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An Optimal Load Cut Policy with Event-Driven Design against Voltage Instability Using Theta-Particle Swarm Optimization

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ABSTRACT

The requirement for minimized cost whilst preserving power system reliability necessitates the development of both efficient system security assessment approaches and appropriate emergency remedial actions. Load shedding is a type of corrective actions that is applied to save power system stability against severe disturbances. This paper proposes an optimal load shedding policy that takes into account voltage stability of power system whenever a predetermined contingency occurs. After specification of load cut candidate points by V-Q sensitivity analysis the amount of load curtailment is determined by solving a non-linear multi-objective problem. A modified Theta-PSO algorithm with the lexicographic method is used to optimize the multi-objective function that consists of load cut amount, loading margin, branches' overload and deviation from voltage limits. In addition, dynamic simulations are performed to determine the critical time of load shedding. The proposed method is tested on Khorasan area of Iran's power system, which shows its better performance compared to the current load shedding scheme.

KEYWORDS: Load curtailment, V-Q Sensitivity Analysis, Modified Theta-PSO, Lexicographic Method, Voltage Stability

INTRODUCTION

Deregulation has changed power system operation during recent years. However, a market-driven approach cannot lessen the importance of system security aspect in operation [1]. In addition, due to the continuous increase of demand for electricity, operation of power systems closer to their transfer capability limits is widespread throughout the world, and voltage stability enhancement approaches have become a vital concern in power systems [2]. Therefore, it is an important task for dispatchers to be aware of the voltage stability margin of the system to apply appropriate actions to prevent voltage collapse. Massive research work can be found in literature to improve voltage stability margin (VSM) [3–8]. Either of two types of system disturbances generally generates voltage instability: unplanned component outage and load increase. Since trip of a heavily loaded transmission line or outage of a large generating unit may cause voltage collapse occurrence immediately, so load shedding as a last resort tool can mitigate a system blackout in these conditions. However, it is too important owing to economical reasons that an optimal load curtailment scheme is implemented to achieve minimization of the financial losses.

There are two kinds of defense type against voltage collapse and the associated risk of system blackout [9,10]:

- Preventive action: system security margins assessment with respect to credible (typically N-1) contingencies. For this purpose, it is quite common to compute load margin, i.e. the largest amount of load increase that the system can tolerate in its present condition without instability happening, and applying proper actions to enhance power system stability.
- Corrective action: face more severe disturbances that saving system stability requires to apply special protection systems (SPSs), i.e. protection developed to detect abnormal conditions and implement predetermined corrective actions (other than conventional equipment protection).

This paper deals with the second aspect and concentrates on voltage instability problem. In this context, several schemes can be considered as emergency control actions [11]:

- Shunt compensator switching;
- Emergency controls of generator voltages, which cause rising voltages and reducing reactive losses. It is well-known that the maximum power that a generator can transfer to a load increases with the square of voltage. Therefore, increasing generators voltage may lead more stability of system, if the resulted capability transfer of the maximum power will be larger than the power required for loads restoration [10].
- Optimization of transformers tap setting or blocking them in their current position. All these actions intend to prevent the load power restoration and increase the sensitivity of load to voltage.
- Load shedding, which is considered as a last resort and effective tool to mitigate voltage collapse only if performed before critical time with both adequate amount and proper location of load cut [12,13]. The power system is classified to five states according to

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its condition (i.e. normal, alert, emergency, extreme emergency and restorative). Load shedding is implemented under the emergency and extreme emergency states, when many operational limits are violated and hence the system approaches collapse point. There are three categories for load shedding schemes [14]. In the first group, the minimum amount of load cut is determined by time-based simulations incorporating dynamic aspect of the instability phenomenon like under-frequency load shedding schemes. The second category attempts to indicate optimal load curtailment amount by using dynamic load parameters estimation. Finally, the third group uses optimal power flow equations as a framework for calculation of minimum amount of load cut [9-12,14].

