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DG- Allocation Based on Reliability, Losses, and Voltage Sag Considerations – An Expert System Approach

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***Abstract* -** Expert System (ES) as a branch of Artificial Intelligence (AI) methodology can potentially help in solving complicated power system problems. This may be more appropriate methodology than conventional optimization techniques when contradiction between objectives appears in reaching the optimum solution. When this contradiction is the hindrance in reaching the required system operation through the application of traditional methods ES can give a hand in such case.

In this paper, the knowledge- based ES technique is proposed to reach near-optimum solution which is further directed to the optimum solution through particle swarm optimization (PSO) technique. This idea is known as Hybrid-Expert-System (HES). The proposed idea is used in getting the optimum allocation of a number of distributed generation (DG) units on Distribution System (DS) busbars taking into consideration three issues; reliability, voltage sag, and line losses. Optimality is assessed on the economic basis by calculating money benefits (or losses) resulting from DG addition considering the three aforementioned issues. The effectiveness of the proposed technique is ascertained through example.

***Keywords* –** Expert system; Artificial Intelligence; particle swarm optimizatiom; Hybrid Expert System; Disteributed generation; reliability; voltage sag.

I. INTRODUCTION

The problem of optimum allocation of DG units is one of the most challenging problems emerged since the advent of DG technology in DS. This is due to the inherent characteristics of the electric power systems with their contradicting behavior. As an example, raising the generating capacity of the grid may lead to improving voltage sag phenomenon at some busbars and -at the same time- impairing this phenomenon at other busbars. Another example is the case when seeking at getting the optimum placing of a number of DG units which minimizes the overall transmission losses. This placing may not achieve the required reliability level, or, at least does not verify the best possible reliability indices. Many other contradictions are found among grid operation, control, and protection. Although most of literature about the problem of DG allocation deal with radial systems which are relatively simple [1-5]. The problem is still complex and needs some assumptions to simplify the solution. In many cases these assumptions limit the usability of the suggested methods and the benefit gained from them. On the other hand few authors consider ring and interconnected systems which add more complexity to the problem [6].

It becomes an agreement among all authors that the Artificial Intelligence (AI) techniques are the only suitable methods for solving the problem of optimum DG allocation. Conventional optimization techniques cannot be applied because of the non-convexity of the objective function and the different nature of the problem variables which contain electrical, statistical, and economical variables. However the common drawback in most of the AI optimization methods is that these methods do not have a robust algorithm which assures that the solution is the absolute minimum (the least value) in case of minimization problem. This is similar to the case of nonconvex objective function in conventional optimization.

This paper suggests utilizing Hybrid Expert System (HES) for improving and accelerating the solution of optimum DG allocation either by conventional optimization methods or by AI techniques. ES is not an optimization technique rather than it helps in getting adequate and quick pragmatic answers for problems that defy effective solution. In the present work a rule chain containing heuristic rules is adopted to help in getting a “near optimum” DG allocation.

This solution can be used as a starting population in the PSO methods which helps in reducing number of iterations and gives better results.

II. NOMENCLATURE

NS: Total number of busbars in the grid.
ND: Number of DG units.
TLL: Total power losses in grid lines, in p.u. kW.
CK: Cost of p.u. kWh loss in grid lines.
8760: Average number of hours per year.
CL: Total annual line loss cost of the grid, $.
CVS(j-k): Voltage of busbar #j when S.C. occurs on busbar #k.
NV(k): Estimated number of S.C. on bus #k, per year.
F(j): Loss cost from load isolation resulting from voltage sag or from forced outage at bus #j in p.u. kW.
R(k): Availability of busbar k.
VC(j): Critical trip voltage at busbar #j due to voltage sag.
VS(j): Voltage at busbar #j during S.C..
CS: Total annual loss cost due to voltage sags, $.
CT: Total annual cost in the grid due to line losses and voltage sags, $.
V_i, V_j: Voltages of busbars #i, j resulting from load flow solution.
V_i*, Vj* Conjugates of , respectively.
y_i: Series admittance of line between busbars i and j.
yij: Shunt admittance of line between busbars i and j.
R, X: Series resistance and reactance of line respectively, in p.u..
P_i, Q_i: Active and reactive net injected power at busbar #i, in p.u.
P_{ij} : Real power transmitted by line i-j.

