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An Effective Load Shedding Scheme to Mitigate Voltage Collapse Using a Multi Objective Optimization Technique and BFO

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ABSTRACT

Among different protection schemes that save power system stability against a variety of disturbances, load shedding is considered as an effective and last-resort tool to avoid voltage instability. This paper proposes a special protection system design to minimize the load curtailments necessary to restore the equilibrium of operating point with relaxation of both steady state and dynamic restrictions. An optimal load shedding approach is proposed to enhance voltage stability employing a combination of modal analysis and Bacterial Foraging Optimization (BFO). As a corrective control action after contingencies the proposed approach is organized as a multi-objective optimization problem which reveals the best location and the lowest level of load shedding for special protection systems (SPSs) in the direction of improving the voltage stability margin as well as the voltage profile. The load shedding activation time that mitigates power system voltage collapse in spite of load curtailment must be indicated by dynamic simulation to prevent both over load shedding and voltage instability. The proposed approach is applied to Gharb and Bakhtar areas of the Iranian transmission network for its annual peak load at 2011. Simulation results verify the effectiveness of the proposed scheme in comparison with the current scheme.

KEYWORDS: Bacterial Foraging Optimization, Load Shedding, Modal Analysis, Multi-Objective Optimization, Special Protection System, Voltage Stability

INTRODUCTION

Once coupled mainly with weak systems and long lines, voltage problems are currently as well a source of concern in developed power systems as a consequence of heavier loadings. The voltage instability phenomenon arises when a disturbance, increase in load demand, or change in power system operational condition instigates an escalating and uncontrollable drop in voltage level [1]. Commonly, most of the methods applying to voltage stability analysis are based on static models of the power system to avoid dealing with the corresponding intricate dynamic models [2, 3]. Performance indices to predict closeness to voltage stability boundary have been a permanent concern of researchers and power system operators, as these indices can be used online or offline to help dispatchers determine how close the system is to a possible voltage instability state [4].

In essence, the control operations to maintain power system stability can be divided into preventive and corrective actions [5]. Preventive actions almost maintain the required quality and reliability of power supply while corrective control actions operate in the course of single and multiple contingencies with the aim of preventing power system collapse. Corrective actions usually affect generators and/or loads, and therefore are acceptable only in the presence of severe contingencies [6].

An apt action to maintain power system stability is to utilize special protection systems at appropriate locations curtailing a suitable level of load [7]. Special protection system methods are defined as protection schemes designed to detect abnormal system states that lead to unusual stress on the power system and to take some predetermined actions to cope with the observed state in a controlled manner [8].

Numerous methods are proposed for SPSs (i.e. frequency load shedding, load shedding taking into account generator and load dynamics, load shedding based on minimizing the level of load curtailment using optimal power flow equations), while each method considers a distinctive index. Despite most of the above mentioned techniques consider power flow equations in addition to voltage profile as an apt index for load shedding, power system instability is probable due to unavailable capacity of reactive power reserve to deal with extra loading and impending disturbances [9, 10].

When a power system is found to be vulnerable to a particular disturbance through security assessment, the dispatcher can take either preventive or corrective actions such as generation rescheduling or load shedding in order to save the system security [11]. Besides security margin calculation, determination of the best actions to restore a given level of security is important. This question is probably more important in electricity markets where the decision for generation rescheduling or load shedding must be taken by the system operator in a transparent and widely accepted manner [12].

In this paper, at first stage, load increase in the study region (at peak time) leads to small signal stability problem. Preventive control action must be applied to save the system stability and so transformer taps and terminal voltage of generators should be set as best as possible to get the highest voltage stability margin. For contingencies that may cause system instability, a corrective control action as load shedding must be applied to maintain system stability.

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Indeed, the required time by load shedding schemes may considerably reduce their capability to save voltage stability of a system for which the speed of response is an important factor [13]. In this investigation, the development of an optimal load shedding scheme with dynamic constraints is proposed through the use of a critical load shedding time. To determine the right time to start load shedding, dynamic simulations are necessary. Also, this paper utilizes a combination of modal analysis and bacterial foraging optimization (BFO) to minimize load shedding as well as enhance voltage profile and stability margin. Since modal analysis is an appropriate method for static assessment of voltage stability, the proposed scheme firstly applies modal analysis to determine system's weak points. Then the optimal load shedding level considering the above mentioned index as well as voltage profile and stability margin are obtained by applying a BFO-based multi-objective optimization method. At the same time, by dynamic simulation, voltage threshold and load curtailment start time are calculated in the worst contingencies. Finally, the proposed scheme is applied to Gharb and Bakhtar areas of the Iranian transmission network for its annual peak load at 2011. The effectiveness of proposed scheme in comparison with the current scheme is demonstrated.

MODAL ANALYSIS

One of the most proper methods for static analysis of voltage stability is modal analysis [1]. In this method characteristics of system's voltage stability can be evaluated by calculating eigenvalues and eigenvectors of the Jacobean matrix. To calculate the Jacobean matrix of the system, the linearized equations of the system power flow can be used by means of the following expression [1]:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{P\theta} & J_{PV} \\ J_{Q\theta} & J_{QV} \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta V \end{bmatrix} \tag{1}$$

ΔP	Active power changes of PV and PQ buses
ΔQ	Reactive power changes of PQ buses
$\Delta \theta$	Changes of voltage angle
ΔV	Changes of voltage amplitude