This paper proposes an optimal load shedding policy that takes into account voltage stability of power system whenever a predetermined contingency occurs. This scheme calculates the optimal amount of load shed in an hour ahead horizon against severe contingencies, which are able to make the power system unstable. In other words, the suggested defense plan is applied in study mode with an event-driven base that can prevent voltage instability in the studied area whenever such catastrophic events happen. In the first stage after contingency analysis and indicating the credible contingencies that increase the risk of voltage collapse, effective buses for load shedding are selected by *V-Q* sensitivity analysis. In the second stage a nonlinear multi-objective function is defined to calculate the optimal amount of load cut regarding desired parameters in multi objective function that are load margin of the studied area, load shed amount and operational constraints. To optimize the multi-objective function a modified Theta-PSO (MTPSO) algorithm and the lexicographic method are used. After determination of both location and amount of load cut, the critical time for load shedding implementation must be calculated by dynamic simulations. Finally, the proposed method is applied in Khorasan area of Iranian transmission network in 2012 year to test its efficiency comparing with current load shedding scheme of this area. This paper is organized as follows; in section II the *V-Q* sensitivity analysis method is demonstrated, in section III the terms of the multi-objective function are expressed, in section IV the modified TPSO algorithm that is used for solving optimization problem is illustrated and finally in section V the proposed method is tested and simulation results are presented.

V-Q SENSITIVITY ANALYSIS

To calculate the Jacobian matrix of power system, the linearized equations of the system power flow can be used via the following expression [15]:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \theta} & \frac{\partial P}{\partial |V|} \\ \frac{\partial Q}{\partial \theta} & \frac{\partial Q}{\partial |V|} \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta |V| \end{bmatrix} \quad (1)$$

where ΔP, ΔQ, $\Delta \theta$, $\Delta |V|$ represent variation in bus real powers, reactive powers, voltage angles and voltage magnitudes, respectively; $\frac{\partial P}{\partial \theta}$, $\frac{\partial Q}{\partial \theta}$, $\frac{\partial P}{\partial |V|}$, and $\frac{\partial Q}{\partial |V|}$ are the elements of the Jacobian matrix indicating the sensitivity between the injected powers and bus voltages. According to the large dimensions of the Jacobian matrix that causes time consuming calculations, the reduced Jacobian matrix is used where the assumption of $\Delta P = 0$ is implemented in online environments [15]:

$$\Delta Q = J_R . \Delta |V| \quad (2)$$

$$J_R = \left(\frac{\partial Q}{\partial |V|} \right) - \left[\left(\frac{\partial Q}{\partial \theta} \right) \left(\frac{\partial P}{\partial \theta} \right)^{-1} \left(\frac{\partial P}{\partial |V|} \right) \right] \quad (3)$$

where J_R is the reduced Jacobian matrix of the system. The effect of ΔP is considered by investigating the relationship between *V* and *Q* at different conditions of system. From equation 2 we may write [15]:

$$\Delta |V| = J_R^{-1} . \Delta Q \quad (4)$$

The matrix J_R^{-1} is the reduced *V-Q* Jacobian. Its i^{th} diagonal element is the *V-Q* sensitivity at bus *i*. For computational efficiency, this matrix is not explicity formed and as mentioned the *V-Q* sensitivities are calculated by solving equation 2. The voltage instability phenomenon occurs when at least one of the system eigenvalues, obtained from Jacobian matrix, is negative. In other words, the system is stable whilst λ_{min} (representing minimum eigenvalue of Jacobian matrix) has a positive value [2,15].

The *V-Q* sensitivity at each bus demonstrates the slope of the *Q-V* curve at the given operating point. A positive *V-Q* sensitivity value is expressive of a stable operation; the smaller the sensitivity, the more stable the system. As stability decreases, the magnitude of the sensitivity increases, becoming infinite near voltage collapse point. Conversely, a negative *V-Q* sensitivity is indicative of voltage instability occurrence. A small negative sensitivity represents a very unstable operational condition [15]. Consequently, by means of *V-Q* sensitivity concept buses with larger sensitivity are selected as candidate points for load shedding.

