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Optimal Design of Load Shedding and Generation Reallocation in Power Systems Using Fuzzy Particle Swarm Optimization Algorithm

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Abstract: Load shedding and generation reallocation (LSGR) schemes are important and powerful tools in the present day power systems to maintain system stability. In this study, a new method has been presented on the basis of Fuzzy Particle Swarm Optimization (FPSO) algorithm in order to reduce the LSGR in the form of real optimization. By real optimization in this method, it means using the discrete variables for LSGR problem by real steps of load decreasing in every buses and reallocation steps in power plant productions. Also, by considering the system frequency as an essential variable and using the electrical load model with the essential constraints, the LSGR problem is solved. Referring to the above facts and considering the large number of variables in optimization issue, utilization of the FPSO algorithm is very useful in finding the optimal procedure for LSGR problem. Finally, in order to test the proposed method, it has been implemented on the IEEE 14-Bus system and acceptable results have been obtained.

Key words: Load shedding, generation reallocation, fuzzy particle swarm optimization algorithm

INTRODUCTION

During emergency conditions, one of the main operator's tasks is to keep as many customers on-line as possible. For these various, more or less traditionally tools, such as Generation Reallocation (GR), modification of exchange schedules with neighboring systems, line switching and finally, Load Shedding (LS) are available. With minimum operator activity, constraint violations should be removed and still maximum amount of load served. During normal operation, the focus is on safe and economical operation of the power system. This is achieved to typically minimize transmission losses or production cost. In an emergency situation, safe operation combined with minimal LSGR is the main objective problem. To do this, power plant productions are minimally disturbed and minimum amount of load has to be dropped. Therefore, it can be concluded that the LSGR problems will carry with itself an optimization process that its objective function is made up of load shedding and generation reallocation values and constraints of the above optimization are restriction of system variables.

To solve the LSGR problem, various procedures have been presented. In most cases, the problem of load shedding have been discussed by Aik (2006), Hooshmand *et al*. (1998), Halevi and Kottick (1993), Xu and Girgis (2001) and since the amount of power production in power plants with due to continual varying of system frequency, so ignoring generation reallocation in power plants makes the above mentioned optimization farther from real conditions over the system. Also in many presented methods (Halevi and Kottick, 1993; Yao *et al*., 2005; Xu and Girgis, 2001; Tso *et al*., 1997), frequency deviations as an essential variable in optimization process have not been discussed. Moreover, due to the depending of the electrical loads of the system on voltage and frequency variations, electrical load models have not been considered (Halevi and Kottick, 1993; Yao *et al*., 2005; Xu and Girgis, 2001; Hsu *et al*., 2005; Thalassinakis *et al*., 2006; Ding *et al*., 2006; Tso *et al*., 1997) and the loads have been discussed as fixed amounts which are far from the real facts.

Other important problems, which should be considered in load shedding, are its omission from system busses in periodical order. In other words, the amount of load shedding can't be considered as a continuous variable, because by outage of the feeders in every bus, a specific percent of your option load is omitted. Therefore, the load variations make the optimization of the problem not to act as a real case (Hooshmand *et al*., 1998; Palaniswamy and Sharma, 1985; Halevi and Kottick, 1993; Xu and Girgis, 2001; Luan *et al*., 2002; Hsu *et al*., 2005).

In the published literature on the topic of LSGR problem, different techniques such as linear optimization (Hooshmand *et al*., 1998; Halevi and Kottick, 1993), nonlinear optimization (Aik, 2006; Verzija, 2006), employing frequency relays (You *et al*., 2003), dynamic programming (Verzija, 2006; Ding *et al*., 2006) and intelligent systems have been used. Also with due to lack of uncertainty in the constraints of power system, employing the optimization with fuzzy technique in the LSGR problem has been noticed (Hooshmand *et al*., 1998; Tso *et al*., 1997). In this method, the load shedding values have been considered as continuous variables. In some studies also load shedding problem have been solved by using genetic algorithm (Yao *et al*., 2005; Luan *et al*., 2002). Also in Hsu *et al*. (2005), Purnomo *et al*. (2002) and Thalassinakis *et al*. (2006) application of neural network technique in load shedding problem has been presented. In addition, in Ding *et al*. (2006) and Tso *et al*. (1997) the load shedding problem by using a set of dominating rules over power systems is formulated and then load shedding is done intelligently. But using this technique doesn't lead to ideal optimization.

In this study, a new method based on FPSO algorithm for solving the LSGR optimization problem, together with electric loads and frequency deviation of the system and other essential constraints is presented. In this method, the aim is to consider the real ruling conditions over power system variables those are:

- Considering load shedding and generation reallocation like discrete variables with due to existing and variable steps at that variation in constructing the alphabet set of FPSO algorithm
- Considering system frequency variations in changes of power plant productions and load flow equations;
- Considering the real model of electric loads dependency on voltage and frequency
- Finally, modeling of power system constraints as well as operational limitations is considered as good as possible

THE CRISP LSGR FORMULATION

As, it was explained earlier, the LSGR problem is a constrained optimization problem. The objective function is made up of load shedding and generation reallocation values. The concerned constraints consist of: load flow limits, line flow limits, voltage magnitude, maximum and minimum of loads and generation active and reactive powers, the limit of frequency deviation and tap-changer of transformers.

THE OBJECTIVE FUNCTION

The LSGR problem can be formulated as an optimization problem, which attempts to minimize load shedding and generation deviations from the nominal state. These objectives are transformed into the minimization of a scalar penalty function J that is the sum of two terms. The first term penalizes load shedding and the second penalizes deviations in the generation schedule. More precisely, J is defined by:

$$J = \sum_{i=1}^{NB} l_i(\Delta PL_i, \Delta QL_i) + \sum_{i=1}^{NG} g_i(\Delta PG_i, \Delta QG_i) \qquad (1)$$

where, l_i and g_i are nonlinear penalty functions, which will take a unique minimum value at the nominal state. One of the most acceptable objective functions is a quadratic function. Based on Eq. 1, the quadratic objective function is defined by:

$$J = \sum a_i.\Delta PL_i^2 + \sum b_i.\Delta QL_i^2 + \sum c_i.\Delta PG_i^2 + \sum d_i.\Delta QG_i^2 \qquad (2)$$

where, PG (PL) and QG (QL) represent active and reactive powers of a generator (a load) and represents deviation from nominal value. In appendix A, it is discussed how the coefficients a_i, b_i, c_i and d_i in the objective function of the above equation may be selected. If the above mentioned optimization problem acts in linear form, the best method for linearizing that function is employing the four piecewise linear portions that causes the least error in the problem (Hooshmand *et al*., 1998).

