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OPTIMAL UNDER VOLTAGE LOAD SHEDDING TO PREVENT FREQUENCY INSTABILITY WITH CONSIDERING LOAD INTERRUPTION COST

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Abstract- In this study, a static method which makes best load shedding scheme to reach a maximum voltage security margin, prevent voltage instability and emendation of power system frequency during generation unit outage is developed. Minimization of total load interruption cost with considering frequency emendation constraint, Voltage security margin, and alleviating transmission line over loadings have great significance in fitness function to reach a coordinated load shedding pattern. In this paper, Load interruption cost has been modeled as a quadratic function and frequency constraint modeled based on extra load must be shed caused by generator outage contingencies in under study power system. HGAPSO and PSO are used as optimization tools for solving mentioned problem during contingency conditions. The proposed approach is carried out on IEEE 14 and 30 bus test systems and results are discussed.

Keywords: Load Shedding, Frequency Instability, Load Interruption Cost.

I. INTRODUCTION

The imbalance between power generation and load requisition is a mainly cause of subnormal frequency operation of the power system. As the system frequency falls, there is also a spontaneity reduction of load caused by frequency dependent characteristics of system load. So, all load shedding schemes, so far suggested and in force, do take load characteristics into consideration for computing or predicting the load proposed to be shed.

The aim of any load shedding programs is to disconnect the minimum load that is needed to arrest falling frequency to an allowable value. If the load shed is more than needed, then it will definitely arrest the declining frequency but at the cost of loss of revenue to safeguard utility besides inconvenience of feeder restoration. If load relief is inadequate, then system frequency will not be arrested [1]. In addition, the time of load interruption is important and very effectively to overall cost of load shedding and load shedding must be make best the cost of load interruption. So, load shedding scheme must select cheapest loads.

Briefly, mainly causes of power system under frequency operation are listed as follows:

1- In steady state condition, a steady decline in frequency is observed when online generating capacity becomes incommensurate to meet the load demand of the system. This may happen in the case of gradual raise in load with fixed generation availability.

2- Caused by fault happening, some of the generators may be disconnected or any vital line may be tripped by contingency event during operating a large interconnected power system. In such a case, the accessible generation cannot cope up load resulting in slowing down of turbines. Therefore, system frequency falls. The power system may become unstable unless load is reduced by load shedding scheme as latest selection switch of control operations.

3- Sudden trip outs of generating units or substantial transmission lines carrying heavy loads, in this case, there is a sudden fall of power system frequency. The rate of fall of frequency caused by system imbalance in demand and power system generation depends on the inertia of system, quantity of deficiency in generation in MW, automatic load reduction caused by frequency dependent characteristics of system load.

Moreover, system voltage stability is one of the most important categories in power system, which must be considered in load shedding strategies. Voltage stability refers to the ability of power system to maintain steady voltages at all buses in the system after being subjected to disturbance from a given initial operating condition [2]. Load shedding can be used to overcome voltage instability problem, effectively. There are too many methods for estimating voltage stability, which debated in literatures.

References [3, 4] introduce FVSI (Fast Voltage Stability Index) for under voltage load shedding to assessment voltage stability and load prioritization. In [5], the proposed method is based on indicator sensitivities to change in load to be shed. However, the analysis based on static models, and the dynamic aspects associated with voltage stability phenomenon are not taken into account. Reference [6] tried to describe the WSCC system wide voltage stability paragon, which based on V-Q and P-V curve methodologies.

Besides, *P-V* and *V-Q* analysis, full, long term dynamic simulations [7], power system fast dynamic simulations [8], modal analysis [9, 10], and security constrained optimal power flow (OPF) analysis [11] are effective tools for providing insight into the voltage instability and collapse phenomenon and its analysis. In this paper, a new approach has been developed for optimum load shedding based on multi-objective optimization, minimum load interruption cost, lines over loadings and maximization of voltage security margin with considering frequency constraint. A quadratic function has been selected as load interruption cost for minimization of the total power shed. Operating constraints on the loads to be shed have been accounted. HGAPSO and PSO are used as effective optimization tools for solving the minimum weighted load shedding problem during contingency conditions. This proposed method is executed on IEEE 14 and 30 bus test systems during two contingencies and results are discussed.