Where $J_{P\theta}$, $J_{Q\theta}$, J_{PV}, $J_{QV}$are the elements of the Jacobean matrix that represent the sensitivity between the injected powers and bus voltages. The eigenvalues of the Jacobean matrix (λ_i) can be considered as voltage stability index. Where all of the eigenvalues are positive, voltage stability of the system is achieved; but if at least one of the eigenvalues is negative, the system voltage would not be stable. Consequently, the lower value of λ_i means that the *i*th mode is more unstable. The least eigenvalue is called critical eigenvalue (critical mode). According to the large dimensions of the Jacobean matrix and time-consuming calculations, which are important in online environments, the reduced Jacobean matrix is used where the assumption of $\Delta P = 0$ is implemented [1]:

$$\Delta Q = J_{\mathrm{RQ}V} . \Delta V \tag{2}$$

$$J_{RQV} = J_{QV} - J_{Q\theta} J_{P\theta}{}^{-1} J_{PV} \tag{3}$$

The eigenvalues of the reduced Jacobean matrix J_{RQV} can be taken into account as a respective criterion of voltage instability limit. This matrix can be shown as follows [1,3]:

$$J_{\mathrm{RQ}V} = X . \Lambda . Y \tag{4}$$

where X is the right eigenvector of J_{RQV},Λ is the diagonal matrix of eigenvalues, and Y is the left eigenvector of J_{RQV}. The smallest eigenvalue of matrix $\mathrm{J_{RQV}}$, which becomes zero at the voltage instability boundary, is obtained from modal analysis on the $\mathrm{J_{RQV}}$ in the vicinity of the maximum loadability point. This eigenvalue is known as the critical mode of voltage instability. The same critical mode is obtained from modal analysis of the load flow Jacobian J in (1) [1, 14].

Another useful capability of modal analysis is determination of participation factors of buses, lines and generators in each mode. The partial participation of k^{th} bus in i^{th} mode, which is known as bus participation factor, can be calculated by means of the following expression:

$$P_{ki} = X_{ki} . Y_{ki} \tag{5}$$

where X_{ki}, Y_{ki} are the elements of right and left eigenvectors. The magnitude of bus participation in each mode demonstrates the effectiveness of remedial actions implemented in that bus for stabilizing the mode. For instance, to perform load shedding schemes with the intention of improving static voltage stability, bus participation factors should be calculated; then those buses with the highest participation factors must be chosen for load interruption.

Moreover, the relative participation of k^{th} branch in i^{th} mode, which is called branch participation factor, is equal to the ratio of reactive losses of branch k to the maximum loss of all branches. Branch participation factors indicate, for each mode, which branches consume the most reactive power in response to an incremental change in reactive load. The participation coefficients of generators in each mode indicate which generators supply most reactive power in response to changes in reactive loading of the system. These factors reveal some important information about the best dispatch model of reactive reserve between all machines in order to keep the voltage stability margin [1].

BACTERIAL FORAGING OPTIMIZATION ALGORITHM

E.coli bacteria, that are present in human intestines, search for the nutrients through their foraging mechanism, which consists of four processes known as, chemotaxis, swarming, reproduction, elimination and dispersal. Bacterial foraging optimization algorithm (BFOA), inspired from the foraging mechanism of E.coli bacteria, is a stochastic search method. This method searches for the optimum solution of an optimization problem through simulating the four mentioned processes [15], which are detailed in the following.

Chemotaxis

The motion of *E. coli* bacteria in the human intestine to find nutrient-rich areas is performed with the aid of the locomotory organelles known as flagella by chemotactic movement. This motion in a direction different from the previous one is called tumble. Suppose that $\theta^i(j,k,l)$ stands for the position of the each member in the population of S bacteria at the j^{th} chemotactic step, k^{th} reproduction step, and l^{th} elimination. The movement of the bacterium can be modeled through (6):

$$\theta^i(j+1,k,l)=\theta^i(j,k,l)+C(i)\varphi(j) \tag{6}$$

Where $C(i),(i=1,2,..,S)$ is the size of the step taken in the tumble; $\varphi(j)$ indicates the random direction of the movement, i.e. tumble; $J(i,j,k,l)$ is the fitness, which also indicates the cost at the location of the i^{th} bacterium $\theta^i(j,k,l)\in R^n$. If the cost $J(i,j+1,k,l)$ at $\theta^i(j+1,k,l)$ is better (lower) than $J(i,j,k,l)$ at $\theta^i(j,k,l)$, then another step of size $C(i)$ in the same direction will be taken. Otherwise, the bacterium will tumble through taking another step of size $C(i)$ in random direction $\varphi(j)$ in order to find better nutrient area.

Swarming

In addition to the individual motion, *E. coli* bacteria represent a group behavior known as swarming effect. When a group of E. coli cells is put in the center of a semisolid agar with a single nutrient chemo-effector, they move out of the center in a swarming ring of cells by following the nutrient gradient made by consumption of the nutrient by the group. The bacteria swarm through attractant and repellant mechanisms, which can be modeled as (7):

$$J_{cc}(\theta,j,k,l)=\sum_{i=1}^{S}J_{cc}^{i}(\theta,\theta^{i}(j,k,l))=\sum_{i=1}^{S}\left[-d_{attract}\exp\left(-w_{attract}\sum_{m=1}^{p}(\theta_m-\theta_m^i)^2\right)\right]$$
$$+\sum_{i=1}^{S}\left[-h_{repellant}\exp\left(-w_{repellant}\sum_{m=1}^{p}(\theta_m-\theta_m^i)^2\right)\right] \tag{7}$$

Where $J_{cc}(\theta,j,k,l)$ is the cost function value, which should be added to the real cost function (to be minimized) to construct a time varying objective function;S is the total number of bacteria and p is the number of parameters to be optimized, which are present in each bacterium. $\theta=\left[\theta_1,\theta_2,...,\theta_p\right]^T$ represents a point in the p-dimensional search space.$d_{attract}$ indicates the intensity of the attractant released by the bacterium and $w_{attract}$ is a measure of the width of the attractant signal. Similarly, $h_{repellant}=d_{attract}$ illustrates the intensity of the repellant and $w_{repellant}$ is a measure of the width of the repellant signal.