MULTI-OBJECTIVE FUNCTION DEFINITION

In the proposed method to design an efficient load shedding scheme a multi-objective function is defined. This multi-objective function consists of four single objective functions, which are in conflict with each other. In addition, this problem may have many constrains leading to the following formulation:

$$\min\{OF_1(X), OF_2(X), ..., OF_h(X)\} \quad (5)$$

$$C_i(X) \le 0 \quad i = 1, 2, ..., g \quad (6)$$

Where $OF_i(X)$ are the objective functions, by the number of h, and $C_i(X)$ are the constraints, by the number of g, for the multi-objective optimization problem. After determination of candidate buses, the amount of load to be shed must be calculated. For this task some factors such as load margin of the area indicating voltage stability margin, the minimum amount of curtailed load, the amount of branches' overload and deviation of voltage limits must be considered in the objective functions. Here all of the objectives are a function of load cut amount. In the following, these functions are presented according to their importance in the suggested scheme:

$$OF_1(P_{cut}) = 1/LM \quad (7)$$

$$OF_2(P_{cut}) = \sum_{i=1}^{LC} P_{cut} \quad (8)$$

$$OF_3(P_{cut}) = \sum_{j=1}^{B}\sum_{i=1}^{B}(S_{ij} - S_{ij(\max)}) \qquad if \quad S_{ij} \ge S_{ij(\max)} \quad (9)$$

$$OF_4(P_{cut}) = \sum_{i=1}^{B}(|V_{(i)}^*| - |V_{(i)}|)^2 \qquad if \quad |V_i| \notin \left(|V_{min}|, |V_{max}|\right) \quad (10)$$

LM	Load margin of the area
LC	Number of load cut points
B	Total number of the area buses
P_{cut}	The load cut amount
S_{ij}	The apparent power flow between bus *i* and
$S_{ij(\max)}$	The maximum loadability of a branch
$\lvert V_{(i)}^*\rvert$	The magnitude of voltage reference at bus *i*
$\lvert V_{\min}\rvert$	The lower limit of voltage magnitude
$\lvert V_{\max}\rvert$	The upper limit of voltage magnitude

This optimization is an inverse problem that minimizing the load cut amount requires maximization of the other single objective functions. One way to handle this multi-objective optimization problem is the lexicographic method. Here, a pre-defined ordering is established between the competing objectives and then, each objective is optimized one at a time. This technique needs a decision-maker to establish a priority for each objective [16]. Lexicographic method is based on this assumption that the objectives can be ranked in the order of their importance. We can assume, without loss of generality that the objective functions are in the order of importance so that OF_1 is the most important objective function and OF_k the least important one to the decision maker. The lexicographic method consists of solving a sequence of single objective optimization problems of the form:

$$\min OF_l(X) \quad (11)$$

$$s.t. \;\; OF_j(X) \le OV_j^* \;\; , j = 1, 2, ..., l-1 \quad (12)$$

Where OV_j^* is the optimal value of the above problem with l=j. Therefore, $OV_j^* = \min\{OF_l(X)\}$ and each new problem of the form in the above problem in the sequence adds one new constraint as l goes from 1 to k (k is the number of objective functions). The lexicographic method is usually useful when dealing with few objectives (three or four). It should also be noted that sometimes its performance is tightly subject to the ordering given by the set priorities [16,17].

Equality and inequality constraints of the single objective functions, which must be satisfied are given as follows:

-Active and reactive power balance constraints

$$AP_{Gen} = AP_{Load} + AP_{loss} \quad (13)$$

$$RP_{Gen} = RP_{Load} + RP_{loss} \quad (14)$$

-Voltage collapse threshold

$$\lambda_{\min} > 0 \quad (15)$$

-Active power of generating units constraint

$$AP_i^{\min} \le AP_i \le AP_i^{\max} \quad (16)$$

-Reactive power of generating units constraint

$$RP_i^{\min} \le RP_i \le RP_i^{\max} \quad (17)$$

Where AP_{Gen} and RP_{Gen} are total active and reactive power of generators, AP_{Load} and RP_{Load} are total network demand of active and reactive power. At last, this multi-objective function can be solved by MTPSO algorithm.