THE PROBLEM CONSTRAINTS

To minimize the linearized objective function of Eq. 2, the following constraints may be considered:

- **Generation constraints:** Generators active power is adjusted by the static response of the governor expressed by:

$$PG_i = PGset_i - \frac{P_{Ri}}{R_i}.\Delta f$$

where, P_{Ri}/P_{Ri} denotes the governor response characteristics. Then with above equation, the active and reactive power generation is considered to lie within its minimum and maximum limits:

$$PG_i^{min} \le PG_i \le PG_i^{max} \qquad (3)$$

$$QG_i^{min} \le QG_i \le QG_i^{max} \qquad (4)$$

- **Load constraints:** The majority of a power system loads contain specifications which depend on frequency and voltage system. So for doing load shedding optimization and precise, it is appropriate to consider a real model for loads that can be considered as follows (Hooshmand *et al*., 1998; Palaniswamy and Sharma, 1985; Purnomo *et al*., 2002):

$$PL_i = PLset_i(1 + k_{pi}.\Delta f)\left[p_{pi} + p_{ci}\left(\frac{V_i}{V_{LBi}}\right)^{N1} + p_{zi}\left(\frac{V_i}{V_{LBi}}\right)^2\right]$$

$$QL_i = QLset_i(1 + k_{qi}.\Delta f)\left[q_{pi} + q_{ci}\left(\frac{V_i}{V_{LBi}}\right)^{N2} + q_{zi}\left(\frac{V_i}{V_{LBi}}\right)^2\right]$$

In this model, every load can be considered as a combination of load with fixed power, fixed current of load, fixed impedance and load based on frequency. As a result, with this load models, power demands should be limited so that, for instance, even during emergency conditions, a minimum amount of load is served for a critical bus. Then, the load constraints can be expressed as:

$$PL_i^{min} \le PL_i \le PL_i^{max} \quad (5)$$

$$QL_i^{min} \le QL_i \le QL_i^{max} \quad (6)$$

- **Bus voltage magnitude constraints:** This constraint may have different values for a load bus or a generator bus. The range is, however, limited as follows:

$$V_i^{min} \le V_i \le V_i^{max} \quad (7)$$

- **Frequency limit:** Due to the importance of system frequency variation in controlling emergency conditions, we should have:

$$f^{min} \le f \le f^{max} \quad (8)$$

- **Transformer tap constraint:** A transformer tap may be effectively employed in the optimization process as a control variable. Then, by considering the upper and lower limits of tap-changer constraints, the constraint can be considered as:

$$t_i^{min} \le t_i \le t_i^{max} \quad (9)$$

- **Line flow angle stability constraints:** Among main constraints over transmission lines is angle stability that is defined as:

$$o \le |\delta_i - \delta_j| \le \Psi_{ij}^{max} \quad (10)$$

that i and j are the number of send and end buses of transmission lines.

- **Load flow constraints:** This is set forth as an equal constraint in the problem. By considering the emergency condition, presentation of frequency characteristics in load flow equation is necessary. The following equation should be satisfied in order to obtain the balance of active and reactive power at each node i:

$$PG_i(f) - PL_i(V,f) - P_i(V,\delta) = o \quad (11)$$

$$QG_i - QL_i(V,f) - Q_i(V,\delta) = o \quad (12)$$

in which,

$$P_i(V,\delta) = V_i\sum_{j=1}^{NB} V_j.Y_{ij}\cos(\delta_i - \delta_j - \theta_{ij})$$

$$Q_i(V,\delta) = V_i\sum_{j=1}^{NB} V_j.Y_{ij}.\sin(\delta_i - \delta_j - \theta_{ij})$$

THE LSGR MODEL

If the problem is considered in a nonlinear form, Eq. 2 as an objective function and Eq. 3-12 are considered as the constraints of the problem. Presently, if the problem is solved in a linear method, the objective function and the above constraints should be linearized. This is accomplished by conventional linearization techniques. The linearized equations are expressed in terms of the variable increments ΔPG_i, ΔQG_i, ΔPL_i, ΔQL_i, Δv_i, $\Delta\delta_i$, Δt_i, Δf, where for instance, ΔPG_i = PG_i and ° denoted initial value of variables. Thus, the derived Linear Programming (LP) optimization problem can be expressed as:

$$\text{Min Linearized of}\begin{pmatrix} J = \sum a_i.\Delta PL_i^2 + \sum b_i.\Delta QL_i^2 + \\ \sum c_i.\Delta PG_i^2 + \sum d_i.\Delta QG_i^2 \end{pmatrix}$$

Subject to:

$$\begin{cases} PG_i^{min} - PG_i^o \le \Delta PG_i \le PG_i^{max} - PG_i^o \\ QG_i^{min} - QG_i^o \le \Delta QG_i \le QG_i^{max} - QG_i^o \\ PL_i^{min} - PL_i^o \le \Delta PL_i \le PL_i^{max} - PL_i^o \\ QL_i^{min} - QL_i^o \le \Delta QL_i \le QL_i^{max} - QL_i^o \\ V_i^{min} - V_i^o \le \Delta V_i \le V_i^{max} - V_i^o \\ t_i^{min} - t_i^o \le \Delta t_i \le t_i^{max} - t_i^o \\ f^{min} - f^o \le \Delta f \le f^{max} - f^o \\ -\Psi_{ij}^{max} - \delta_i^o + \delta_j^o \le \Delta\delta_i - \Delta\delta_j \le \Psi_{ij}^{max} - \delta_i^o + \delta_j^o \\ \begin{bmatrix}\Delta PG \\ \Delta QG\end{bmatrix} - \begin{bmatrix}\Delta PL \\ \Delta QL\end{bmatrix} - \begin{bmatrix} J_1 & J_2 & J_5 & J_7 \\ J_3 & J_4 & J_6 & J_8 \end{bmatrix}.\begin{bmatrix}\Delta\delta \\ \Delta V \\ \Delta f \\ \Delta T\end{bmatrix} = \begin{bmatrix} o \\ o \end{bmatrix} \end{cases} \quad (13)$$