Reproduction

The *E. coli* bacteria evolve in the nature through reproducing themselves. For the bacteria, a reproduction step occurs after all chemotactic steps, which is based on the following equation:

$$J_{health}^{i}=\sum_{i=1}^{N_c+1}J(i,j,k,l) \tag{8}$$

Where J_{health}^{i} is a measure for the health of bacterium i such that higher J_{health}^{i} means higher cost or lower health; $N_c$is the number of steps in the chemotaxis process. All bacteria of the population are sorted in the order of ascending J_{health}^{i} values. To keep a constant population size, bacteria with the highest J_{health} (lowest health) die. Each remaining more healthy bacterium reproduces itself by splitting into two bacteria. Mathematically, each remaining individual $\theta=\left[\theta_1,\theta_2,...,\theta_p\right]^T$ is copied and generates another individual with the same parameters.

Elimination-Dispersal

Elimination and dispersal phenomena can take place in the evolutionary process such that the bacteria in a region are killed or a group is dispersed into a new part of the environment. As a heuristic optimization algorithm, elimination and dispersal processes of BFOA are used to enhance the diversity of the individuals and the ability of the global optimization. To perform elimination-dispersal in BFOA, bacteria are removed with a probability of P_{ed} and instead of each eliminated bacterium, a new individual is randomly generated (dispersed) within the search space to keep the population size constant.

DERIVATION OF PROPER OBJECTIVE FUNCTION

According to participation factors, the buses that have the most contributions in the critical mode represent candidate places for installation of SPSs to prevent power system instability after severe contingencies [16,17]. Apart from the basic features that are essential for designing a fast load shedding scheme, there are some issues based on the experiences gained which are effective in the reliability enhancement [18].

After determination of candidate buses, the amount of load to be shed must be calculated. For this computation some factors such as λ representing margins of voltage stability, voltage profile of buses, and the minimum amount of curtailed load must be considered in the objective function. Therefore, it would be a multi-criterion optimization problem where the minimization of one function conflicts with other functions [19]. Also, this problem can have many constrains leading to the following formulation:

$$\min\{F_1(X), F_2(X), \ldots, F_n(X)\}$$
$$g_i(X) \le 0 \quad i = 1, 2, \ldots, m \tag{9}$$

n Number of objective functions

m Number of problem constraints

Where $F_i(X)$ are single objective functions and $g_i(x)$ are the problem constraints that should be satisfied. The merit function approach can be used to handle this problem. In this approach, according to the importance of F_i in comparison with the other objective functions, a utility function $U_i(F_i)$ is defined, while the common objective function is the summation of all utility functions [19]. It is possible that one objective function has more importance than the others. Therefore, weight values W_i are used to give weight to each utility function. In this approach, the utility function can be defined by applying global criterion method [20] and each objective function has a special weight W_i. The mathematical description of the above mentioned method is given by (10):

$$Min\ F(X) = \sum_{i=1}^{n} W_i \times U_i(F_i(X)) = \sum_{i=1}^{n} W_i \times \left(\frac{F_i(X) - F_i(X^*)}{F_i(X^{**}) - F_i(X^*)}\right) \tag{10}$$

where $F(X)$ is the common objective function; X^* and X^{**} are solutions of the single objective optimization problems shown in (11) and (12):

$$Min\, F_i(X^*)$$
$$g_i(X^*) \le 0 \quad i = 1, 2, \ldots, m \tag{11}$$

$$Max\, F_i(X^{**})$$
$$g_i(X^{**}) \le 0 \quad i = 1, 2, \ldots, m \tag{12}$$

For selecting weight values W_i an Analytical Hierarchy Process (AHP) is used. The AHP is a decision making approach which makes dual comparisons between factors and choices, and then compares their weight or importance [21, 22]. In the AHP method, firstly matrix A should be formed as expression (13):

$$A = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & & \\ a_{n1} & \cdots & a_{nn} \end{bmatrix} \tag{13}$$

where a_{ij} is the corresponding element for comparison of *i*th objective function with *j*th one. In this paper, calculation of a_{ij} is done by the order of TABLE 1.

The compatibility of A is measured by:

$$a_{ij} = a_{ik} * a_{kj} \quad k = 1, 2, \ldots, n \tag{14}$$

TABLE 1

COMPARISON BETWEEN OBJECTIVES

Equal importance	**1**
Relative importance	**3**
Much importance	**5**
Very much importance	**7**
Absolute importance	**9**

Suppose that the decision makers' judgments are no longer consistent, the eigenvector W corresponding to the largest eigenvalue λ_{max} contains the priority weights of the decision elements in terms of the corresponding element in the hierarchy level. The priority weights are calculated as (15) [21, 23].

$$(A - \lambda_{\max} I)W = 0 \tag{15}$$

Here all of the objectives are functions of the amount of loads to be shed. The sequence of objective functions according to their importance is:

$$F_1(P_{shed}) = 1/\lambda_{cr} \tag{16}$$

$$F_2(P_{shed}) = \sum_{i=1}^{N} P_{shed} \tag{17}$$

$$F_3(P_{shed}) = \sum_{i=1}^{M} (V_{pu(ref)} - V_{pu(i)})^2 \tag{18}$$

λ_{cr}	Eigenvalue of the critical mode
N	Number of candidate buses
M	Number of buses in the region
$V_{pu(ref)}$	Reference of per unit voltage
P_{shed}	The amount of shed load

Based on the above scalar objective functions which have parallel changes with variation of P_{shed}, it is only needed to calculate the proper weight values to minimize the common objective function mentioned in (10). Equality and inequality constraints of the objective functions which must be satisfied are given as follows:

-Voltage stability constraint

$$\lambda_{cr} > 0 \tag{19}$$

-Generation and Consumption constraints

$$P_G = P_D + P_{loss} \tag{20}$$

$$Q_G = Q_D + Q_{loss} \tag{21}$$

-Bus Voltage constraint

$$V_{\min} \le V_i \le V_{\max} \tag{22}$$

-Line Flow constraint

$$S_{ij} \le \left| S_{(ij)\max} \right| \tag{23}$$

-Transformer tap setting constraint

$$0.9 \le T_P \le 1.1 \tag{24}$$

-Active generation constraint

$$P_{\min} \le P_i \le P_{\max} \tag{25}$$

-Reactive generation constraint

$$Q_{\min} \le Q_i \le Q_{\max} \tag{26}$$

MODELING A REAL POWER SYSTEM

In order to evaluate the performance of the proposed schemes, introduced in the previous sections, and compare them with the conventional under voltage load shedding (UVLS) schemes, a real power system is simulated in PSS/E software package. High-voltage network of the Gharb and Bakhtar, a part of the Iran's national transmission grid, is considered as the test case to analyze performance of the proposed schemes for a real-world power system. The Gharb and Bakhtar network is a grid with 109 buses at 230 and 400 kV levels. Total load of this system is about 3950MW in peak hours.