THETA-PARTICLE SWARM OPTIMIZATION ALGORITHM

Kennedy and Eberhart introduced PSO algorithm in 1995 as a modern heuristic optimization method [18]. PSO is a population-based technique in which random solutions named ‘particles’ move around in a multidimensional problem search space. The particles adjust their position according to their own experience and sharing their information with each other and consequently run toward best path to seek optimum solution in an iterative process. Two vectors determine the status of a particle on the search domain: its position and velocity, which in each iteration are updated by following equations:

$$V_{i,iter+1} = wV_{i,iter} + c_1 r_1 (P_{i,iter}^{best} - X_{i,iter}) + c_2 r_2 (G_{iter}^{best} - X_{i,iter}) \quad (18)$$

$$X_{i,iter+1} = X_{i,iter} + V_{i,iter+1} \quad (19)$$

where $V_{i,iter}$ and $X_{i,iter}$ are the velocity vector and the position vector of i^{th} particle at iteration *iter*, respectively; $P_{i,iter}^{best}$ is the best previous position of the *i*th particle in the iteration *iter* and G_{iter}^{best} is the global best position among the entire population in iteration *iter*, respectively; w is inertia weight factor which controls the global and local detection abilities of particles; c_1 and c_2 are cognitive and social coefficients, respectively; r_1 and r_2 are two random numbers between 0 and 1.

The main idea of Theta-PSO algorithm is to consider the ‘phase angle vector’ in its both velocity and position vectors and in comparison to the conventional PSO algorithm this assumption leads to reach faster stable convergence [19 and 20]. In Theta-PSO, the increment of phase angle substitutes for the increment of velocity and mapping of the phase angle indicates the position of particles. Theta-PSO can be formulated in vector notation as follows:

$$\Delta\theta_{i,iter+1} = w\Delta\theta_{i,iter} + c_1 r_1 (\theta_{i,iter}^{best} - \theta_{i,iter}) + c_2 r_2 (\theta_{iter}^{gbest} - \theta_{i,iter}) \quad (20)$$

$$\theta_{i,iter+1} = \theta_{i,iter} + \Delta\theta_{i,iter+1} \quad (21)$$

$$X_{i,iter} = \frac{X_{\max} - X_{\min}}{2} \sin\theta_{i,iter} + \frac{X_{\max} + X_{\min}}{2} \quad (22)$$

Object ($X_{i,iter}$)=objective , i =1, 2,…, $N_{particle}$ (23)

Where $\theta_{i,iter}$ and $\Delta\theta_{i,iter} \in (-(\pi/2), +(\pi/2))$. c_1, c_2, w, r_1, r_2 and $X_{i,iter}$ are the same as those in (18) and (19) mentioned; $\theta_{i,iter}$ is the phase angle of *i*th particle in iteration *iter*; $\Delta\theta_{i,iter}$ is the increment of the phase angle of particle *i* in iteration *iter;* $\theta_{i,iter}^{best}$ is the phase angle of the individual best solution of the *i*th particle in iteration *iter;* θ_{iter}^{gbest} is the phase angle of the global best solution in iteration *iter;* X_{max} and X_{min}

are the permissible maximum and minimum position of particles, respectively. Object ($X_{i,iter}$) is the fitness value of the *i*th particle in the iteration *iter*.

Applying this technique, makes the space search limited to a small area in Theta-phase. The reasons are (i) all of the variables are in the same range, (ii) a segment-to-segment searching process is fulfilled and (iii) the searching procedure is much more compressed than the real domain. Consequently, Theta-PSO algorithm seeks the allowable area more accurately. In addition, the nonlinear characteristics of the optimization problem are considered more efficiently by using the nonlinear mapping to calculate the objective function variables. Therefore, this technique is implemented in the proposed method to enhance the multi-objective problem optimization.

Theta-PSO algorithm has better optimization performance when handling some simple benchmark functions in comparison with basic PSO algorithm [19]. To improve the efficiency of Theta-PSO, we modify the inertia weight '*w*' to decrease linearly during the iterations [22]:

$$w = (w_{\max} - w_{\min})\left(\frac{iter_{\max} - iter}{iter_{\max}}\right) + w_{\min} \tag{24}$$

where $iter_{\max}$ is the maximum number of iterations.