Remark: It should be noted that for the deviation of the above LP problem, the line flow stability Eq. 10 has been linearized based on the absolute linearization. Also, the system model (load flow equations) described by Eq. 11-12 has been linearized by truncation of Taylor expansion. In the last constraints of Eq. 13, J_1 to J_8 are sub-matrices of Jacobian matrix and will be:

$$J_1 = \frac{\partial P}{\partial \delta},\quad J_2 = \frac{\partial P}{\partial V},\quad J_3 = \frac{\partial Q}{\partial \delta},\quad J_4 = \frac{\partial Q}{\partial V}$$
$$J_5 = \frac{\partial P}{\partial f},\quad J_6 = \frac{\partial Q}{\partial f},\quad J_7 = \frac{\partial P}{\partial T},\quad J_8 = \frac{\partial Q}{\partial T}$$

STRUCTURE OF FPSO ALGORITHM

Review of PSO technique: Since the PSO method is the base of suggested FPSO method, this section reviews briefly the PSO method. This algorithm was suggested in (Gaing, 2004). According to this algorithm, a group of particles (as the variables of the optimization problem) flies in the searching space. The velocity of each particle is adjusted according its own movement experience and its companion's movement experience. It is clear that in the searching apace, some of the particles have a better position in keeping the track for the best solution. As a result, other particles try to reach to the particles that have better situations. Each particle is aware of both its position with respect to the neighboring particles and with respect to whole group. It is assumed that the searching apace is g-dimensional. To simulate this algorithm the following parameters are defined:

- n = No. of particles in the group
- m = No. of members in the particle
- k = The number of iteration (or generation)
- p_{best} = The best solution that a particle of the group has achieved up to now
- g_{best} = The best solution that the group of particle (as a whole) has achieved up to now.
- c_1 and c_2 = Weighting acceleration constants which represents to what extent each particle pull to p_{best} and g_{best}
- w = Inertia weight factor adjusts the balance between the global and local explorations in the searching space
- $v_j^{(k)} = \left[v_{j,1}^{(k)} \quad v_{j,2}^{(k)} \quad \cdots \quad v_{j,g}^{(k)}\right]$ = The velocity of particle j at iteration k in the g-dimensional searching space
- $x_j^{(k)} = \left[x_{j,1}^{(k)} \quad x_{j,2}^{(k)} \quad \ldots \quad x_{j,g}^{(k)}\right]$ = The position of particle j at iteration k in the g-dimensional searching space.
- $p_{best,j}^{(k)} = \left[p_{best,j,1}^{(k)} \quad p_{best,j,2}^{(k)} \quad \ldots \quad p_{best,j,g}^{(k)}\right]$ = The best previous recorded position of particle j at iteration k in the g-dimensional searching space

Then, the velocity and position of particle j at iteration can be obtained from:

$$\begin{aligned} v_{j,g}^{(k+1)} &= w.v_{j,g}^{(k)} + c_1 \cdot \text{Rand}()\left(P_{bestj,g} - x_{j,g}^{(k)}\right) + \\ & c_2 \cdot \text{rand}() \cdot \left(g_{bestg} - x_{j,g}^{(k)}\right) \quad , \quad v_{min} \le v_{j,g}^{(k)} \le v_{max} \end{aligned} \tag{14}$$

$$x_{j,g}^{(k+1)} = x_{j,g}^{(k)} + v_{j,g}^{(k+1)}, \qquad \begin{matrix} j = 1,2,\ldots,n \\ g = 1,2,\ldots,m \end{matrix} \tag{15}$$

where, Rand () and rand () are two random functions that produce random umber in the range of 0 to 1. Also, in Eq. 14, the inertia weight factor w is decreased varied linearly from 0.9 to 0.4. In general w can be determined from:

$$w = w_{max} - \frac{w_{max} - w_{min}}{k_{max}} * k \tag{16}$$

where, k_{max} and k are the maximum and current number of iteration (or generation), respectively.

One of the difficulties of using this algorithm is choosing c_1 and c_2.

ALGORITHM OF FPSO

Since the performance of PSO is nonlinear, the use of linear equations such as Eq. 16 is not suitable. For example, applying Eq. 16 leads to this issue that the algorithm searches global solution first and then looks for the local solution. Thus this creates a linear relationship between the local and global searches.

In the suggested FPSO method, the inertia weight factor w, is varied according to a nonlinear model. To model the nonlinear variations weight factor w, the fuzzy logic is used. In order to fuzzify the variation of factor w, two fuzzy inputs are defined which are described below:

- The first input is called current best performance evaluation (CBFE) and describes the point that has the best performance. In this research the normalized form of CPBE, denoted by NCPBE, is used. This input is determined from:

$$NCBPE = \frac{CBPE - CBPE_{MIN}}{CBPE_{MAX} - CBPE_{MIN}} \tag{17}$$

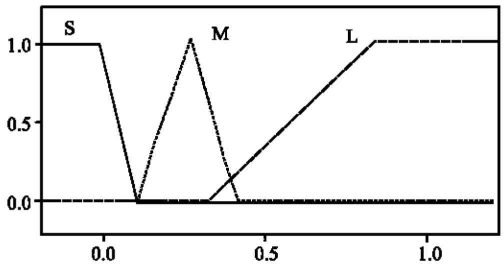

Fig. 1: The membership function of the normalized CBPE

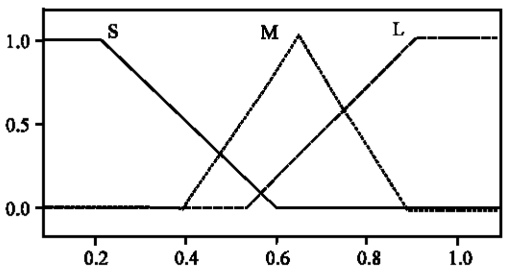

Fig. 2: The membership function of inertia weight factor w

In this equation, $CBPE_{MIN}$ shows the best performance is to be guessed that the FPSO is achieved it. Also $CBPE_{MAX}$ is the worst acceptable performance of FPSO.

- The second fuzzy input is the current value of the inertia weight factor w.