In this section, modeling of power system components is discussed briefly. In this study the sixth-order model is used for the modeling of system generators. The GAST, IEEEG1 and TGOV1 governor models are used for governor modeling and ESST1A, ESAC2A, and ESAC5A models are used for Automatic Voltage Regulator (AVR) modeling of the system generators. In this modeling, dependency of the loads on voltage and frequency are considered. Tables 2, 3 and 4 contain system data for the simulated network. In TABLE 2, active and reactive loads of stations of Gharb and Bakhtar areas are presented. In TABLE 3, generators' load flow data for Gahrb and Bakhtar areas, such as active and reactive power generation of each unit at peak time, maximum/minimum active and reactive power generation capacity, stator resistance and stator inductance of each unit, are presented. In TABLE 4, data of generators' dynamic model for Gharb and Bakhtar areas are given, which include number of units of each power plant, model type in dynamic simulation, transient open circuit time constants (T'_{do} , T'_{qo}), sub-transient open circuit time constants (T''_{do} , T''_{qo}), inertia constant (H), damping coefficient (D), synchronous reactances (X_d, X_q), transient reactances (X'_d, X'_q), sub-transient reactances (X''_d= X''_q) and stator leakage inductance (X_l).

TABLE 2. STATIC LOAD DATA OF GHARB AND BAKHTAR AREAS

Bus Name	Area Name	Pload (MW)	Qload (MVAR)
Arak	Bakhtar	54	7
Arak2	Bakhtar	171	59
Iralco	Bakhtar	197	103
Alminiumsa	Bakhtar	262	185
Farahan	Bakhtar	82	22
Asadabadi	Bakhtar	153	62
Fooladevian	Bakhtar	4	1
Shazand	Bakhtar	123	38
Hamedan	Bakhtar	127	21
Mofateh	Bakhtar	197	29
Labon	Bakhtar	76	24
Bahman	Bakhtar	181	46
Malayer	Bakhtar	112	37
Kiankordsa	Bakhtar	15	7
Azna	Bakhtar	100	35
Aznas	Bakhtar	106	29
Mahallat	Bakhtar	107	26
Saveh	Bakhtar	259	91
Anaran	Bakhtar	109	32
Khoramaba1	Bakhtar	96	35
Khoramaba2	Bakhtar	78	12
Kuhdasht	Bakhtar	63	12
Darreh Shar	Bakhtar	5	3
Sanandaj	Gharb	168	49
Badr	Gharb	26	3
Kangavar	Gharb	98	24
Islamabad	Gharb	59	18
Ilam	Gharb	78	24
Manesht	Gharb	38	9
Chamran	Gharb	50	16
Kermansha2	Gharb	124	25
Ooramanat	Gharb	50	15
Shargkersh	Gharb	177	26
Sarpolzahab	Gharb	228	93
Kermansha	Gharb	26	10
Divandareh	Gharb	44	7
Saghez	Gharb	71	21
Dehloran	Gharb	38	7

TABLE 3. GENERATORS LOAD FLOW DATA OF GHARB AND BAKHTAR AREAS

Units	Pgen (MW)	Pmax (MW)	Pmin (MW)	Qgen (MVAR)	Qmax (MVAR)	Qmin (MVA)	Mbase (MVA)	R Source (pu)	X Source (pu)
Shazand S1	315	325	220	115.2	160	-70	406.25	0.01016	0.1986
Shazand S2	310	325	220	114	160	-70	406.25	0.01016	0.1986
Shazand S3	310	325	220	114	160	-70	406.25	0.01016	0.1986
Shazand S4	300	325	220	112.8	160	-70	406.25	0.01016	0.1986
Mofateh S1	244	250	75	130.15	160	-40	312.5	0.01008	0.231
Mofateh S2	244	250	75	130.15	160	-40	312.5	0.01008	0.231
Mofateh S3	244	250	75	130.15	160	-40	312.5	0.01008	0.231
Mofateh S4	246	250	75	130.29	160	-70	312.5	0.01008	0.231
Sanandaj G11	115	159	50	33.23	71	-40	200	0.01	0.179
Sanandaj G12	115	159	50	33.23	71	-40	200	0.01	0.179
Sanandaj G13	115	159	70	33.22	71	-40	200	0.01	0.179
Sanandaj G14	115	159	50	33.23	71	-40	200	0.01	0.179
Sanandaj S1	118	159	50	33	71	120	-60	200	0.01
Sanandaj S2	0	159	70	0	71	120	-60	200	0.01
Zagros G11	120	160	50	40	72	-40	200	0.01	0.179
Zagros G12	120	160	50	40	72	-40	200	0.01	0.179
Zagros G11	120	160	50	40	72	-40	200	0.01	0.179
Zagros G12	120	160	50	40	72	-40	200	0.01	0.179
Bistoon S1	320	320	160	140	145	-120	400	0.01021	0.236
Bistoon S2	320	320	160	140	145	-120	400	0.01021	0.236