In addition, it is difficult for basic Theta-PSO algorithm to overcome the local minima when dealing with some complicated or multi-mode objective functions. Therefor to overcome this problem, in this investigation we have implemented a mutation operator in the phase angle (θ) calculation if the personal fitness value has not improved compared the last iteration's result. i.e., if $F_{i,iter} > F_{i,iter-1}$, a mutation operator is proposed in the basic Theta-PSO algorithm as following:

$$\theta_{i,iter+1} = -\theta_{i,iter} \times r_2\left(\frac{iter}{iter_{\max}}\right) \tag{25}$$

Owing to symmetrical range of phase angle a minus value of $\theta_{i,iter}$ is selected.

SIMULATIONS AND RESULTS

Control actions in the modern power system dispatching centers are performed in either real-time or study mode. Some of them like state estimation are real-time tasks and some others like dynamic security assessment (DSA) are performed in study mode [21]. The suggested policy for load shedding is based on an event-driven design that activated whenever a predetermined severe disturbance occurs. These defense plans against such terrible incidents that may cause voltage instability within few seconds must be fast enough to prevent fast voltage decay [2]. For this purpose, to determine the critical time of load cut, time-based simulations are necessary. The suggested load curtailment policy has a time-consuming calculation process including optimization of a nonlinear multi-objective function and time-based simulations that requires performing in study mode.

The procedure of the proposed scheme is categorized in three stages; at first stage, most effective contingencies, which lead voltage collapse, are determined. These contingencies are derived using experiences of former incidents and contingency analysis methods [22,24]. In addition, it is noticeable that these contingencies include only single outages of components but it is maybe that some of them make other forced outages because of activation of branches overload protection or under voltage protection of equipment. In the second stage based on credible contingencies, for each contingency one defense plan is developed. To provide these load curtailment schemes, indication of candidate points for load shedding with calculation of load cut amounts are required. In the third stage, the critical time for load shedding must be determined by time-based simulations. In other words, load shedding after the critical time cannot mitigate voltage instability.

Khorasan area of Iran power grid is simulated in PSS/E software to test the efficacy of the suggested load shedding policy. Khorasan area consists of 277 buses in 400 KV and 132 KV voltage level, 302 lines and 64 transformers. Also, this area contains 42 generating units feeding the total load of the area which is about 2450 MW at peak hours in year 2012. The GAST, IEEEG1 and TGOV1 types of governor models and ESST1A, ESAC2A, and ESAC5A types of Automatic Voltage Regulator (AVR) models are used to simulate the sixth-order model of the system generators.

In TABLE 1 some of the credible contingencies incorporating in voltage instability mode are presented. These are most effective disturbances, which are able to approach the system to voltage collapse point. In addition to contingencies, the resulted values of λ_{min} after each contingency are shown in TABLE 1.

TABLE 1

CREDIBLE CONTINGENCIES OF KHORASAN AREA

Contingency	Component Type	Voltage Level	λ_{min}
C.C KAVE-BIRJAND	Line	400 KV	0.236
BIRJND (T1/ T2)	Transformer	400 / 132 KV	0.272
TORBAT JAM-C.C KAVE	Line	400 KV	0.285
C.C NEYSHABOUR-SHADMEHR	Line	400 KV	0.294
SHADMEHR-MODARES	Line	400 KV	0.298
GHOLAMAN-JALALABAD	Line	132 KV	0.337
SARBISHEH-NEHBANDAN	Line	132 KV	0.354
GHAEN (G11/G12/G13)	Generator	132 KV	0.379

Although BIRJAND transformer outage has larger value of λ_{min} than worst single contingency (C.C KAVE-BIRJAND), this outage is the most serious event among all single contingencies leading to voltage collapse. It is due to over loading of another transformer of the station and its fast trip by overload protection in a few seconds, which makes the system unstable ($\lambda_{min} < 0$). In the following, the proposed method is applied to cope with the voltage instability resulted by this disturbance. Obviously, testing the suggested method in the worst case can guarantee its efficiency against all of single contingencies. Candidate buses for load shedding are indicated by *V-Q* sensitivity analysis, so selected ones are listed in TABLE 2 according to their participation in voltage instability occurrence in a descending way. Also the voltages of these buses in base case are presented.