The fuzzy output is the variation of factor w. The membership functions of the fuzzy inputs and the fuzzy output are depicted in Fig. 1-3. In Fig. 1-3, S, M and L, stand for small, medium and large, respectively. Also, the fuzzy rules related the fuzzy system is given in Table 1.

The FPSO Flowchart: Finally, the structure of each particle in FPSO algorithm for designing the amounts of load shedding and generation reallocation is:

$$x = \left[\Delta PL_i \quad \Delta QL_i \quad \Delta PG_i \quad \Delta QG_i\right] \tag{18}$$

where, n is the number of population. In order to compute the amounts of LSGR problem using FPSO algorithm, the following steps should be performed.

Step 1: Specify the upper and lower limits of each variable.

Step 2: Form the initial population at random with desirable chromosome.

Step 3: Choose k =1.

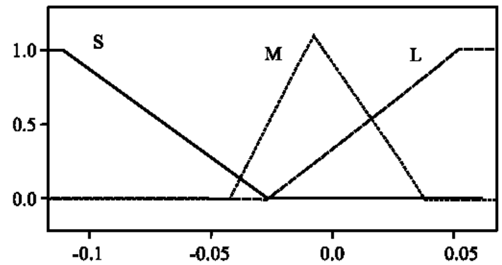

Fig. 3: The membership function of variations of inertia weight factor w

Table 1: The fuzzy rules related to the fuzzy system

w→ NCBFE↓	S	M	L
S	L	S	S
M	L	M	S
L	L	M	S

Step 4: Generate x_j^k randomly in the specified limit.

Step 5: Compute the evaluation function $f(x_j)$ (which is the objective function shown in Eq. 2 and assign it to $P_{best\,j}^{k}$, for j = 1,2,...,n.

Step 6: Determine G_{best} from $G_{best} = \min(f(p_{best\,j}))$

Step 7: Compute $v_{j,g}^{(k+1)}$ from Eq. 14. Note that in the FPSO algorithm, the inertia weight factor w which is needed for Eq. 14, is obtained according to the fuzzy logic discussed in this study.

Step 8: If $v_{j,g}^{(k+1)} \le v_g^{min}$ then $v_{j,g}^{(k+1)} = v_g^{min}$

Step 9: If $v_{j,g}^{(k+1)} \ge v_g^{min}$ then $v_{j,g}^{(k+1)} = v_g^{max}$

Step 10: Compute $x_{j,g}^{(k+1)}$ from Eq. 15.

Step 11: Update $P_{best\,j}$ according to the following:

$$\begin{aligned}&\text{for } j = 1:n\\&\text{if } \quad f(P_{best\,j}) \ge f\left(x_j^{(k+1)}\right) \quad \text{then:}\\&p_{best\,j} = x_j^{(k+1)}\end{aligned}$$

Step 12: Update G_{best} according to the following:

$$\begin{aligned}&\text{for } \quad j = 1:n\\&\text{if } \quad f(G_{best}) \ge \min\left(f\left(P_{best\,j}\right)\right) \quad \text{then:}\\&G_{best} = P_{best\,j}\end{aligned}$$

Step 13: Set k = k+1.

Step 14: Determine G_{best} for the $x_{optimal}$ or continue, as:

if $k \neq k_{max}$ go to step 7, else
$X_{optimal} = G_{best}$

Step 15: End.

THE LSGR PROBLEM BASED ON THE FPSO ALGORITHM

Here, we are determined to explain how to use the proposed FPSO algorithm for the LSGR optimization problem. The flowchart of the process by utilizing FPSO has been shown in Fig. 4. In this method, first system data exit should enter which include specifications of generators, loads, buses, lines and other constant parameters (stage 1). Also in this stage, the amounts of load shedding steps for all loads and steps of production variation of power plants should be specified. These steps of loads are applied to construct alphabet set of each load variations and generator productions. If a load is important it can not omitted or reduced, therefore you can imagine figure zero the load shedding steps in alphabet set. Consequently, it can be said that the problem is performed with regarding the load importance and load shedding with real and performable steps in power system.

In the next stage, by doing load flow in normal operation of system, the initial conditions of optimization process will obtain (stage 2). Now, emergency case i.e. disturbance in the system, is simulated that is a case of line tripping, overloading of the lines, generation shedding (totally or partially), load power increase and etc. (stages 3 and 4). With doing load flow in the fifth stage, emergency conditions dominating system variations is specified (6th stage) that whether existing constraints have been violated or not? If emergency conditions are so, we should think of doing load shedding and generation reallocation.

For doing so, by employing the FPSO algorithm, first the primary population is selected at random process considering the elected Alphabet set (stage 7). As mentioned in previous section, genes of each chromosome are the variation amount in power plant generations and the values of load shedding of each buses load. Each one of the genes is out of Alphabet set concerned with it is elected. So for every bus load, the real value of load shedding steps should be determined which is one of the most important and basic of this method where load shedding and generation reallocation should be like a real optimization. In this stage, undesirable chromosomes are omitted and replaced with desirable ones. By undesirable chromosome, it is meant that the amounts of generators production of system are equal or less than the amount of system loads.

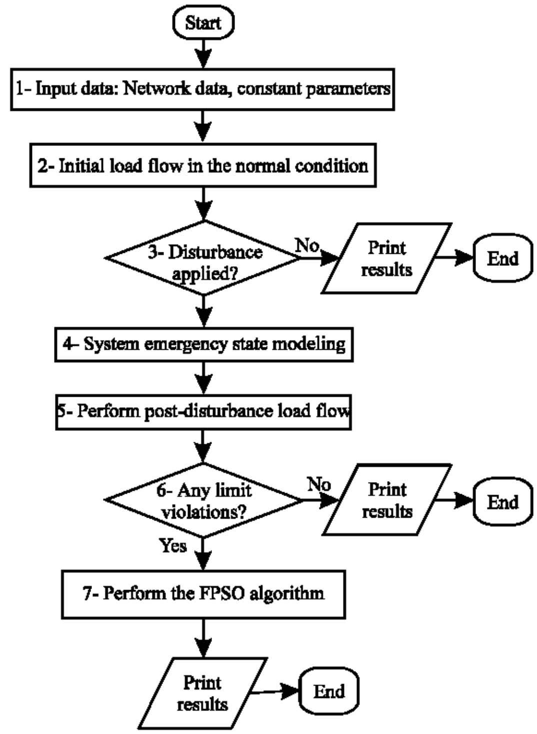

Fig. 4: Flowchart for solving the LSGR problem by using FPSO Algorithm

By forming this process, the desired population becomes convergence and the best chromosome is determined under the title of real optimization of LSGR problem for the desired system.