II. MULTI-OBJECTIVE OPTIMIZATION PROBLEM

It is considered that following equation is a multi-objective function with its constraints:

$$\begin{cases} \min(f_1(x), f_2(x), ..., f_M(x)) \\ \text{subject to}: \begin{cases} h_k = b \\ x^{(L)} \le x \le x^{(U)} \end{cases} \end{cases} \tag{1}$$

In this paper to solve multi-objective problem, Equation (1) is changed to no constraint function with penalty factors as follows [12, 13]:

$$\begin{aligned} &\min[(f_1(x), f_2(x), ..., f_M(x)) + \lambda(b - h_k) + \\ &+\lambda_x \sum_{N_x^{\lim}} (\Delta x)^2] \end{aligned} \tag{2}$$

$$\Delta x = \begin{cases} x - x^{(U)} & \text{if} \quad x > x^{(U)} \\ x^{(L)} - x & \text{if} \quad x < x^{(L)} \end{cases}$$

III. MODELING OF OPTIMIZATION PROBLEM

In this study, the proposed objective function consists of three objectives, two of them are covered technical item as transmission line over loadings and voltage security margin, third one is included economical items, as follows:

A. Minimize Transmission Line over Loadings

The amount of over loadings in all over loaded transmission lines is derived as:

$$OF_1 = \min : \begin{cases} \sum(\left|S_{ij}^p\right| - S_{ij}^{\max}) \text{ if } \left|S_{ij}^p\right| > S_{ij}^{\max} \\ 0 \qquad\qquad\qquad \text{if } \left|S_{ij}^p\right| < S_{il}^{\max} \end{cases} \tag{3}$$

B. Maximize Voltage Security Margin

The first step in voltage stability evaluation is finding suitable evaluation index. There are many proposed indexes for voltage stability analysis but the selected index should make physical and engineering concept about system voltage stability margin for system operators and it must determine distance between operating point and load ability situation [14].

In this study, Voltage Security Margin (VSM) is used as an index to security assessment [15]. In this study, a toolbox has been developed to evaluated voltage security margin based on network load ability limit index. Firstly, system load ability limit was calculated as follows. Power system load ability limit can be modeled as nonlinear optimization problem, which tries to maximize system loading with power flow equation solve ability constraint. To access this purpose, the problem can be formulated as follows:

$$\begin{aligned} &\max.: P_D^{Sys} \\ &\text{s.t.}: \begin{cases} P_{Gi} - P_{Di} - f_i(v, \delta) = 0 \\ Q_{Gi} - Q_{Di} - g_i(v, \delta) = 0 \\ P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max} \\ Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max} \\ P_{Ti} \le P_{Ti}^{\max} \end{cases} \end{aligned} \tag{4}$$

The main constraint for voltage stability is power flow equation solve ability, therefore Equation (4) try to find maximum loading under the feasibility of power flow equation, which corresponds to system load ability limit. The Lagrange method as optimization tool can be applied to solve Equation (4). For this purpose, maximization of system load ability problem with its constraints converted into non-constrained optimization problem by Lagrange method as formulated as Equation (5):

$$\begin{aligned} &L = -P_D^{Sys} + [\lambda]^T [P_G - P_D - f(v, \delta)] + \\ &+[\gamma]^T [Q_G - Q_D - g(v, \delta)] \end{aligned} \tag{5}$$

where, $[\lambda]$ and $[\gamma]$ are vectors of Lagrangian multipliers [16].

B.1. Load Modeling

The pattern of demand and generation increscent at buses is one of the main factors, which dominates the load ability limit, so to include their effects; it can be modeled as follows [17]:

$$\begin{aligned} &P_{Di} = [P_{Di}^{(0)} + \beta_i Pf_i (P_D^{Sys} - P_D^{Sys(0)})] \left(\frac{v_i}{v_i^{(0)}} \right)^{kpvi} \\ &Q_{Di} = [Q_{Di}^{(0)} + \beta_i Qf_i (P_D^{Sys} - P_D^{Sys(0)})] \left(\frac{v_i}{v_i^{(0)}} \right)^{kqvi} \quad , \sum_{i=2}^{NB} \beta_i = 1 \end{aligned} \tag{6}$$

B.2. Generation Increase Pattern

Pattern of generation increase definition based on calculation of participation factor of every generator to supply total active load of system formulation is [17]:

$$\begin{aligned} &P_{Gi} = \alpha_i P_D^{Sys} \qquad 0 \le \alpha_i \le 1 \\ &\sum_{i=2}^{NB} \alpha_i \le 1 \qquad P_{Gi}^{\min} \le \alpha_i P_D^{Sys} \le P_{Gi}^{\max} \end{aligned} \tag{7}$$

To access solution of Equation (5), Newton-Raphson method is employed. For this purpose, the first derivatives of Equation (5) are calculated as follows:

$$F_x = \frac{\partial L}{\partial X} = 0, \quad X = [v, \delta, \lambda, \gamma, P_D^{Sys}] \tag{8}$$