TABLE 2

CANDIDATE BUSES FOR LOAD CUT ACCORDING TO THEIR SENSITIVITY VALUES

Bus	Voltage (p.u.)	Sensitivity Value
BOOALI	0.928	1.36
NEHBANDAN	0.931	1.17
ASADIEH	0.939	1.15
SAHLABAD	0.943	1.05
GHOLAMAN	0.946	0.95
HAJIABAD	0.948	0.92
SALEHABAD	0.962	0.92
SADEH	0.971	0.89
ESFANDAN	0.982	0.83
CHOGHART	0.998	0.82

These ten buses, which have most effect on voltage stability mode, are selected as candidate points for load shedding. In Fig. 1 the Q-V curve of BOOALI bus as the most vulnerable bus, regarding voltage stability margin is shown. In Fig. 2 the Q-V curve of BIRJAND bus that is not enough productive to be selected for load cut is plotted.

Fig. 1) Q-V curve of BOOALI bus in normal condition

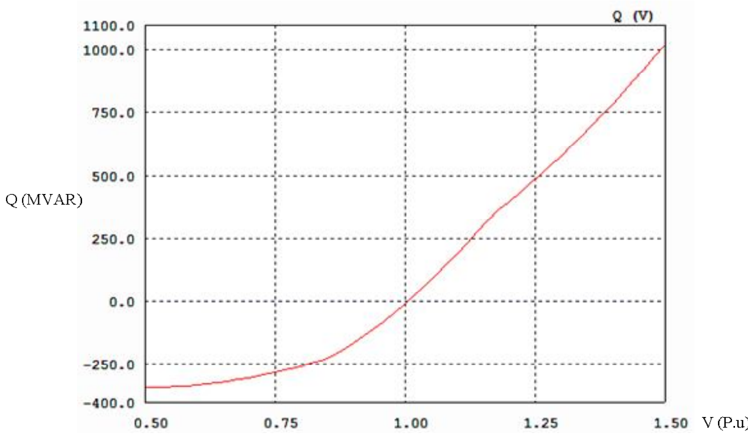

Fig. 2) Q-V curve of BIRJAND bus in normal condition

Comparison between these two figures illustrates that BOOALI bus is too sensitive about reactive power changes, and injecting reactive power about -13 MVAR to this bus leads voltage collapse whereas this amount is about -340 MVAR for BIRJAND. It should be noted that in the studied area as the voltages of buses reach under 0.5 p.u, the under voltage protection open all circuit breakers of the station, therefore the threshold of voltage collapse is 0.5 p.u in practice. In Fig. 3, the P-V curves of the buses referred to in TABLE 2 are plotted under the normal condition. Also the P-V curves of TABLE 2 buses after the outage of one of the BIRJAND transformers are shown in Fig. 4.