SIMULATION RESULTS

For illustration purposes, the LSGR problem, based on FPSO algorithm is tested on modified IEEE14-Bus system shown in Fig. 5. The specifications of this system are provided along with its constraints in appendix B. For simulation of the above power system, the following faults (i.e., disturbances) are considered: line outage, generation reduction, outage of generators, transmission overloads and load increase of buses.

It is necessary to mention that the algorithm is so designed that initially only generation reallocation (GR) is tried to solve the problem. Provided that it is unsuccessful, both Load Shedding and Generation Reallocation (LSGR) will be enabled.

Here, the results on two separate examples are obtained and provided in Table 2 and 3. It is assumed that in pre-disturbance condition, the system is operating in its economical state. Also, the results of various cases of crisp and FPSO modes of the problem are determined. The details are described in the following parts.

Table 2: The simulation results of example I

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
System state	Pre fault	Post fault	Post fault	Post fault	Post fault	Post fault
Optimization method	----	----	Crisp	FPSO	Crisp	FPSO
Operation mechanism	GR	GR	GR	GR	GR	GR
Load model of	----	----	----	----	Bus 8	Bus 8
PG1 (p.u.)	2.326	2.437	1.688	1.802	1.340	1.781
PG11	0.400	0.255	0.857	0.902	0.653	0.891
PG12	0.000	0.000	0.000	0.000	0.000	0.000
PG13	0.000	0.000	0.149	0.000	0.653	0.013
PG14	0.000	0.000	0.000	0.000	0.000	0.000
QG1 (p.u.)	-0.291	-0.234	0.024	-0.283	0.706	-0.281
QG11	0.151	0.041	-0.153	0.281	-0.374	0.244
QG12	0.120	0.120	0.325	0.193	-0.399	0.283
QG13	0.700	0.700	0.407	0.637	0.463	0.478
QG14	0.259	0.274	0.328	0.229	0.375	0.104
PL1 (p.u.)	0.000	0.000	0.000	0.000	0.000	0.000
PL2	0.035	0.035	0.035	0.035	0.035	0.035
PL3	0.061	0.061	0.061	0.061	0.061	0.061
PL4	0.478	0.478	0.478	0.478	0.478	0.478
PL5	0.076	0.076	0.076	0.076	0.076	0.076
PL6	0.135	0.135	0.135	0.135	0.135	0.135
PL7	0.000	0.000	0.000	0.000	0.000	0.000
PL8	0.149	0.149	0.149	0.149	0.130	0.128
PL9	0.090	0.090	0.090	0.090	0.090	0.090
PL10	0.295	0.295	0.295	0.295	0.295	0.295
PL11	0.217	0.217	0.217	0.217	0.217	0.217
PL12	0.942	0.942	0.942	0.942	0.942	0.942
PL13	0.112	0.112	0.112	0.112	0.112	0.112
PL14	0.000	0.000	0.000	0.000	0.000	0.000
QL1 (p.u.)	0.000	0.000	0.000	0.000	0.000	0.000
QL2	0.018	0.018	0.018	0.018	0.018	0.018
QL3	0.016	0.016	0.016	0.016	0.016	0.016
QL4	0.039	0.039	0.039	0.039	0.039	0.039
QL5	0.016	0.016	0.016	0.016	0.016	0.016
QL6	0.058	0.058	0.058	0.058	0.058	0.058
QL7	0.000	0.000	0.000	0.000	0.000	0.000
QL8	0.050	0.050	0.050	0.050	0.044	0.043
QL9	0.058	0.058	0.058	0.058	0.058	0.058
QL10	0.166	0.166	0.166	0.166	0.166	0.166
QL11	0.127	0.127	0.127	0.127	0.127	0.127
QL12	0.190	0.190	0.190	0.190	0.190	0.190
QL13	0.075	0.075	0.075	0.075	0.075	0.075
QL14	0.000	0.000	0.000	0.000	0.000	0.000
V1 (p.u.)	1.060	1.060	1.058	1.061	1.059	1.060
V2	1.050	1.050	1.050	1.076	1.035	1.033
V3	1.050	1.050	1.050	1.076	1.049	1.057
V4	1.038	1.038	1.027	1.012	0.997	1.007
V5	1.047	1.048	1.029	1.021	1.016	1.013
V6	1.049	1.050	1.050	1.076	1.048	1.055
V7	1.048	1.046	1.042	1.076	1.040	1.005
V8	1.026	1.003	0.997	1.049	0.993	0.973
V9	1.039	1.036	1.031	1.076	1.019	1.006
V10	1.041	1.036	1.030	1.076	1.022	1.002
V11	1.045	1.045	1.037	1.033	1.008	1.027
V12	1.010	1.010	1.019	0.997	0.951	0.999
V13	1.071	1.059	1.079	1.100	1.063	1.069
V14	1.090	1.090	1.095	1.100	1.100	1.023
δ1 (degree)	0.000	0.000	0.000	0.000	0.000	0.000
δ2	-15.503	-14.793	-12.351	-13.986	-6.612	-14.346
δ3	-15.983	-14.880	-11.879	-13.949	-4.607	-14.445
δ4	-10.492	-9.8860	-8.7430	-9.6290	-6.598	-9.594
δ5	-9.1080	-8.5280	-7.2610	-8.2220	-5.078	-8.207
δ6	-16.014	-14.859	-11.856	-13.929	-4.586	-14.425
δ7	-13.717	-13.297	-11.838	-12.770	-8.741	-12.909
δ8	-16.666	-16.926	-15.317	-16.090	-11.521	-16.346
δ9	-15.614	-15.175	-13.297	-14.448	-9.074	-14.754
δ10	-15.369	-15.054	-13.424	-14.374	-9.849	-14.637
δ11	-4.932	-4.1390	-3.2340	-3.7680	-2.136	-3.785