Then, factors of each equations is calculated, which contains $\Delta v, \Delta\delta, \Delta\lambda, \Delta\gamma$ and ΔP_D^{Sys}. By carrying out mentioned equations, the following matrix can be obtained:

$$\begin{bmatrix} F_v^{(0)} \\ F_\delta^{(0)} \\ F_\lambda^{(0)} \\ F_\gamma^{(0)} \\ F_{P_D^{Sys}}^{(0)} \end{bmatrix} = \begin{bmatrix} F_{vv} & F_{v\delta} & F_{v\lambda} & F_{v\gamma} & F_{vP_D^{Sys}} \\ F_{\delta v} & F_{\delta\delta} & F_{\delta\gamma} & F_{\delta\gamma} & F_{\delta P_D^{Sys}} \\ F_{\lambda v} & F_{\lambda\delta} & F_{\lambda\lambda} & F_{\lambda\gamma} & F_{\lambda P_D^{Sys}} \\ F_{\gamma v} & F_{\gamma\delta} & F_{\gamma\lambda} & F_{\gamma\gamma} & F_{\gamma P_D^{Sys}} \\ F_{P_D^{Sys} v} & F_{P_D^{Sys}\delta} & F_{P_D^{Sys}\lambda} & F_{P_D^{Sys}\gamma} & F_{P_D^{Sys} P_D^{Sys}} \end{bmatrix} \begin{bmatrix} \Delta v \\ \Delta\delta \\ \Delta\lambda \\ \Delta\gamma \\ \Delta P_D^{Sys} \end{bmatrix} \qquad (9)$$

The proposed method has been carried out using MATLAB software and based on described method, the voltage stability toolbox has been developed.

B.3. Voltage Security Margin

The system load ability limit calculated in previous section, used to determine voltage security margin as voltage stability criteria:

$$VSM^{Sys} = \frac{P_D^{Sys} - P_D}{P_D^{Sys}} \qquad (10)$$

where, P_D represent total load of on stream system. VSM^{Sys} as an indicator of system voltage stability must be maximizing by proposed load shedding scheme and this index is proposed in this paper. Therefore, the second part of main objective function is:

$$OF_2 = \min\ -VSM^{Sys} \qquad (11)$$

According to Equation (11), load shedding scheme tries to shed large amount of loads which have more sensitivity to VSM and maximization of voltage security margin.

C. Reduce Load Interruption Cost

There are many studies of the interruption cost in many countries [19-25]. Therefore, another objective, which is considered in this study to improve load shedding schemes is load interruption cost. Table 1 show that the cost of an interruption load depends on its type, size and the duration of costumer interruption [26, 27].

Table 1. Sector interruption cost ($/Kw)

User sector	Interruption Duration (min) & Cost ($/KW)				
	1 min	20 min	60 min	240 min	480 min
Larger users	1.005	1.508	2.225	3.968	8.240
Industrial	1.625	3.868	9.085	25.16	55.81
Commercial	0.381	2.969	8.552	31.32	83.01
Agricultural	0.060	0.343	0.649	2.064	4.120
Residential	0.001	0.093	0.482	4.914	15.69

Table 1 gives the interruption cost for five discrete outage durations. In direction of load shedding purpose, the nonlinear curve between duration (minute) and costs ($) is fitted for each classes of load. Curve fitted on cost ($/kW) and time by:

$$cost\,(\$/\text{kW}) = at^2 + bt + c \qquad (12)$$

where, *a*, *b*, *c* are constant coefficients and *t* is duration of load interruption. Equation (12) shows cost of interrupted load by load shedding scheme, which depends on time of interruption. Load interruption cost for each classes of load is derived as:

$$IC\,(\$) = \left(at^2 + bt + c\right)\left(P_D^0 - P_D^p\right) \qquad (13)$$

where, P_D^0 and P_D^p represent active power demand in base case and post contingency respectively. In addition, it is considered, which each bus includes five feeders with one class of load in each feeder. The load of each feeder is a part of total load on bus. Therefore, this has a participation factor. In addition, cost of load in each bus can be formulated as:

$$\begin{aligned} total\ cost &= IC_L.PF_L + IC_I.PF_I \\ &+ IC_C.PF_C + IC_A.PF_A + IC_R.PF_R \end{aligned} \qquad (14)$$

where, *PF* is participation factor and *L*, *I*, *C*, *A* and *R* are abbreviation of load classifications. Load shedding scheme must make best the cost of interruption load. Therefore, the next term of optimization problem is given as follows:

$$OF_3 = \min \sum_{i=1}^{N_{Bus}} total\ cost_i \qquad (15)$$

D. Constraints

The equality and inequality constraints are described in Equations (16) to (25). Active and reactive power balance equations are expressed as Equations (16) and (17), respectively.

$$\sum_{i=1}^{N_{Bus}} \left(P_{Gi}^p - P_{Di}^p\right) - P_L^p = 0 \qquad (16)$$

$$\sum_{i=1}^{N_{Bus}} \left(Q_{Gi}^p - Q_{Di}^p\right) - Q_L^p = 0 \qquad (17)$$

Control variables constraints are the real power of load demand of bus, which are shown by Equation (18).