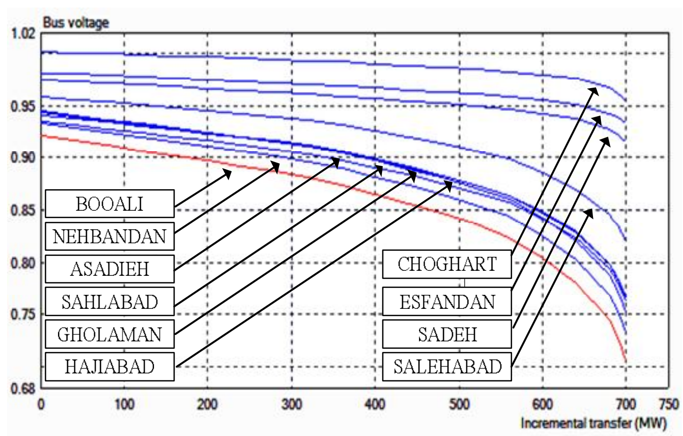

Fig. 3) P-V curves of the TABLE 2 buses in normal condition

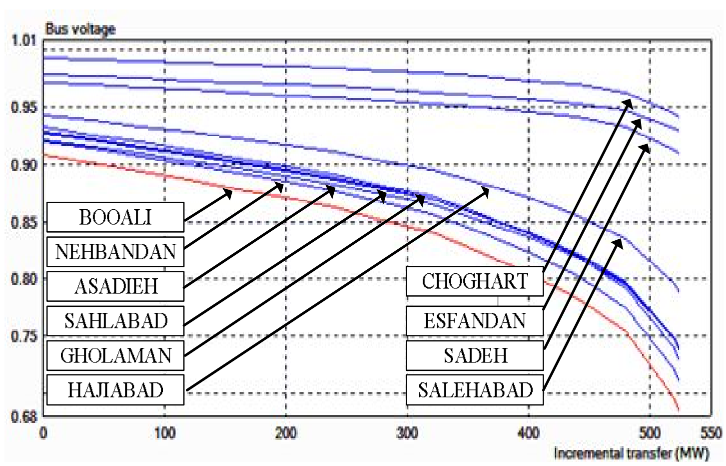

Fig. 4) P-V curves of the TABLE 2 buses after BIRJAND transformer outage

After this outage as Fig. 3 and Fig. 4 show the load margin of area decreases about 175 MW. In Fig. 5 and Fig. 6 the P-V curves of TABLE 2 buses are shown where the current load shedding scheme and the proposed one are applied, respectively.

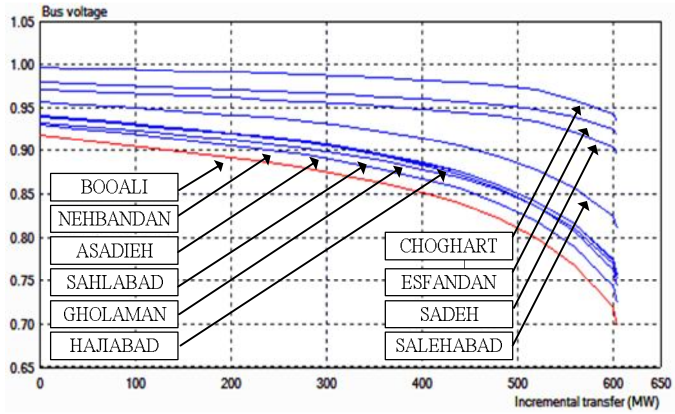

Fig. 5) P-V curves of the TABLE 2 buses after activation of current Khorasan SPSs

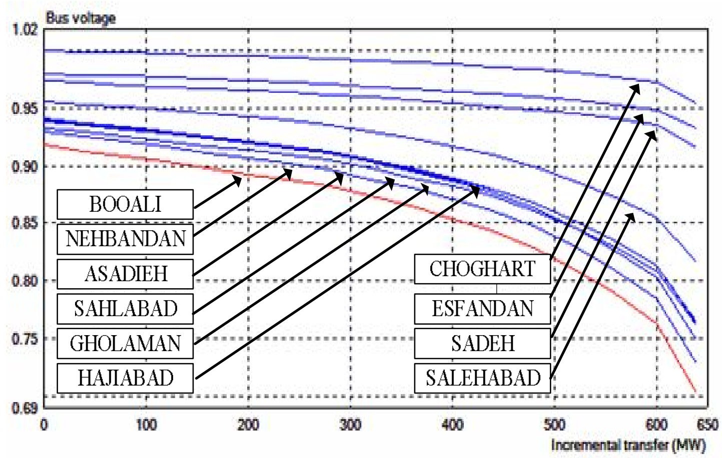

Fig 6) P-V curves of the Table 2 buses after implementation of the proposed load shedding scheme

The load margin of the studied area after implementation of the proposed load shedding scheme increases about 40 MW more than the current scheme as shown in figures 5 and 6. In TABLE 3, the load cut amounts after implementation of both current and proposed SPSs of Khorasan area are presented. It is important to note that these amounts are derived by optimization of the multi-objective function based on the outage of BIRJAND station transformers.

TABLE 3

LOAD CUT AMOUNTS FOR BOTH LOAD SHEDDING SCHEMES

Proposed load shedding scheme		**Current load shedding scheme**	
Bus load	Load cut amount	Bus load	Load cut amount
BOOALI	18 MW	BOOALI	14 MW
NEHBANDAN	16 MW	NEHBANDAN	9 MW
ASADIEH	14 MW	ASADIEH	10 MW
SAHLABAD	13 MW	SAHLABAD	13 MW
GHOLAMAN	12 MW	GHOLAMAN	10 MW
HAJIABAD	12 MW	HAJIABAD	28 MW
SALEHABAD	11 MW	SALEHABAD	7 MW
SADEH	10 MW	SADEH	9 MW
ESFANDAN	8 MW	ESFANDAN	11 MW
CHOGHART	7 MW	CHOGHART	17 MW

The results show that weak buses require more load shedding for a stable operation; the larger the sensitivity, the larger the amount of load cut. Moreover, the current state of load shedding scheme of the area is based on experiences of former incidents regarding voltage profile of weak buses.