Table 2: Continued

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
δ12	-12.539	-11.846	-11.149	-11.813	-8.849	-11.968
δ13	-15.153	-14.183	-11.179	-13.282	-3.888	-13.735
δ14	-13.717	-13.297	-11.838	-12.77	-8.741	-12.909
t1	0.978	0.978	0.978	1.037	1.008	0.987
t2	0.969	0.969	0.969	1.100	0.991	0.969
t3	0.932	0.932	1.046	1.028	0.979	1.016
f (Hz)	50.000	49.280	49.990	49.998	49.929	49.978
Fitness value	----	----	5.192	1.762	27.925	23.410
Emergency conditions	----	f	----	----	----	----

Table 3: The simulation results of example II

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
System state	Pre fault	Post fault	Post fault	Post fault	Post fault	Post fault
Optimization method	----	----	Crisp	FPSo	Crisp	FPSo
Operation mechanism	LSGR	LSGR	LSGR	LSGR	LSGR	GR
Load model of	----	----	----	----	Bus 13	Bus 13
PG1 (p.u.)	2.326	2.186	0.803	1.22	0.907	1.082
PG11	0.400	1.625	0.141	0.267	0.138	1.65
PG12	0.000	0.000	0.000	0.000	0.000	0.000
PG13	0.000	0.000	0.000	0.025	0.000	0.342
PG14	0.000	0.000	0.000	0.000	0.000	0.000
QG1 (p.u.)	-0.291	0.012	0.933	0.722	0.914	1.049
QG11	0.151	0.476	-0.300	-0.380	-0.290	0.524
QG12	0.120	0.458	-0.258	-0.310	-0.269	-0.380
QG13	0.700	0.631	0.261	0.728	0.305	0.547
QG14	0.259	0.450	-0.06	-0.057	-0.046	0.472
PL1 (p.u.)	0.000	0.000	0.000	0.000	0.000	0.000
PL2	0.035	0.035	0.000	0.000	0.000	0.035
PL3	0.061	0.061	0.061	0.061	0.061	0.061
PL4	0.478	0.478	0.000	0.000	0.000	0.478
PL5	0.076	0.076	0.000	0.000	0.000	0.076
PL6	0.135	0.135	0.025	0.035	0.135	0.135
PL7	0.000	0.000	0.000	0.000	0.000	0.000
PL8	0.149	0.149	0.149	0.149	0.149	0.149
PL9	0.09	0.090	0.000	0.000	0.000	0.09
PL10	0.295	1.295	0.479	0.485	0.480	1.295
PL11	0.217	0.217	0.000	0.000	0.000	0.217
PL12	0.942	0.942	0.000	0.000	0.000	0.942
PL13	0.112	0.112	0.112	0.112	0.108	0.101
PL14	0.000	0.000	0.000	0.000	0.000	0.000
QL1 (p.u.)	0.000	0.000	0.000	0.000	0.000	0.000
QL2	0.018	0.018	0.000	0.000	0.000	0.018
QL3	0.016	0.016	0.016	0.016	0.016	0.016
QL4	0.039	0.039	0.000	0.000	0.039	0.039
QL5	0.016	0.016	0.000	0.000	0.000	0.016
QL6	0.058	0.058	0.011	0.015	0.058	0.058
QL7	0.000	0.000	0.000	0.000	0.000	0.000
QL8	0.050	0.050	0.050	0.050	0.050	0.050
QL9	0.058	0.058	0.000	0.000	0.000	0.058
QL10	0.166	0.866	0.32	0.325	0.321	0.866
QL11	0.127	0.127	0.000	0.000	0.000	0.127
QL12	0.190	0.190	0.000	0.000	0.000	0.190
QL13	0.075	0.075	0.075	0.073	0.068	0.075
QL14	0.000	0.000	0.000	0.000	0.000	0.000
V1 (p.u.)	1.060	1.060	1.058	1.061	1.058	1.060
V2	1.050	0.923	1.003	1.076	1.004	0.986
V3	1.050	0.952	1.004	1.076	1.002	1.024
V4	1.038	0.981	0.994	1.03	0.991	0.957
V5	1.047	0.995	1.007	1.034	1.003	0.969
V6	1.049	0.939	1.003	1.076	0.995	1.009
V7	1.048	0.955	0.974	1.037	0.974	0.991
V8	1.026	0.883	0.973	1.076	0.969	0.953
V9	1.039	0.884	0.989	1.076	0.989	0.959
V10	1.041	0.878	0.984	1.07	0.983	0.959
V11	1.045	1.045	1.003	1.007	1.004	1.033

Table 3: Continued

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
V12	1.010	1.010	0.953	0.953	0.933	0.995
V13	1.071	1.070	1.017	1.100	1.019	1.045
V14	1.09	1.090	0.963	1.009	0.965	1.069
δ1 (degree)	0.000	0.000	0.000	0.000	0.000	0.000
δ2	-15.503	-25.379	-8.079	-3.495	-9.342	-18.779
δ3	-15.983	-24.324	-8.409	-4.368	-10.101	-17.198
δ4	-10.492	-12.792	-3.002	-1.335	-3.512	-10.398
δ5	-9.1080	-10.911	-2.842	-1.422	-3.343	-8.615
δ6	-16.014	-24.694	-8.329	-4.089	-10.151	-17.589
δ7	-13.717	-22.694	-6.739	-2.479	-7.564	-18.158
δ8	-16.666	-28.037	-9.652	-4.374	-11.013	-21.529
δ9	-15.614	-27.692	-8.488	-3.148	-9.555	-21.654
δ10	-15.369	-28.364	-8.683	-3.045	-9.664	-22.668
δ11	-4.932	-3.928	-0.819	0.371	-1.048	-2.375
δ12	-12.539	-13.954	-1.498	-0.047	-1.871	-11.215
δ13	-15.153	-22.942	-7.693	-3.947	-9.159	-15.839
δ14	-13.717	-22.694	-6.739	-2.479	-7.564	-18.158
t1	0.978	0.978	0.978	0.978	0.978	1.100
t2	0.969	0.969	1.100	0.969	1.100	1.100
t3	0.932	0.932	0.998	1.100	1.009	1.047
f (Hz)	50	49.113	49.926	49.814	49.923	49.999
Fitness value	----	----	163.163	141.948	160.057	44.583
Emergency conditions	----	f V2,6,8,9,10 δ4 – δ10 δ5 – δ13	----	----	----	----

Example I: To illustrate the application of the method, it is assumed that there is 50% (0.2 p.u.) generation loss at bus 11 of the system. In order to analyze the fault, first the initial load flow has to be done to determine the initial conditions. Case 1 of Table 2 represents the normal conditions where all system variables are within their respective limits. Considering the desired generation loss, the results of load flow are shown in case 2. As may be seen, it is regarded that the system frequency is reduced to 49.28 Hz. In other words, the power system has turned on to an emergency state. Now, if we do the crisp optimization method, we see that by employing the generation reallocation procedure in power plants, the dominating emergency conditions will remove, that the LF results are shown in the third case in Table 2. In this method, the amount of objective function will equal 5.192.