$$P_{Di}^{\min} \le P_{Di}^p \le P_{Di}^0 \qquad (18)$$

In Equation (18), we have restricted load shedding of buses between pre contingency value and $P_{Di}^{\min}$. In other word, it has assumed that the load shedding in bus *i* cannot be greater than $P_{Di}^0 - P_{Di}^{\min}$. Operating constraints are as follows:

$$\left|S_{ij}^p\right| \le S_{ij}^{\max} \qquad (19)$$

$$Q_{Gi}^{\min} \le Q_{Gi}^p \le Q_{Gi}^{\max} \qquad (20)$$

$$Q_{Ci}^{\min} \le Q_{Ci}^p \le Q_{Ci}^{\max} \qquad (21)$$

$$V_i^{\min} \le V_i^p \le V_i^{\max} \qquad (22)$$

$$\frac{\Delta P_{Di}}{P_{Di}^0} = \frac{\Delta Q_{Di}}{Q_{Di}^0}, \text{fixed power factor} \qquad (23)$$

$$\left|\delta_i - \delta_j\right| - \psi_{ij} \le 0 \qquad (24)$$

$$f^{\min} \le f^{P.Sys} \le f^{\max} \qquad (25)$$

where, V_i^p represent post contingency bus voltage.

E. Frequency Calculation

In a network with several generators, the generator frequencies are assumed constant in post of system fluctuations damping. In addition, total generator moments J_0 are got as following formula [10]:

$$J_0 = \frac{\sum J_i S_i}{\sum S_i} \quad (26)$$

where, J_i (kg - m^2) and S_i represent moment of ith machine and nominal apparent power of same machine respectively, δ is resultant of generator rotor angles, which known as Center of Angle (COA) and got from Equation (27):

$$\delta = \frac{\sum \delta_i \delta_j}{\sum S_i} \quad (27)$$

where, δ_i, δ_j are rotor angle of ith and jth generator. In addition, for rotors, demeanor equation is equal to:

$$J_0 \frac{d^2\delta}{dt^2} = T_a = T_m - T_e \quad (28)$$

where, T_a represent accelerator torque, T_m and T_e are summation of mechanical torque and summation of electrical load torque respectively. By multiplying ω with two sides of Equation (28) and (29) will derive as follows:

$$\omega J_0 \frac{d^2\delta}{dt^2} = \omega T_a = \omega T_m - \omega T_e = P_m - P_e \quad (29)$$

where, H_0 is equal than stored energy in machine with synchronous speed dividing by nominal power and formulated as Equation (30):

$$H_0 = \frac{1}{2} J_0 \omega_s^2 / S_0 \quad (30)$$

where, S_0 represent summation of system nominal power as well as ω_s is synchronous speed. In addition, by using Equations (29) and (30), compressed system dynamic equation is equal to:

$$\frac{2H_0}{\omega_s^2} \frac{d^2\delta}{dt^2} = T_m^{pu} - T_e^{pu} \quad (31)$$

In this paper, it is assumed, load with damping factor D is depending on system frequency as follows:

$$D = \frac{\Delta P \times f_0}{P_0 \times \Delta f} \quad (32)$$

where, P_0 existing load active power in system, f_0 is initial system frequency, Δf is variations of frequency, D is load damping constant and ΔP is variation of load, which caused by frequency variations.

Based on dependence of load and frequency, Equation (31) has been modified and minimum of steady state frequency (neglecting generator governor efficacy) is equal to:

$$f_{ss} = f_0 \left(1 - \frac{\Delta P}{D \times P_0} \right) \quad (33)$$

Therefore, in generator outage contingency, the amount of load to be shed to purpose of steady state frequency emendation is equal to:

$$P_{LS} = PG_{shed} - P_{Lf} \quad (34)$$

where, PG_{shed} represent active power generation capacity of generator, which removed from network and P_{Lf} is reduction of system load caused by frequency reduction to Δf. The P_{Lf} expressed as Equation (35):

$$P_{Lf} = (P_0 - P_{LS}) D \frac{\Delta f}{f_0} \quad (35)$$

Finally, the amount of load to be shed to purpose of steady state frequency emendation and setting frequency deviation to Δf is equal to:

$$P_{LS} = PG_{shed} \frac{f_0}{f_0 - D \times \Delta f} - P_0 \frac{D \times \Delta f}{f_0 - D \times \Delta f} \quad (36)$$

So, Equation (25) becomes as:

$$\begin{cases} PLS_{\min} = PG_{shed} \dfrac{f_0}{f_0 - D(f_0 - f^{\min})} - \\ -P_0 \dfrac{D(f_0 - f^{\min})}{f_0 - D(f_0 - f^{\min})} \end{cases} \quad (37)$$

$$\begin{cases} PLS_{\max} = PG_{shed} \dfrac{f_0}{f_0 - D(f_0 - f^{\max})} - \\ -P_0 \dfrac{D(f_0 - f^{\max}}{f_0 - D(f_0 - f^{\max})} \end{cases} \quad (38)$$

where, $PLS_{\min} \le P_{LoadShed} \le PLS_{\max}$ and $PLS_{\min}$ and $PLS_{\max}$ represents minimum and maximum summation of load active power respectively.