III. PROBLEM FORMULATION

The problem can be stated as follows: "It is required to get the best possible allocation of a number of DG units at busbars of a DS taking into consideration three factors; line power losses, voltage sag and reliability".
As a common practice, the objective function of the problem is derived on the form of cost function of loss costs of the followings:

1. Loss cost due to transmission power loss (CL). This cost reduces by reducing transmission line power loss.

2. Loss cost due to load isolation by undervoltage protection resulting from S.C. occurring somewhere at any busbar in the DS (CV). This cost may be reduced by minimizing the effect of S.C. occurring at one busbar on the transient voltage drops at other DS busbars.

3. Loss cost due to load interruption (CR). This can be minimized by maximizing the reliability indices at the grid loads.

Mathematically, the problem can be written as:

$$Minimize\ CT = CL + CS + CR \tag{1}$$

Subject to

$$V_{i\min} \le V_i \le V_{i\max} \quad where;\ i \forall NS \tag{2}$$

$$P_{ij} \le P_{ij\max} \quad where;\ i, j \forall NS \tag{3}$$

Conceptually, the calculation of CT is based on the following functions:

4. Load flow: this function uses any traditional method such as Newton-Raphson and Gauss-Seidel methods from which TLL is calculated. DG are modelled as PQ busses. Hence, the first part of equation (1) is calculated as follows;

$$CL = (TLL) \bullet (Ck) \bullet 8760 \tag{4}$$

5. Voltage sag: this function determines the grid buses which will be tripped by undervoltage relays when a three-phase S.C. occurs on one bus in the grid. This is calculated for S.C. on all buses, one at a time. Expected loss cost due to voltage sags is calculated as:

$$CS = \sum_{k=1}^{NS} \sum_{j=1}^{NS} CVS(j-k) \tag{5}$$

$$CVS(j-k) = NS(k) \bullet A(j) \tag{6}$$

Where;

$$\begin{aligned} A(j) &= F(j) \bullet PL(j) \quad && if\ VS(j) \le VC(j) \\ A(j) &= 0 && if\ VS(j) > VC(j) \end{aligned} \tag{7}$$

6. Reliability; Reliability assessment in radial DS is relavively simple as load connected to any bus requires that all components from the supply point be avaliable. However, this concept cannot be applied to the case when both main substation and DG feed the grid at the same time as the grid becomes no longer radial. For this reason, most of researchers assume one DG only for reliability assement and allows the DG operate independently (island) where the main power is not present [7,8].

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However, two issues have to be considered in order to simulate practical requirements. These are:

1. Some distribution grids are fed from more than one point. This makes the grid as ring or even interconnected configuration.

2. It is essential to evaluate the reliability indices at load points considering both DG units and main supply feeding the grid at the same time. This represents most of practical applications.

The two aforementioned issues violate the condition of series reliability and draw attention to the importance of reliability evaluation of ring and interconnected systems. In the present work, reliability of ring and interconnected network is calculated following the method suggested in [9]. Cost of load interruptions resulting from forced outage of any component in the DS is calculated as

$$CR = \sum_{k=1}^{k=N} \{(1 - R(k)) \bullet PL(k) \bullet F(k) \qquad (8)$$

IV. HYBRID EXPERT SYSTEM

Rule-Based Expert System is a branch of Artificial Intelligent system created to solve problems in a particular domain. It has been developed to assist in finding pragmatic answers for problems that defy effective solution [10]. All knowledge in an ES is provided by people who are experts in that domain. ES may contain heuristic rules which differ from other rules in that, they are not formulated as a result of ordinary accepted knowledge but are rules that only an expert would know. In general, to create an ES a team consisting of expert and knowledge engineer gathers the facts, rules and heuristic rules for a domain and organizes them into an AI program. The same problem may find different solutions according to the ES used in this program [11].

As a matter of fact, not all problems can be or should be solved by mean of an ES. Further, even among those solution by ES is appropriate, the results found may be marginally accepted. In this paper we suggest HES to improve results and reduce the calculation effort. The proposed methodology utilizes ES first to get- near optimum- solution to the problem under study, then this solution is considered as the initial population for the PSO method. In this work, a rule chain containing three heuristic rules is adopted to help in getting near-optimum solution for the DG units allocation which can be taken as starting populations in the PSO technique. These are:

Rule #1

IF	Node has high load and it is connected with high resistance lines.
THEN	Begin with this node for DG installation for loss minimization.

Rule #2

IF	The cost of load tripping at the node is high and the load is critical.
THEN	Installation of DG at this node has the second preference.