Now, if we employ optimization method with the proposed FPSO algorithm (case 4), it will be noticed that by employing generation reallocation in production of the power plants, the emergency conditions have been eliminated. But, by this method, the amount of objective function (the same amount of fitness function of desired chromosome) equals 1.762. These results have been shown in the fourth case. Since, the value of objective function in the generation reallocation problem indicates the deviations of the generators production from the nominal state, as a result, the reduction of this value based on the FPSO method represents a more acceptable solution compared with the crisp solution.

The same disturbance is reapplied, but now with the load of bus 8 considered to be dependent on voltage and frequency with the following coefficients (Palaniswamy and Sharma, 1985; Purnomo *et al*., 2002):

$$k_{p8} = 0.03,\quad P_{p8} = 0.2,\quad P_{c8} = 0.3,\quad P_{z8} = 0.5$$
$$k_{q8} = 0.00,\quad q_{p8} = 0.2,\quad q_{c8} = 0.3,\quad q_{z8} = 0.5$$

For all other loads, $p_{pi} = q_{pi} = 1.0$ and other parameters are zero. The results of generation reallocation solution, with crisp and FPSO methods are shown by cases 5 and 6 of Table 2, respectively. In the crisp method, the amount of objective function is based on Eq. 2 equals 27.925 and while the amount of fitness function by employing FPSO algorithm reduces 23.41, that shows more desirable generation scheduling in the generators. Also, in the crisp optimization method, the system frequency equals 49.929 Hz. Meanwhile in the proposed method, the frequency system has increased to 49.978 Hz. With due regard to the many conditions of the case and the practical restrictions in power systems, application of FPSO technique has had a lot of influence in finding a real optimal answer applicable in determining the amount of generation scheduling.

Example II: One of the cases of bringing emergency conditions up is a sudden overload in power system. In this example, it is assumed that in bus 10 of Fig. 5, its associated active power is increased by 1.0 pu (with

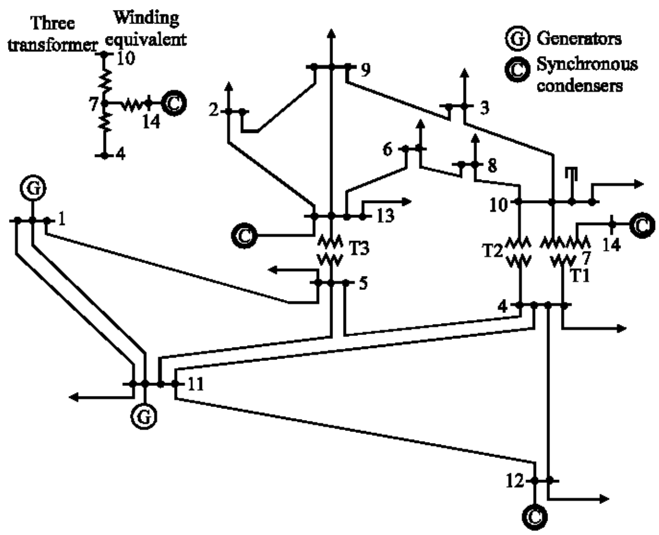

Fig. 5: Single line diagram of the modified IEEE 14-Bus system

power factor = 0.82 lag). The normal pre-disturbance results are shown by case 1 of Table 3. Case 2 represents the severe emergency conditions after the disturbance. As may be seen, the system frequency, the phase angle difference of lines 2 and 3 and voltage magnitude of busses 2, 6, 8, 9, 10 have crossed their permissible limits. The frequency drop is 0.887 Hz (more than maximum permissible limit of 0.2 Hz). Thus, the system is in the emergency state. To eliminate this problem, the crisp and FPSO modes of LSGR problem will be adopted, where the results are shown by cases 3 and 4 of Table 3, respectively. Also, comparison of cases 3 and 4 indicates that the value of objective function of the crisp solution is 163.163, but this amount with FPSO method is reduced to 141.948. These results indicate that the total deviations in generation schedule and load curtailment values for the FPSO method are less than the crisp method. Also the amount of load shedding in the proposed method is less than crisp optimization method that the problem will cause reducing the dissatisfaction of consumers in the proposed procedure.

Now, the same disturbance is reapplied, but with load of bus 13 considered to be dependent on voltage and frequency with the same coefficients as in Example I. The results of load flows in the cases 5 and 6 of Table 3 confirm that in crisp optimization method, emergency conditions have been removed by employing load shedding and generation reallocation. Whereas, if the proposed method is used, it is needless to load shedding and only by employing generation reallocation, the system will restore to the normal state. Presently, the amount of objective function in crisp optimization method is at the amount of 160.057. That will reduce in the proposed method of the amount of objective function (it is the amount of fitness function) to 44.583. The reason of abundant decrease in the amount of objective function in the proposed algorithm will be the nonexistence of load shedding in the system. These results show that the proposed algorithm solution for the LSGR problem is more appropriate than the crisp method.

CONCLUSIONS

A new method for the optimal LSGR problem based on the FPSO algorithm in power systems was presented in this study. With due regard to the many conditions of the case, the practical restrictions in load curtailment of buses and generation schedule of power plants, application of FPSO has had a lot of influences in finding a real optimal answer which is applicable in determining the amount of load shedding and generation reallocation. In this paper, an attempt has been made to consider frequency variation, model of electric loads depending on voltage and frequency and other constraints in optimization problem, system model may be more completely and precisely simulated.

In power system case studies, the simulation results explain that FPSO solution method for the LSGR problem is more flexible than the crisp solution method. Also, the fitness values of the proposed solution are less than the respective value (value of objective function) of the crisp solution. Additionally, the load curtailment values in FPSO case are less than the corresponding crisp case. Moreover, the proposed approach to the solution of the LSGR problem accommodates more realistic models to characterize the behavior of practical power system operations.