TABLE 4. GENERATORS DYNAMIC MODEL DATA OF GHARB AND BAKHTAR AREAS

Power Plant	Units	Model Type	T'_{do}	T''_{do}	T'_{qo}	T''_{qo}	H	D	X_d	X_q	X'_d	X'_q	X''_d	X_l
Bistoon	2	GENROU	8.76765	0.0390	2.11864	0.298	3.6	0	2.07	2.01	0.242	1.25	0.236	0.125
Mofateh	4	GENROU	7.76353	0.0173	0.88	0.105	3.2	0	1.93	1.89	0.266	0.5411	0.231	0.16
Sanandaj (G)	4	GENROU	10.5778	0.0288	1.2736	0.044	5.36	0	2.38	2.22	0.234	0.38	0.179	0.16
Sanandaj (S)	2	GENROU	10.5778	0.0288	0.436	0.257	5.36	0	2.38	2.22	0.234	0.38	0.179	0.16
Shazand	4	GENROU	7.8393	0.0566	0.7114	0.382	3.45	0	2.17	2.17	0.3211	0.3211	0.198	0.157
Zagros	4	GENROU	10.5778	0.0288	1.2736	0.044	5.36	0	2.38	2.22	0.234	0.38	0.179	0.16

DETECTION OF PROPER BUSES FOR INSTALLATION OF SPSS

Voltage stability phenomenon is usually a local problem, and the effect of lines, buses and generators on a specific mode is more tangible than other components of the network. Therefore, at first, a modal analysis is performed and boundary regions on the Gharb and Bakhtar areas of the Iranian transmission network for annual peak load of 2011 which have the same voltage behavior should be investigated. Then, an increase is applied to the loads of the case study areas and the generations are increased accordingly until the divergence limits are reached [24].

The simplest method to specify a loadability limit is based on repeated load flows, performed for increasing values of the system stress, until divergence is met. Avoiding the uncertainty of load flow divergence, the continuation power flow enables us to trace the solution path passing through the loadability limit [25].

When the system is stressed, the critical mode should be determined, which is associated with the smallest real eigenvalue. However, as the system approaches voltage stability boundary, eigenvalues that initially have small real parts may not be critical, and the other eigenvalues may become critical based on the direction of the stress [26].So the load increase is done in many steps until the nose of P-V curve is reached and then the most critical mode of voltage stability is identified by performing modal analysis.

The most critical mode of the area at the peak load is $\lambda = 2.0871$. After optimization of transformer tap settings and generator terminal voltages using BFO to get more voltage stability margin, the value of the most critical mode of the area increases to $\lambda = 2.113$. Ranking of the participation factors of buses, lines and generators are shown in TABLE 5 in a descending manner.

Results describe that Sarpol Zahab which is a heavy loaded station (228 MW, 93 MVAR) due to being far from load reactive compensators has the highest effect on the voltage instability mode. In addition, Bistoon power plant has the most effective generators on the voltage instability mode because of its great capacity (2*320 MW) and proximity to the weak part of the network regarding voltage stability problem. Finally, as the load on Bistoon-Islam Abad line is too high, this line has the greatest participation factor on the voltage instability mode.

The P-V curves of the buses mentioned in TABLE 5 for normal conditions are shown in Fig. 1. In Fig. 2, the P-V curves of the buses mentioned in TABLE 5 with optimized transformer tap settings and generator terminal voltages are shown.

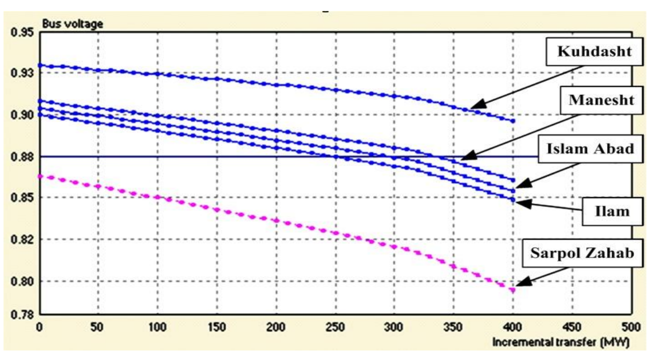

Fig. 1. P-V curves for the buses of TABLE 5 according to their participation factors in normal condition

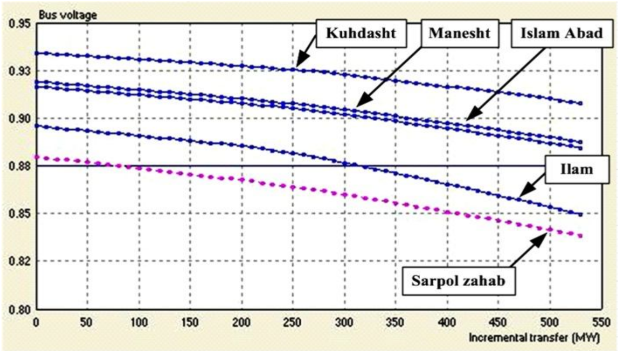

Fig.2. P-V curves of the buses of TABLE 5 after optimization of transformer tap settings and generator terminal voltages

Comparing Fig. 1 and Fig. 2, this can be concluded that the loadability margin has been increased by 35% after optimization of transformer tap settings and generator terminal voltages. According to TABLE 5 the worst single contingency of the lines and generators are indicated. By studying the various outages, it can be concluded that the worst contingency is the outage of Bistoon-Islam Abad line (230 KV), which highly reduces the most critical mode of the system ($\lambda = 0.467$) and weakens the system. Even if one of Bistoon units is out of service, trip of this line leads to power system voltage instability ($\lambda \leq 0$). In Fig. 3, P-V curves and in TABLE 6, voltages of buses in TABLE 5 after outage of Bistoon-Islam Abad line are shown.