Equation (37), express system frequency constraint based on summation of load active power ($P_{LoadShed}$) to be shed. This object is reached by optimal determination of control variables. Control variables are shown in Table 2.

Table 2. Control variables

P_{D1}^p	P_{D2}^p	…..	$P_{D\,N_{Bus}}^p$

IV. HYBRID GENETIC ALGORITHM AND PARTICLE SWARM OPTIMIZATION

Particle Swarm Optimization (PSO) is a new evolutionary computation technique first introduced by Kennedy and Eberhart in 1995 [28]. Like other stochastic searching techniques, the PSO is initialized with generating a population of random solutions, which is called a swarm. Each individual is referred to as a particle and presents a candidate solution to the optimization problem. A particle in PSO has a memory in which retains the best experience, which is gained in the renewable of search space. In this technique, each candidate solution is associated with a velocity vector [29, 30].

The velocity vector is constantly adjusted according to the corresponding particle's experience and the particle's companion's experience. Therefore, in PSO algorithm, the best experiences of the groups are always shared with all particles and so, it is expected that the particles move toward better solution areas. The g_{best} in PSO is an implementation where the neighborhood is entire swarm, while l_{best} in PSO refers to the implementation where a smaller neighborhood size is used. According to the above mentioned concepts, g_{best} in PSO operation has introduced in references [31, 32].

V. HGAPSO ALGORITHM FOR OPTIMAL LOAD SHEDDING

The HGAPSO tries to find minimum of objective function. First, mentioned objective function is defined to satisfy all requirements of the optimization problem.

A. Initialization

It is supposed that $P_{Di}^{\min} = 0.5 P_{Di}^{0}$ for all buses. The equation means that, load shedding in bus *i*, cannot be greater than 50 percent of load demand in this bus. Also in this paper, the interruption time for each classes of load is 30 minutes. Toolbox has been developed for any durations of load interruption with MATLAB software. In addition, it is hypothesized that the minimum and maximum frequency equal to 49.5 Hz and 50.3 Hz respectively. In addition, maximum difference angle of send and receive end of transmission lines (ω_{ij}) is equal to 45 degrees.

B. Fitness Evaluation

The objective function is computed using Equations (3) to (37). The effect of load shedding pattern on reducing transmission line over loadings, load interruption cost and maximization system voltage security margin are considered in this study. It is used corresponding coefficient for each objective, and for each particle, the fitness value is calculated. The overall introduced objective function during this study is:

$$\left\{\begin{array}{l} f(x) = \min[k_1 \dfrac{OF_1}{\left\{\begin{array}{ll} \sum\limits_{i=1}^{N_{line}} \left(\left|S_{ij}^{0}\right| - S_{ij}^{\max}\right) & if \ \left|S_{ij}^{0}\right| > S_{ij}^{\max} \\ 0 & if \ \left|S_{ij}^{0}\right| \le S_{ij}^{\max} \end{array}\right.} - \\ -k_2 \dfrac{OF_2}{VSM^{Sys0}} + k_3 \dfrac{OF_3}{\sum\limits_{i=1}^{N_{bus}} Total\ Cost_i^{\max}} + \\ +\lambda_1 (\sum\limits_{i=1}^{N_{bus}} (P_{Di}^{0} - P_{Di}^{p}) - PLS_{\max})^2 + \lambda_2 (PLS_{\min} - \\ -\sum\limits_{i=1}^{N_{bus}} (P_{Di}^{0} - P_{Di}^{p}))^2 + \lambda_3 (\sum\limits_{i=1}^{N_{bus}} (P_{Gi}^{p} - P_{Di}^{p}) - P_L^{p}) + \\ +\lambda_4 (\sum\limits_{i=1}^{N_{bus}} (Q_{Gi}^{p} - Q_{Di}^{p}) - Q_L^{p}) + \lambda_5 F_v(V_i) + \lambda_6 F_Q(Q_{Ci}) + \\ +\lambda_7 F_\delta(\delta_i, \delta_j)] \end{array}\right. \quad (39)$$

where, S_{ij}^{0} is apparent power transmission of lines, post contingency and before load shedding. VSM^{Sys0} is pre contingency system voltage security margin. $total\ cost_i^{\max}$ is cost of 50 percent of load in five classes for each bus. k_1, k_2, k_3 are arbitrary gain factors. λ_1, λ_2, λ_3, λ_4, λ_5, λ_6, λ_7 are penalty factors. In addition, penalty functions have been defined as F_v, F_Q, F_δ, guarantees comply voltage violation, reactive power generation and transmission line power angle stability constraints.