According to the previous explanation in the studied area, the under-voltage protection cause opening all circuit breakers of any station whenever its voltage reaches under 0.5 p.u. Therefore, to prevent cascading outages of power system components due to under-voltage protection, load shedding must be performed before the voltage goes under 0.5 p.u. To this end, time-based simulations are required to determine the critical time of load shedding. Running dynamic simulations in PSS/E software indicates the critical time for load shedding as shown in Fig. 7. This figure illustrates that after tripping the second transformer of BIRJAND station, voltages of vulnerable buses decrease rapidly as the voltage of BOOALI reaches 0.5 p.u just 1.46 second after this outage. Consequently, load curtailment must be performed before this time (considering circuit breakers, relays and communication delay) until can mitigate blackout resulted by voltage instability source. In addition it is useful to know that voltage will be unstable at t=3.318 sec if the under voltage protection is not activated.

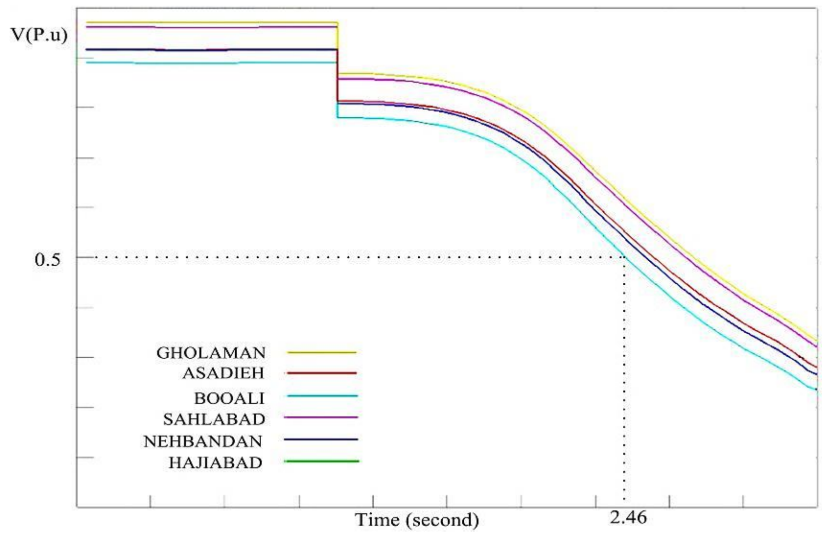

Fig. 7) Voltage of some of TABLE 2 buses after the outage of second transformer of BIRJAND station at t=1 (voltage unstable at t=3.318)

A comparison among the results derived by implementation of both current state and proposed load shedding schemes is presented in TABLE 4. This table contains a comparison among single objective functions values resulted after load shedding.

TABLE 4
COMPARISON OF THE CURRENT STATE AND PROPOSED METHOD

Load Shedding Scheme	TLC[1] (MW)	LM[2] (MW)	SVD[3] (p.u)	SBO[4] (p.u)
Current state	128	600	0.977	**0.011**
Proposed method	121	640	0.943	**0**

[1]TLC: Total Load Cut
[2]LM: Load Margin
[3]SVD: Sum of Voltages Deviation
[4]SBO: Sum of Branches Overload

The results of TABLE 4 represent that despite smaller load cut amount in comparison with the current state, the proposed load shedding scheme leads to more voltage stability margin with less violation of operational constraints.

CONCLUSION

Owing to voltage stability weakness of Khorasan area against severe contingencies, presently a load shedding scheme is developed for this area. To enhance the voltage stability of this area an optimal load cut policy with event-driven design is proposed. This scheme is based on optimization of a multi-objective function by MTPSO to find the minimum amount of load cut whenever a severe disturbance occurrence may lead to voltage collapse. Applying this scheme against such incidents proves its efficiency in simulations, when a comparison is performed between the results of the proposed scheme and the current one.

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