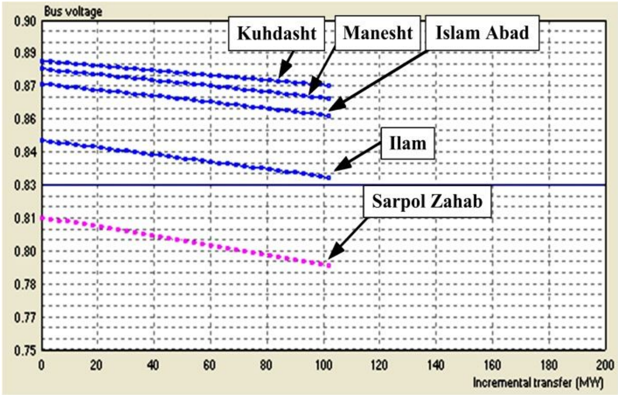

Fig. 3. P-V curves of buses in TABLE 5 after outage of Bistoon-Islam Abad line

TABLE 5
MOST EFFECTIVE BUSES, LINES, GENERATORS IN MOST CRITICAL MODE

PFR[1]	Bus	Transmission Line	Generator
1	Sarpol Zahab	Bistoon-Islam Abad	Bistoon
2	Ilam	Kermanshah2-Islam Abad	Bistoon
3	Islam Abad	Mofateh-east Kermanshah	Sanandaj
4	Manesht	Kermanshah2-Sanandaj	Sanandaj
5	Kuhdasht	Sanandaj-Chamran	Sanandaj

[1]PFR: Participation Factor Ranking

TABLE 6
VOLTAGE OF MOST EFFECTIVE BUSES AFTER WORST SINGLE CONTINGENCY AT PEAK TIME

Bus	Voltage (p.u.)
Sarpol Zahab	0.810
Ilam	0.857
Islam Abad	0.878
Manesht	0.889
Kuhdasht	0.891

The current state of SPSs in Gharb and Bakhtar areas are as shown in TABLE 7. Presently, the selection criterion of buses for installation of the SPS is the voltage profile and recent contingencies of the system. Because of low voltage in Sarpol Zahab and Ilam buses in normal condition, the threshold of the SPS activation is 0.85 per unit. In addition, it should be noted that the first block of load shedding after 1 second is for off-peak hours, and as a result less load curtailment is necessary.

TABLE 7
SPECIAL PROTECTION SYSTEM IN GHARB AND BAKHTAR AREAS

Bus	**Activationthreshold**	**1st LSB[1](1sec)**	**2nd LSB (1.5sec)**
Sarpol Zahab	0.85 Pu	19 MW	15 MW
Ilam	0.85 Pu	47 MW	10 MW
Islam abad	0.9 Pu	40 MW	3 MW
Kangavar	0.9 Pu	40 MW	53 MW

[1]LSB: Load shedding block

It is obvious that in peak hours by applying the outage of Islam Abad-Bistoon line, all buses with installed SPSs have voltages less than the threshold limit. According to TABLE 7, the first block of load shedding is executed and after this, the voltage magnitudes are still below oltage. As a result, after 0.5s, the second block of load shedding is implemented and the resu obtained based on the current SPSs.

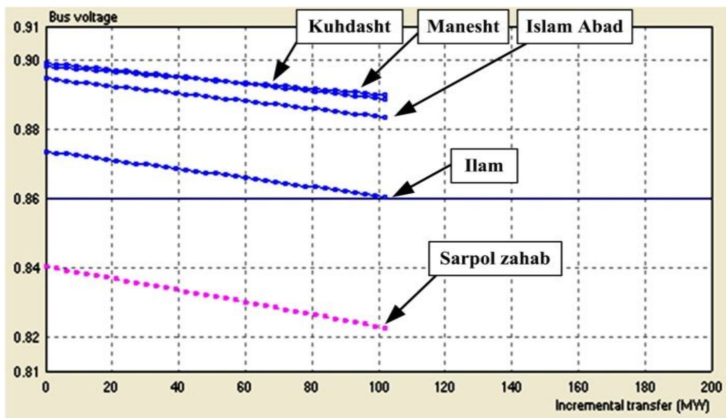

Fig. 4. P-V curves of the buses in TABLE 5 after applying the second block of load shedding based on the current SPSs

After determination of load shedding relays installation points by means of modal analysis, the optimum amount of loads to be shed for the highest stability margins and best voltage profile is obtained using optimization of common objective function intertwined with BFO and AHP methods. Amount of load shedding according to the proposed method is presented in TABLE 8.

TABLE 8
AMOUNT OF LOAD SHEDDING ACCORDING TO PROPOSED METHOD

Bus	After 1.5 sec	After 2 sec
Sarpol Zahab	35 MW	31 MW
Ilam	29 MW	24 MW
Islam Abad	21 MW	16 MW
Manesht	16 MW	17 MW
Kuhdasht	12 MW	11 MW

According to the results of TABLE 5, it is expected that the most proportions of load cut amount are allocated to the buses which have the maximum effect on the voltage instability mode. The results of TABLE 8 verify that the majority of load shedding relays (equal to 66 MW) needed to save system stability are installed in Sarpol Zahab station. Moreover load cut amounts have increased noticeably in peak hours that illustrateweakness of the Gharb and Bakhtar areas from voltage stability view point, especially during heavy loaded periods of time. Load shedding activation time would be determined after dynamic simulations.

For load areas with voltage stability problems, a contingency may leave the system vulnerable to a fast voltage collapse if a second contingency occurs. The second contingency may be a line or generator outage caused by undesirable operation of protective relaying. Overloads and low voltages resulted from the first contingency usually lead to the relaying. Under-voltage load shedding should be sufficiently fast to arrest the rapid voltage decrease [27, 28].

To determine voltage activation criterion of load shedding relays and ensure that load shedding scheme is fast enough to mitigate voltage collapse and prevent excessive load cut, dynamic simulation should be fulfilled. In Fig. 5, voltages of buses in TABLE 5 after N-2 contingency occurrence (Bistoon-Islam Abad line trips at t=1sec when one of Bistoon power plant's units is out of service) at off-peak time are shown. Here there is no load shedding and power system voltage instability occurs.