$$F_v(V_i^p) = \begin{cases} V_i^p - V_i^{\max} & \text{if } V_i^p > V_i^{\max} \\ V_i^{\min} - V_i^p & \text{if } V_i^p < V_i^{\min} \\ 0 & \text{if } V_i^{\min} < V_i^p < V_i^{\max} \end{cases} \quad (40)$$

$$F_Q(Q_{Ci}^p) = \begin{cases} Q_{Ci}^p - Q_{Ci}^{\max} & \text{if } Q_{Ci}^p > Q_{Ci}^{\max} \\ Q_{Ci}^{\min} - Q_{Ci}^p & \text{if } Q_{Ci}^p < Q_{Ci}^{\min} \\ 0 & \text{if } Q_i^{\min} < Q_{Ci}^p < Q_i^{\max} \end{cases} \quad (41)$$

$$F_\delta(\delta_i, \delta j) = \begin{cases} \left|\delta_i - \delta_j\right| & \text{if } \left|\delta_i - \delta_j\right| > \psi_{ij} \\ 0 & \text{if } \left|\delta_i - \delta_j\right| < \psi_{ij} \end{cases} \quad (42)$$

VI. SIMULATION RESULTS

The IEEE-14 bus and IEEE-30 bus are used as test systems. The IEEE-14 bus network consists of 2 generators, 11 consumers and 15 interconnected lines [33] and IEEE-30 bus network consists of 6 generators, 21 consumers and 41 interconnected lines [33]. In this section the relation between the amount of load shedding in power system and transmission line over loadings, load interruption cost and voltage security margin is studied.

A. Contingency in 14-Bus IEEE

In this study, the contingency has been performed by generator 2 outage. generator 2 generates 80 MW and system frequency will have been fallen by this contingency. In addition, the over loading of line 1-2 and the other lines and decreasing in voltage security margin have been occurred. Some of network condition in post and pre contingency before performs of load shedding scheme are shown with Table 3. According to Equations (37) and (38), minimum amount of load, which must be shed.

Table 3. Indexes of network condition during contingency

Indexes system	Summation of Transmission line over loadings (MVA)	Voltage Security Margin (pu)
14 bus pre contingency	0	0.3346
14 bus post contingency	61.6272	0.3011

By load shedding scheme, is equal to 74.6156 MW. In addition, maximum amount of load, which must be shed by load shedding scheme, is equal to 83.0823 MW. New operating condition after this contingency by proposed load shedding scheme are shown with Table 4. 1th and 4th columns of Table 4 are load shedding with security gravitation and show almost 24.5% improving in voltage security margin, also, transmission line over loadings have been alleviated with load shedding. Second and 6th columns of Table 4 are load shedding scheme with economical gravitation.

In this gravitation, loads have been selected with interruption cost consideration. It is axiomatic, loads, which have lowest interruption cost are in priority. In addition, second and 6th columns of Table 4, represent improving 21.23% in voltage security margin in presence of reducing load interruption cost by HGAPSO. Third and 7th columns of Table 4 are load shedding scheme with operational gravitation. According to these columns, 18.73% improving in voltage security margin and alleviation of transmission line over loadings have been executed with load shedding scheme.

Table 4. Results of applying load shedding scheme and new operating conditions in IEEE 14-bus test system

	HGAPSO				PSO			
	Amount of load shedding (MW) and percent of base load							
Bus No.	Voltage security margin [securest]	Load interruption cost [economical]	Transmission line over loading [operational]	Coordinated [tradeoff among security, cost,operational]	Voltage security margin [securest]	Load interruption cost [economical]	Transmission line over loading [operational]	Coordinated [tradeoff among security, cost, operational]
2	0(0)	1.04(4.81)	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)
3	47.1(5000)	47.1(50.00)	47.1(50.00)	47.1(50.00)	47.1(50.00)	47.1(50.00)	47.1(50.00)	47.1(50.00)
4	3.1(27.70)	5.56(49.63)	3.01(26.91)	3.99(35.58)	3.67(32.73)	4.05(36.20)	0(0)	5.6(50.00)
6	3.63(7.59)	0.65(1.37)	1.05(26.84)	0(0)	5.82(12.17)	0(0)	22.71(47.52)	5.44(11.39)
7	1.99(26.14)	3.8(50.0)	0(0)	1.73(22.78)	0.87(11.43)	3.8(50.00)	0(0)	3.8(50.00)
9	6.66(22.57)	0(0)	0(0)	7.79(26.42)	0(0)	0(0)	0(0)	0(0)
10	0(0)	0(0)	1.63(18.10)	2.3(25.61)	3.53(39.23)	0.63(7.03)	0(0)	1.11(12.33)
11	0.06(3.53)	0(0)	0.42(11.97)	1.75(50.00)	0.42(11.99)	1.75(50.00)	1.75(50.00)	1.75(50.00)
12	1.13(18.48)	2.24(36.69)	2.17(35.52)	1.06(17.33)	1.6(26.22)	3.05(50.00)	3.05(50.00)	3.05(50.00)
13	5.14(38.10)	2.9(50.00)	0(0)	2.48(42.77)	4.16(30.81)	6.75(50.00)	0(0)	6.75(50.00)
14	5.74(38.52)	7.45(50.00)	7.45(50.00)	3.11(20.90)	7.45(50.00)	7.45(50.00)	0(0)	0(0)
Total load shedding	74.6114	74.5938	74.6081	74.6096	74.6119	74.5865	74.6128	74.6043
Larger user load	8.5321	7.1937	2.5658	8.8918	5.3236	6.7500	4.5426	7.8389
Industrial load	5.8031	2.5224	12.3228	3.6445	6.6400	2.5665	20.6102	7.0174
Commercial load	22.5678	21.7002	22.0630	24.5097	23.4762	21.8539	19.4500	21.9070
Agricultural load	1.9119	3.5243	0.4188	3.3079	1.2011	5.1700	1.7500	5.1700
Residential load	35.7965	39.6532	37.2376	34.2556	37.9712	38.2461	28.2600	32.6710
Cost ($)	153648.88	131066.06	176174.39	151594.21	156913.73	131648.53	211542.43	156814.75
VSM (pu)	0.3988	0.3823	0.3705	0.3784	0.3864	0.3843	0.3401	0.3609
line over loadings	0	0.6968	0	0	0	0.6644	0.9546	2.1874