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LIST OF SYMBOLS

PG, QG	:	Active and reactive power generation
PL, QL	:	Load active and reactive powers
P, Q	:	Active and reactive powers injections
Pgset, Qgset	:	Setting of active and reactive power of a generator
PLset, QGset	:	Setting of active and reactive power of a load
P_R, R	:	Rated output and rated regulation of a generator
V_i, δ_i	:	Rated voltage and angle of a generator
V_{LB}	:	Load base voltage value
t	:	Tap value of a transformer
f_i, g_i	:	Fitness value and its normalized
f	:	System frequency
NB	:	No. of system buses
NG	:	No. of generators
Y_{ij}, θ_{ij}	:	An element of the admittance matrix Y
p_z, q_z	:	Coefficients of constant impedance load
pc, qc	:	Coefficients of constant current load
p_p, q_p	:	Coefficients of constant power load
k_p, k_q	:	Coefficients of frequency dependent part of the load
a_i to d_i	:	Coefficients of the objective function
Ψ_{ij}^{max}	:	Maximum phase angle difference between buses I and j
Δ	:	Deviation operator

APPENDIX A. SELECTION OF OBJECTIVE FUNCTION COEFFICIENTS

In the above mentioned problem formulation, the aim is to minimize the objective function J, so that while the generators operating conditions minimally disturb from their respective economical operating points, the least amount of load would be curtailed. Provided that, if the production cost function of plant is given by:

$$F_i(P_i) = A_i.PG_i^2 + B_i.PG_i + C_i \tag{A.1}$$

a good practice may be to set:

$$c_i = A_i \qquad i = 1, 2, ..., NG \tag{A.2}$$

On the other hand, at rated operating condition, we approximately, have:

$$PG_i^2 + QG_i^2 = SG_i^2 \tag{A.3}$$

where, Sg_i is the apparent power. For small perturbation in Pg_i and QG_i we have:

$$(PG_i^o + \Delta PG_i)^2 + (QG_i^o + \Delta QG_i)^2 = (SG_i^o)^2 \tag{A.4}$$

So that:

$$\left(\Delta QG_i \middle/ \Delta PG_i\right) = -\left(PG_i^o \middle/ QG_i^o\right) \tag{A.5}$$

or,

$$\left(\Delta QG_i^2 \middle/ \Delta PG_i^2\right) = \left(PG_i^o\right)^2 \middle/ \left(QG_i^o\right)^2 \tag{A.6}$$

In other words, provided the machine is working at rated conditions, d_i may be selected as:

$$d_i = a_i.\left[\left(PG_i^o\right)^2 \middle/ \left(QG_i^o\right)^2\right] \tag{A.7}$$

The machine is not always working at its rated condition. Hence:

$$d_i = a_i.\eta_i.\left[\left(PG_i^o\right)^2 \middle/ \left(QG_i^o\right)^2\right] \tag{A.8}$$

Where:

$$\eta_i = \frac{PG_i^2 + QG_i^2}{\left(PG_i^o\right)^2 + \left(PG_i^o\right)^2} \tag{A.9}$$

The relative importance of generation reallocation with respect to load shedding can be considered by a_i. In fact, the appreciable amount of generation reallocation implies that higher operating costs are tolerable. On the other hand, load shedding produces customer's dissatisfaction and surplus unsold energy. Therefore, in an open market environment, generation reallocation might be worthwhile to a certain extent. Thus, a_i is selected to be:

$$a_i = (20 \quad \text{to} \quad 100).c_i \tag{A.10}$$

while, according to a utility experience, other values may also be selected.

With the assumption of fixed load power factors, we have:

Table B1: Bus data (initial values before LF) and coefficients a_i's and b_i's

Bus No.	V	V^{min}	V^{max}	Coeff. a_i	Coeff. b_i
1	1.06	1.058	1.062	--	--
2	1.00	0.95	1.10	100.0	51.4
3	1.00	0.95	1.10	100.0	26.2
4	1.00	0.95	1.10	100.0	8.2
5	1.00	0.95	1.10	100.0	21.1
6	1.00	0.95	1.10	100.0	43.0
7	1.00	0.95	1.10	--	--
8	1.00	0.95	1.10	100.0	33.6
9	1.00	0.95	1.10	100.0	64.4
10	1.00	0.90	1.10	100.0	56.3
11	1.045	0.90	1.10	70.2	41.1
12	1.01	0.90	1.10	100.0	20.2
13	1.07	0.90	1.10	77.8	52.1
14	1.09	0.90	1.10	--	--

Table B2: Slack and PV bus data and coefficients c_i's and d_i's

Bus No.	PG^{min}	PG^{max}	QG^{min}	QG^{max}	R_i Coeff.	Coeff. c_i	Coeff. d_i
1	0.5	2.5	-0.30	1.00	0.05	2.5	19.6
11	0.2	1.0	-0.40	0.50	0.05	3.5	9.3
12	0.0	0.0	-0.40	0.60	0.05	--	--
13	0.2	1.0	-0.06	0.70	0.05	3.9	3.9
14	0.0	0.0	-0.06	0.45	0.05	--	--

$$\tan\phi_i = \left(\Delta QL_i \middle/ \Delta PL_i \right) \quad (A.11)$$

As a result:

$$b_i = (\tan\phi_i).a_i \quad (A.12)$$

APPENDIX B. THE SPECIFICATION OF MODIFIED IEEE 14-BUS SYSTEM

The modified IEEE 14-Bus system Fig. 5 is considered consisting of five generators, three tap-changer transformers and 20 transmission lines. The lines, transformers and buses data are given in (You *et al*., 2003). The buses data, the minimum (min.) and maximum (max.) of voltage magnitudes and a_i, b_i coefficients of objective function (in conjunction with generators) are shown in Table B1. The max. and min. of active and reactive generator powers and c_i, d_i coefficients of objective function (in conjunction with system loads) are illustrated in Table B 2. The min. and max. values of tap-changers are 0.9 and 1.1, respectively. Also, the maximum permissible limit of system frequency has been violated from nominal 50 Hz to the amount of 0.2 Hz. Finally, it should be mentioned that for all load buses, the steps of load shedding to the amount of 0.01 per unit are regarded which are used in forming the Alphabet set of each load of buses.

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