buses we can see the enhancement of voltage level at these buses which can be sense by compute the voltage recovery of the network Vrec=1.3868% and Table 3 shows a comparison with the results of applying genetic algorithm to enhance voltage stability of the same system (IEEE 30) under the same contingency [25]. The comparison shows that there is a minimization in load to be shed from 72 to 14.53 MW with nearly the same enhancement of voltage level and voltage recovery of the network.

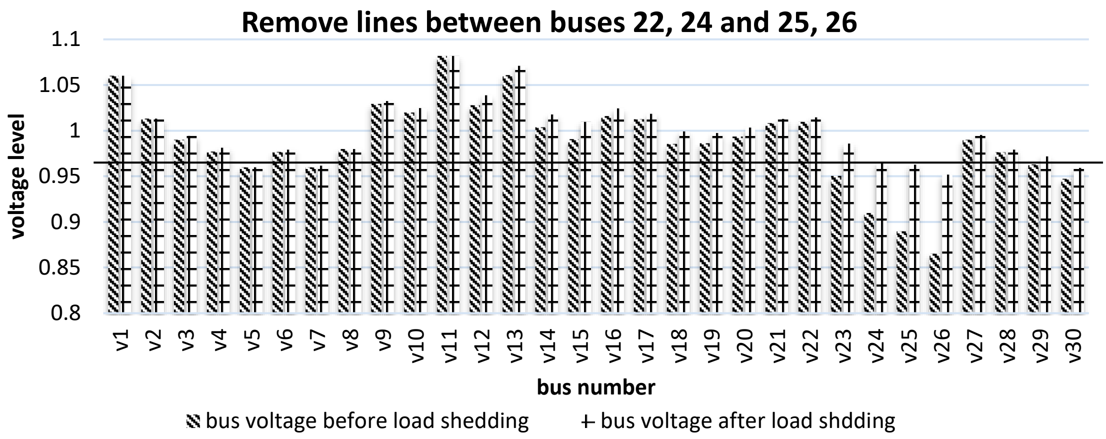

Figure 6. Bus voltage levels before and after load shedding

Table 3. Comparison with previous work

	Remove 2 lines	Violated buses	Voltage	Load shed
Proposed method	22, 24 and 25, 26	24, 25, 26, and 30	1.387%	14.53
Reference [25]	22, 24 and 25, 26	24, 25, 27, and 30	1.216%	72 MW

3.3. Case (3) loaded system and remove base generation of G2

Test the system response under rase load of 40% and G2 at its base load generation (140 MW) then sudden remove of G2 by the results of load flow analyses we find that bus voltage of bus 30 is equal to (0.943 p.u) under critical limit and the new calculated frequency is (49.44 Hz) which mean combinational stability violation and by implement the proposed algorithm and curtail 94.21 MW from load buses brings the frequency to 49.82 Hz and enhance the voltage level of the system to the levels shown in Figure 7. Bus number (30) new voltage is (0.993 p.u) and voltage recovery of the network of 2.598%.

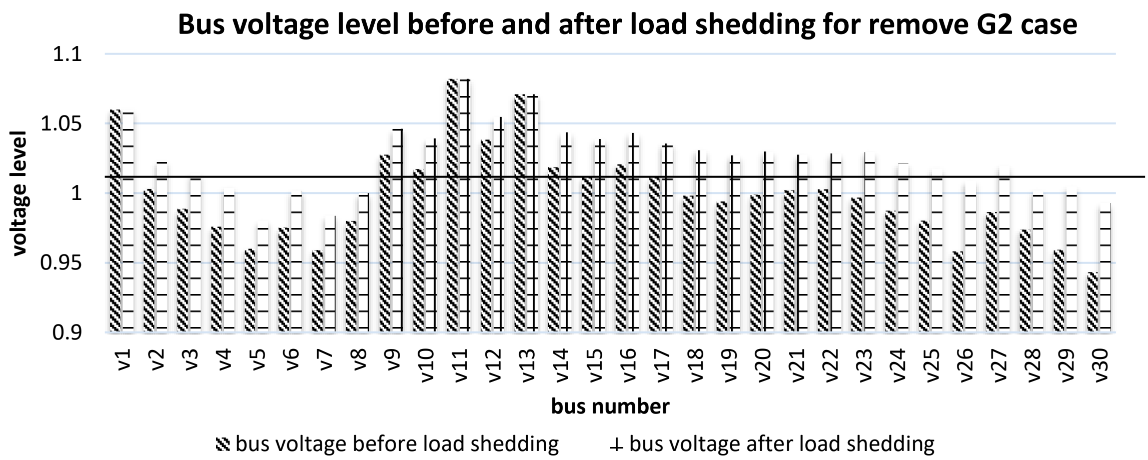

Figure 7. bus voltage levels before and after load shedding

4. CONCLUSION

The amount of load shedding capacity can be calculated using both the primary and secondary frequency controls, which helps to reduce the amount of load shedding capacity. This aids the frequency and voltage in returning to a value within the acceptable range with minimum curtailed load and from comparison with previous work it minimizes the load to be shed by around 20%. The studied cases shows that the proposed method can work on the violation of frequency, Case (1), and voltage, Case (2), independently and if there is combinational effect of the contingencies in Case (3) and resume the system stability by minimum load shedding as it compared with conventional schemes. The proposed method's effectiveness has been demonstrated on a 6-generator 30-bus system in a variety of test circumstances and can be extended by taking the importance of the curtailed load into account and test the proposed method on Middle Euphrates network (portion of Iraqi network). This scheme outperforms a traditional UFLS and UVLS schemes in terms of performance.

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