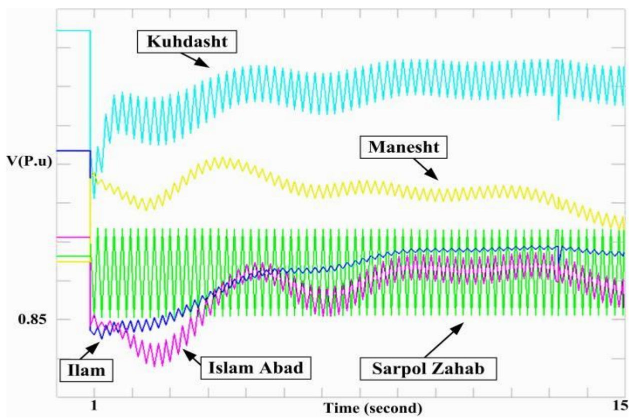

Fig. 5. Voltage of buses in TABLE 5 after N-2 contingency occurrence at t=1 sec (voltage unstable)

In Fig. 6, voltage of buses in TABLE 5 after N-2 contingency at off-peak time are shown when load shedding has not been applied as fast as enough (at t=6 sec) to mitigate voltage collapse.

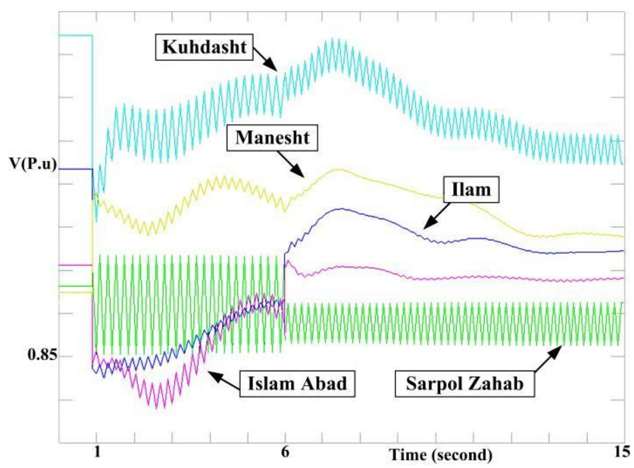

Fig. 6. Voltage of buses in TABLE 5 after N-2 contingency occurrence at t=1 sec and load shedding at t= 6 sec (voltage unstable)

To find out the proper delay time of relays for preventing voltage collapse, more dynamic simulations have been done and it is delineated that load shedding must be applied in less than t=3.2 sec. Consequently, time based simulations determine critical time of load shedding to suppress voltage instability and as a constraint $t_{load\text{-}shedding} < t_{critical}$. In Fig. 7, voltage of buses in TABLE 5 after N-2 contingency occurrence at off-peak time are shown when load shedding is applied in time (at t= 3 sec) to mitigate voltage collapse. Load shedding after t=3.2 sec. (considering circuit breaker and relay delay times) leads to voltage collapse unless the load shed amount increases.

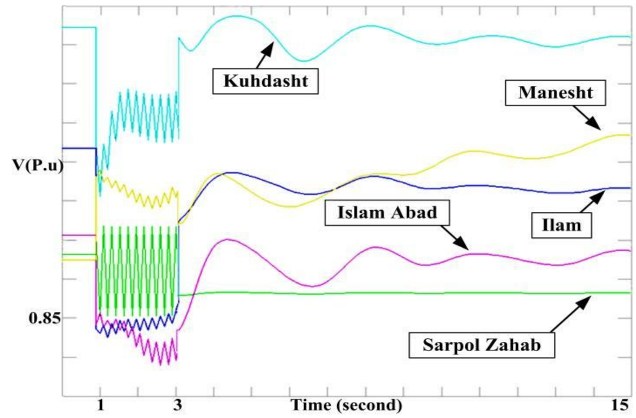

Fig. 7. Voltage of buses in TABLE 5 after N-2 contingency occurrence at t=1 sec and load shedding at t= 3 sec (voltage stability)

The activation criterion of load shedding relays is as follows: 0.85 p.u. for Sarpolzahab and Ilam, 0.88 p.u. for Islam Abad, and 0.9 p.u. for Manesht and Kuhdasht. It should be mentioned that after worst single contingency (Islam Abad- Bistoon line outage) for the most critical mode of peak load, the voltages would be lower than the defined amounts.

For peak time load shedding, the second block of load shedding is activated 0.5s after the first one. The P-V curves of buses in TABLE 5 after optimal load shedding by the proposed method are shown in Fig. 8. Comparison of the proposed method and current one in terms of total load shedding, voltage stability margin and average of voltage profile is presented in TABLE 9.

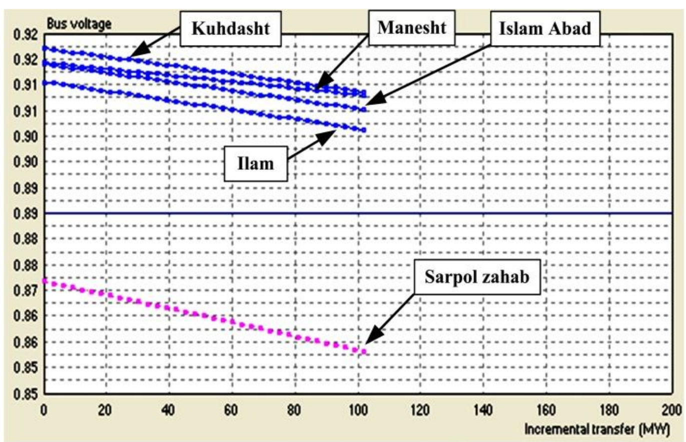

Fig 8. P-V Curves of buses of TABLE 5 after second block of load shedding by the proposed algorithm

TABLE 9

COMPARISON OF THE PROPOSED METHOD AND CURRENT ONE

Scheme	TLS[1] (MW)	VSM[2] (λ)	AVP[3] (p.u.)
Current Position	227	1.456	**0.914**
Proposed Algorithm	220	1.906	**0.931**

[1]TLS: Total load shedding
[2] VSM: Voltage stability margin
[3]AVP: Average of voltage profile

Comparison between Fig. 4 and Fig. 8 illustrates that unlike curr 11891 ng scheme, in the proposed method, voltage of Sarpol Zahab will be more than activation ays (0.85 P.u) after applying the second block of load shedding. Moreover, the results of TABLE 9 show that the proposed method has less load shedding by the amount of 7 MW compared to current scheme, while better voltage stability margin and voltage profile are obtained by the proposed method.