Table 5. Indexes of network condition during contingency

Indexes / system	Summation of Transmission line over loadings (MVA)	Voltage Security Margin (pu)
30 bus pre contingency	0	0.1675
30 bus post contingency	25.4504	0.1478

Table 6. Results of applying load shedding scheme and new operating conditions in IEEE 30-bus test system

	HGAPSO				PSO			
	Amount of load shedding (MW) and percent of base load							
Bus No.	Voltage Security Margin [securest]	Load interruption cost [economic]	Transmission line over loading [operational]	Coordinated [tradeoff among security, cost, operational]	Voltage Security Margin [securest]	Load interruption cost [economic]	Transmission line over loading [operational]	Coordinated [tradeoff among security, cost, operational]
2	0(0)	0(0)	6.32(29.11)	0(0)	0(0)	0(0)	0(0)	0(0)
3	1.2(50.00)	0.81(33.56)	0.98(40.75)	0.9(37.32)	1.2(50.00)	0(0)	1.2(50.00)	1.18(49.17)
4	2.41(31.72)	0.01(0.09)	2.22(29.15)	0(0)	0(0)	0(0)	3.8(50.00)	0(0)
5	0(0)	25.81(27.40)	0(0)	3.41(3.62)	0(0)	30.25(32.11)	0(0)	3.15(3.34)
7	11.4(50.00)	6.71(29.41)	7.20(3.44)	11.22(49.22)	0.64(2.80)	0.01(0.03)	11.4(50.00)	11.40(50.00)
8	15(50.00)	0(0)	12.00(39.99)	15(50.00)	15(50.00)	11.17(37.23)	15(50.00)	15(50.00)
10	2.9(50.00)	1.99(34.25)	0.69(11.93)	2.9(50.00)	0(0)	1.84(31.71)	2.90(50.00)	0(0)
12	1.06(9.45)	3.12(27.87)	2.90(25.92)	5.45(48.65)	0(0)	0.76(6.83)	0(0)	5.6(50.00)
14	0(0)	1.85(29.83)	0(0)	1.27(20.46)	3.1(50.00)	2.78(44.92)	0(0)	3.1(50.00)
15	2.77(33.76)	1.83(22.27)	0.27(3.28)	0(0)	3.83(46.7)	0(0)	0(0)	0(0)
16	0(0)	0.16(4.58)	1.73(49.51)	0.63(18.01)	1.75(50.00)	0(0)	0(0)	1.75(50.00)
17	0(0)	0.58(6.41)	3.76(41.73)	0(0)	0(0)	0(0)	2.35(26.10)	0(0)
18	0(0)	1.6(50.00)	1.59(49.84)	1.6(50.00)	1.01(31.70)	1.6(50.00)	1.6(50.00)	0.72(22.42)
19	4.43(46.65)	0(0)	4.02(42.32)	3.12(32.82)	4.75(50.00)	0.63(6.67)	4.75(50.00)	0(0)
20	0.58(26.43)	0.69(31.28)	0.81(37.01)	1.1(50.00)	1.10(50.00)	0(0)	0(0)	0(0)
21	6.14(35.10)	2.14(12.25)	5.95(34.01)	0.25(1.42)	8.75(50.00)	0.73(4.20)	3.53(20.20)	0(0)
23	1.51(47.18)	0.41(12.79)	0(0)	0.67(21.01)	1.6(50.00)	0(0)	1.58(49.53)	1.6(50.00)
24	2.75(31.60)	2.1(24.12)	0(0)	0(0)	4.35(50.00)	4.35(50.00)	0.45(5.17)	4.16(47.85)
26	1.75(50.00)	1.01(28.87)	0.9(25.83)	1.75(50.00)	1.75(50.00)	0(0)	1.75(50.00)	0(0)
29	0.05(2.11)	0.45(50.00)	0.69(28.59)	0.69(28.61)	0(0)	0(0)	0.98(41.00)	1.16(48.40)
30	0.18(1.74)	2.11(19.90)	2.1(19.81)	4.17(39.34)	5.30(50.00)	0(0)	2.87(27.05)	5.30(50.00)
Total load shedding	54.1375	54.1162	54.1336	54.1214	54.1317	54.1313	54.1703	54.1205
Larger user load	6.7233	4.2978	1.3774	0.2540	8.7993	4.9070	2.3497	4.7833
Industrial load	10.8338	3.0175	13.7650	6.2144	11.8450	3.8533	11.4053	4.3700
Commercial load	10.7008	7.6505	13.1052	13.5366	13.4513	7.2729	12.6055	12.7050
Agricultural load	11.9049	8.4010	7.5327	13.6424	6.6977	2.4003	12.4721	12.0550
Residential load	13.9748	30.7493	18.3533	20.4741	13.3384	35.6979	15.3377	20.2072
Cost ($)	124775.40	66267.60	141392.32	103403.75	143935.76	68610.22	129469.61	96699.73
VSM(pu)	0.1898	0.1692	0.1736	0.1807	0.1863	0.1620	0.1784	0.1852
line over loadings	1.4975	8.5852	0	0	4.2359	9.0430	0	0