Rule #3

IF	The grid is highly interconnected.
THEN	The issue of reliability has less importance in DG allocation.

V. PARTICLE SWARM OPTIMIZATION

PSO is a branch of AI systems emerged in the last three decades as an efficient method of optimization [12]. It is characterized as a population of random space. A particle's location in the multidimensional problem space represents one solution for the problem. When a particle moves to a new location, a different problem solution is generated. This solution is evaluated by fitness function that provides a quantitative value for the solution's utility.

The velocity and direction of each particle moving along each dimension of the problem space will be altered with each generation of movement. In combination, the particle's personal experience and its neighbors' experience influence the movement of each particle through a problem [13].

VI. CASE STUDY

The proposed problem structure was tested on the IEEE 14-bus system given in [14]. Table I contains the system lines and loads raw data

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Table 1. system raw data

Line	**R**	**X**	**Line Avaliability**	**Node**	**PLoad**	**QLoad**	**Node Avaliability**
1-2	0.01938	0.05917	0.951	1	0	0	1
1-5	0.05403	0.22304	0.98	2	0	0	1
2-3	0.04699	0.19797	0.94	3	-0.942	0	0.945
2-4	0.05811	0.17632	0.98	4	-0.478	0.039	0.986
2-5	0.05695	0.17388	0.99	5	-0.076	-0.016	0.991
3-4	0.06701	0.17103	0.99	6	-0.112	0	0.999
4-5	0.01335	0.04211	0.995	7	0	0	0.982
4-7	0	0.20912	0.98	8	0	0	0.963
4-9	0	0.55618	0.98	9	-0.295	0.046	0.963
5-6	0	0.25202	0.995	10	-0.09	-0.058	0.962
6-11	0.09498	0.19890	0.98	11	-0.035	-0.018	0.999
6-12	0.12241	0.25581	0.995	12	-0.061	-0.016	0.999
6-13	0.06615	0.13027	0.995	13	-0.135	-0.058	0.998
7-8	0	0.17615	0.98	14	-0.149	-0.05	0.963
7-9	0	0.11001	0.98				
9-10	0.03138	0.08450	0.99				
9-14	0.12711	0.27038	0.995				
10-11	0.08205	0.19207	0.99				
12-13	0.22092	0.19988	0.94				
13-14	0.17093	0.34802	0.98				

The system contains five generators. The first one which is the slack generator is connected on busbar 1. The second one is fixed on busbar 2. We are seeking at getting the optimum allocation for 3 DG units (G3, G4 & G5) each of 0.1 p.u. power output and 0.1 p.u. reactance, on three busbars of the grid which minimizes the value of CT. Table II shows the DGs data in p.u.

Table 2. Generators data

	G1 (Slack)	G2	G3	G4	G5
Voltage Magnitude	1.06	1.04	1.01	1.07	1.09
Rated Power	-	0.183	0.1	0.1	0.1
Reactance	0+0.02i	0+0.1i	0+0.1i	0+0.1i	0+0.1i

Data needed for the problem solution are as follows;

$NS = 14$, $ND = 3$, $Ck = \$0.5$, $VC(j) = 0.8\ p.u.$

for all buses. Values of F(i) and NS(i) are given in table 3.

Table 3. Values of F(i) and Ns(i)

Busbars #i	NS(i)	F(i)
1	0.03	75000
2	0.09	12000
3	0.05	12000
4	0.09	60000
5	0.09	60000
6	0.9	75000
7	0.06	12000
8	0.7	12000
9	0.09	50000
10	0.08	60000
11	0.09	50000
12	0.09	12000
13	0.09	50000
14	0.03	75000

Following the steps of solution described in section III and applying the PSO method described in section IV results given in table III are obtained. The starting random allocation of DG units consists of busbars 12, 13, and 14. Solution can be accelerated when the

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three heuristic rules of the ES is applied. Rule #1 recommends starting with node #8, rule #2 recommends node #8 hence node #12 followed by node 14. Rule #3 recommends node #9. Combining the three ES rules suggests starting population consisting of nodes 8, 9, and 12 which reduces the number of PSO iterations from 34 to 9 iterations only.