CONCLUSION

From voltage stability point of view, the transmission network of Gharb and Bakhtar areas is one of the weakest regions in the Iran's power system. Both areas experience lots of contingencies, which may lead to voltage collapse and cause extensive blackouts. As a result, the solution of load shedding is implemented in the region. In this paper, a new method using modal analysis intertwined with the BFO is proposed to determine the best points for installation of SPSs and minimization of load shedding while the best stability state and voltage profile is achieved. In addition, dynamic simulations determine proper critical time of load shedding and voltage threshold for relays' activation. Obtained results from the proposed method lead to lower load curtailment, higher voltage stability margin and better voltage profile compared to current load shedding scheme.

REFERENCES

[1] Kundur P. Power system stability and control. New York: McGraw-Hill; 1994.

[2] Grewal G S, Konowalec J W, Hakim M. Optimization of a load shedding scheme. IEEE Industry App Magazine 1998; 4(4): 25-30.

[3] Gao B, Kundur P. Toward the development of a systematic approach for voltage stability assessment of large scale power system. IEEE Trans Power Syst 1996; 11(3): 1314–1324.

[4] Hatziargyriou N D, Van Cutsem T. Indices predicting voltage collapse including dynamic phenomena. CIGRE Technical Report. Task Force, 38-02-11; 1994.

[5] Chattopadhyaya D, Chakrabarti B. A preventive/corrective model for voltage stability incorporating dynamic load shedding. Int J Electr Power Energy Syst 2003;25(5): 363–376.

[6] Van Cutsem T, Vournas C D. Emergency voltage stability controls: an overview. In : Power Engineering Society General Meeting 2007: 1–10.

[7] Masoud Esmaili, Ali Akbar Hajnoroozi, Heidar Ali Shayanfar. Risk evaluation of online special protection systems. Int J Electr Power Energy Syst 2012;41(1):137–144.

[8] Crossley P, Ilar F, Karlsson D. System protection schemes in power networks: existing installations and ideas for future development. In: Int Conf on Developments in Power System Protection. Publication No. 479, IEE 2001, pp. 450–453.

[9] Fernandes S P, Lenzi J R, Mikilita M A. Load shedding strategies using optimal load flow with relaxation of restrictions. IEEE Trans On Power Syst 2008; 23(2): 712–718.

[10] Jin L, Zhiyang L, Liafu L. An effiecint method for undervoltage load shedding. In: Int Conf on Power and Energy Engineering 2009, P. 1–4.

[11] Genc I, Diao R, Vittal V, Kolluri S, Mandal S. Decision tree-based preventive and corrective control applications for dynamic security enhancement in power systems. IEEE Trans Power Syst 2010(3); 25: 1611–1619.

[12] Capitanescu F, Van Cutsem T. Unified sensitivity analysis of unstable or low voltages caused by load increases or contingencies. IEEE Trans Power Syst 2005; 20(3): 321–329.

[13] Capitanescu F, Van Cutsem T, Wehenkel L. Coupling optimization and dynamic simulation for preventive-corrective control of voltage instability. IEEE Trans Power Syst 2009; 24(2): 796–805.

[14] Da Silva L C, Wang Y, Da Costa V F, Xu W. Assesment generator impact on system power transfer capability using modal participation factors. IEE Proc-Gener. Transm. Distrib 2002; 149(5): 564–570.

[15] Tripathy M, Mishra S. Bacteria foraging based to optimize both real power loss and voltage stability limit. IEEE Trans Power Syst 2007; 22(1): 240–248.

[16] Echavarren F M, Lobato E, Rouco L. A corrective load shedding scheme to mitigate voltage collapse. Int J Electr Power Energy Syst 2006; 28(1): 58–64.

[17] Begovic M, Fulton D, Gonzalez M R, Goossens J, Guro E A, Haas R W, Henville C F. Summary of system protection and voltage stability. IEEE Trans Power Delivery 1995;10(2): 631–638.

[18] Jethwa U K, Bansal R K, Date N, Vaishnav R. Comprehensive load-shedding system. IEEE Trans Industry App 2010; 46(2): 740–749.

[19] He S, Wen J Y, Prempain E, Wu Q H, Fitch J, Mann S. An improved particle swarm optimization for optimal power flow. In: Int Conf on Power System Technology, Singapore, November 2004. P. 1633–1637.

[20] Grudinin N. Reactive power optimization using successive quadratic programming method. IEEE Trans Power Syst 1998; 13(4): 1219–1225.

[21] Saaty T L. Fundamental of decision making and priority theory with the analytic hierarchy process. Pittsburg: RWS; 1994.

[22] Saaty T L. Decision making with the analytic hierarchy process. Int J Services Sciences 2008;1(1): 83–98.

[23] Salem M. An application of the analytic hierarchy process to determine benchmarking criteria for manufacturing organizations. Int J of Trade, Economics and Finance 2010; 1(1): 93–102.

[24] Xu Fu, Xifan Wang. Determination of load shedding to provide voltage stability. Int J Electr Power Energy Syst 2011; 33(3): 515–521.

[25] Voltage stability assessment: concepts, practices and tools. IEEE/PES Power system stability subcommittee. IEEE Press 2002.

[26] Mansour Y, Xu W, Alvarado F, Rinzin C. SVC placement using critical modes of voltage instability. IEEE Trans Power Syst 1993; 9(2): 131-137.

[27] Arnborg S, Anderson G. On under voltage load shedding in power systems. Int J Electr Power Energy Syst 1997; 19(2): 141–376.

[28] Nikolaidis V C, Vournas C D. Design strategies for load shedding schemes against voltage collapse in the Hellenic system. IEEE Trans Power Syst 2008; 23(2): 582–591.