Finally, the 4th and 8th columns of Table 4 are considering a tradeoff between security notices, economic and operating conditions. In addition, improving 20.42% in voltage security margin, minimum deviation of economical tendency and alleviating whole of transmission line over loadings are accessories of these studies. According to Table 4, equality of total amounts of load shedding in all gravitations represents the impetus of proposed load shedding scheme to emendation of system frequency deviation as optimization problem constraint.

B. Contingency in 30 bus IEEE

In this study, the contingency has been performed by generator 8 outage. Generator 8 generates 60 MW and system frequency will have been fallen with elimination of this generator. Some of network condition in post and pre contingency before performs of load shedding scheme are shown with Table 5. According to Equations (37) and (38), minimum and maximum load, which must be shed by proposed load shedding to purpose of frequency emendation are 54.1578 MW and 63.3648 MW respectively. Table 6 shows new operating condition after this contingency by proposed load shedding scheme.

Analogous Tables 4 and 6 represent the classified result of load shedding and its results are representing 18.2% improvement in voltage security margin. In addition, minimum deviation of load interruption cost than economical gravitation analysis in presence of transmission line over loadings elimination is sensible from Table 6.

VII. CONCLUSIONS

This paper introduced a new method to find optimal load shedding scheme. This method is identifying the best pattern of load to be shed that provides the maximum voltage stability based on voltage security margin, minimum cost of load shedding scheme based on time of load interruption and classification of load in each feeders of bus and minimum. Proposed load shedding, provide enough margin to voltage instability, during contingency, and setting adequate operational conditions such as elimination of transmission line over loadings, power angle stability of transmission lines and considering of reactive power generation constraints with minimum cost.

NOMENCLATURES

$x^{(L)}$: Lower bound of control variable

$x^{(U)}$: Upper bound of control variable

S_{ij}^{p} : Apparent power transmitted by transmission line in post contingency condition

$S_{ij}^{\max}$: Maximum allowable apparent power of transmission line

P_{Gi} , Q_{Gi} : Active and reactive power generation

P_{Di} , Q_{Di} : Demand active and reactive power

f_i , g_i : Active and reactive power flow equation

P_{Ti} : Power flow within *i*th transmission line

$P_{Di}^{(0)}$, $Q_{Di}^{(0)}$: Primary value of active and reactive power demand

β_i : Load contributions of each bus

Pf_i , Qf_i : Load factor coefficients

$v_i^{(0)}$: Primary value of bus voltage

kpv_i , kqv_i : Active and Reactive power load dependence to voltage

$P_D^{Sys(0)}$, P_D^{Sys} : Total primary active load and total active load

α_i : Participation factor of *i*th generator

P_D : Total load of on stream system

P_D^0 , P_D^p : Active power demand in base case and post contingency

P_G^p , P_D^p , P_L^p : Post contingency active power generations and loads and losses

Q_G^p , Q_D^p , Q_L^p : Post contingency reactive power generations, loads, and losses

ψ_{ij} : Maximum angular difference between end and receive end of transmission lines

$V_i^{\min}, V_i^{\max}$: Minimum and maximum allowable bus voltage

$Q_{Ci}^{\min}, Q_{Ci}^{\max}$ and Q_{Ci}^{p} : Minimum, maximum and post contingency reactive power generation by synchronous condensers

$f^{\min}, f^{\max}$ and $f^{p,Sys}$: Minimum, Maximum and post contingency allowable system frequency

T_m , T_e : Summation of mechanical torque and summation of electrical load torque

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