Table 4. Results of the case study

Iteration Number	Generators Distribution					Line Losses
	G1	G2	G3	G4	G5	
1	1	2	12	13	14	0.13451+0.44637i
2	1	2	11	12	13	0.12426+0.43931i
3	1	2	9	10	14	0.13739+0.48425i
4	1	2	10	12	13	0.11837+0.42714i
5	1	2	11	12	14	0.11911+0.42988i
6	1	2	8	12	13	0.11427+0.42553i
7	1	2	9	10	12	0.12897+0.46042i
8	1	2	10	11	12	0.11876+0.42963i
9	1	2	9	10	11	0.12804+0.46105i
10	1	2	8	11	12	0.11099+0.41879i
11	1	2	10	11	13	0.11797+0.43456i
12	1	2	11	13	14	0.11838+0.42846i
13	1	2	9	10	13	0.12768+0.46575i
14	1	2	9	12	14	0.12116+0.43572i
15	1	2	9	12	13	0.11859+0.42843i
16	1	2	10	11	14	0.12326+0.44395i
17	1	2	8	11	13	0.10912+0.42089i
18	1	2	10	12	14	0.11741+0.42666i
19	1	2	9	13	14	0.11975+0.43336i
20	1	2	8	10	12	0.10918+0.42021i
21	1	2	9	11	12	0.11654+0.42447i
22	1	2	8	12	14	0.11002+0.4198i
23	1	2	10	13	14	0.11619+0.42454i
24	1	2	9	11	14	0.12445+0.44704i
25	1	2	8	10	11	0.11035+0.42422i
26	1	2	8	9	12	0.10749+0.4245i
27	1	2	8	10	13	0.10697+0.42107i
28	1	2	9	11	13	0.11595+0.43049i
29	1	2	8	11	14	0.1092+0.4212i
30	1	2	8	9	10	0.10954+0.43193i
31	1	2	8	9	11	0.10805+0.42773i
32	1	2	8	10	14	0.10774+0.42167i
33	1	2	8	9	13	0.10574+0.42463i
34	1	2	8	9	14	0.10686+0.42443i

Table 5. Costs of the case study

Iteration Number	Line Losses Cost	Voltage Sag Cost	Unavailability Cost	Total Cost
1	589.1321	116.522	3.005	708.6591
2	544.2604	126.2712	2.734	673.2656
3	601.7814	49.872	4.166	655.8194
4	518.477	116.0267	3.005	637.5087
5	521.6899	112.7459	3.101	637.5368
6	500.4813	132.9739	2.266	635.6142
7	564.8807	61.4675	4.088	630.4362
8	520.1535	105.9278	3.334	629.4153
9	560.8087	64.6447	4.954	630.4074
10	486.1372	134.815	2.232	623.1842
11	516.729	99.2065	3.678	619.6135
12	518.513	96.9881	3.606	619.1072
13	559.2217	55.1854	4.133	618.5401
14	530.7001	82.372	4.000	617.0727
15	519.4398	91.4309	3.824	614.6947
16	539.8922	66.5135	5.000	611.4057
17	477.9535	128.2474	2.629	608.8299
18	514.2624	91.4699	3.023	608.7553
19	524.4897	78.9075	3.998	607.3952
20	478.1931	121.2071	2.999	602.3992
21	510.4279	88.8656	3.862	603.1555
22	481.8692	116.8675	3.988	602.7247
23	508.9287	87.0806	3.988	599.9972
24	545.1025	49.8114	4.135	599.0489
25	483.3392	108.0512	3.001	594.3914
26	470.8275	96.8246	3.023	570.6751
27	468.5132	98.0881	3.201	569.8024
28	507.882	56.3075	4.097	568.2866
29	478.29	74.1125	4.001	556.4035
30	479.7864	65.5598	4.999	550.3451
31	473.2767	67.4876	4.001	544.7653
32	471.8799	68.2468	4.000	544.1267
33	463.1405	64.987	4.923	533.0505
34	468.0572	59.3839	4.096	531.5371

VII. DISSCUSSION

This paper is based mainly on economical consideration when dealing with DG allocation on DS busbars. The main conclusions which can be extracted from the present work are:

- Cost of line losses has the maximum value among the three costs (line losses- voltage sag-unavailability).
- Cost of load isolation due to voltage sag has tangible value and should not be ignored in economic studies.
- Cost of loss of supply to loads due to forced outage of network component has minor effect in case of ring and interconnected distribution networks. However this cost cannot be ignored in case of radial systems.
- HES can greatly reduce the number of iterations and calculation effort in PSO application.
- Generally, there is an inverse trend between line loss and voltage sag costs.

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