

Multi-Objective Model for Allocation of Gas Turbines with the Aim of Black-Start Capability Enhancement in Smart Grids

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Abstract—Installation of new power generating units as backup black-start (BBS) sources is a vital issue to improve the acceleration of power network restoration, especially when a serious problem is occurred in main BS units (BSUs) and leads to fail in operation. Accordingly, this work address a new design for the optimal locating of the Gas-based Turbine (GT) as BBS to improve the smart grid performance during both restoration and normal conditions. To this end, there will be incompatible fitness functions to be minimized. Therefore, a multi-objective problem (MOP) including a mixed integer Non-linear programming (MINLP), is formulated. The Pareto answers of the proposed MOP as the best solutions are modified and extracted by utilizing a meta-heuristic method, called crow search algorithm (CSA). A typical test system is employed for evaluation of the given plan. The extracted outcomes reveal that the network can desirably operate from this design not only to favorably enhance the capability of BSUs, but also to improve the power system performance in normal conditions. It also provides the better start-up program of non-black-start (NBS) power sources with the optimal paths during the restoration process.

Keywords—power system restoration, black-start units, crow search algorithm, multi objective design, smart grid.

NOMENCLATURE

P_{g_i}	Output active power of the i -th generator
P_{l_j}	Consumed active power at PQ bus
v_i	Actual value of the voltage for i -th load bus
v_j	Actual value of the voltage for j -th PQ bus
δ_{ij}	Standing phase angle among buses i & j
n	Number of generators
k	Number of PQ buses
Q_{g_i}	Produced reactive power from i -th unit
Q_{l_j}	Injected reactive power to PQ bus
B_{ij}	Susceptance between bus i and bus j
G_{ij}	Conductance between bus i and bus j
V_{ref}	Value of the reference voltage

$V_{i_{min}}$	Lower voltage limit of i -th PQ bus
$V_{i_{max}}$	Upper voltage limit of i -th PQ bus
$P_{j_{max}}$	Max active power for NBSU j
$P_{j_{start}}$	Needed start-up active power for NBSU j
M	The number of all NBSU
$T_{j_{min}}$	Min. needed time of NBSU for connecting to grid
$T_{j_{max}}$	Max. needed time of NBSU for starting
$t_{j_{path-opt}}$	Needed time of path restoration in order to energize NBSU j
$P_{i_{gen-opt}}$	Generation capability of BSU i
$t_{j_{start}}$	The restoration time of NBSU j

I. INTRODUCTION

Power system fast restoration after happening of a blackout is one of the essential challenges from power system operator and planners point of view [1]. Power system restoration process contains three main stages including black-start phase, cranking paths restoration and load pickup [2]. In the preparation step, not only the black-start units (BSUs) are carefully commissioned, but also the cranking transmission routs are quickly energized to successfully supply large non-black-start units (NBSU) in order to be restored [3]. Note that, the preparation goal is to maximize the generation capability which is considered as objective function in various studies such [1-4].

An algorithm for generator restoration has been formulated as a MILP in [1] and [3]. The authors in [1] applied firefly algorithm (FA) in order to desirably search the optimal sequence of NBSUs, cranking transmission routs and load pick up process in the presence of renewable energy resources. Moreover, a similar strategy to find and update the restoration sequence of large NBSUs and also to favorably enhance the capability of generation within network restoration has been presented in [3].

The authors in [4] proposed an initial restoration process for units employing a MILP model so that the final phase of restoration is carried out manually using numerous trials. An optimal lack-start strategy based on the notion of vague-valued fuzzy logic measure has been developed in [5-6].

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A model based on steady-state to successfully improve the total generator active power output by means of optimal NBSUs restoration has been proposed in [7]. In [8], Dijkstra method has been applied in order to determine the optimal start-up sequences of generators with the aim of finding the shortest path during power system restoration.

A network reconfiguration scheme including two separate steps has been developed in [9], where the first step assigned to the optimal restoration plan of large units while the second step associated with finding the optimal cranking routs. A combined optimization method which considers both the sequence of generation units as well as the transmission path has been developed in [10].

Due to the author's best knowledge, the black-start units (BSUs) sequences have been done according to the existing units without considering their optimal location. It must be pointed that although the hydro and Gas Turbines (GTs) are known as the main BSUs, however, it is possible that these units do not have enough capabilities to crank the NBS units [11]. For instance, the hydro power plants may be not accessible due to lack of sufficient flow [12]. Also, continuous operation of main GT may put the system at risk due to the technical problem in fuel system that may cause unit trip. In addition, the failure of control system for both generation technologies may stop the process [13-14]. On this basis, redundant BSUs are crucial to crank the restoration quickly [15-17]. In the case of normal conditions, the new installed GTs can be started very fast in order to help the system to increase its generation in the shortest possible time [18-19]. Therefore, it will be more economical to place these units in the locations where not only avoid voltage violation but also minimize power losses.

This paper proposes a model for optimal placement of GTs, as appropriate candidates for redundant BSUs, is solved taking into account increment the capability of black-start generation and also improvement of the power system performance in normal conditions. To this end, a multi-objective function is used to determine the optimum locations of GTs, the best routs and the best unit restoration considering the black-start capability criterion, simultaneously. The multi-objective function not only minimize the Unavailable Energy Capability (UEC) of the system during the restoration process but also minimize the voltage deviations and active power losses in transmission network during normal condition using the best Pareto optimal set. Afterward, fuzzy-based CSA is developed to achieve the best compromise solution. The proposed model is simulated on the 39-bus grid. The rest of the paper is organized as below. The mathematical formulation of the model is presented in Section II. Section III deals with numerical studies. Finally, Section IV concludes the paper.

II. MATHEMATICAL MODEL FORMULATION

The proposed multi-objective model includes three objective functions as given in the following section. The first objective function is associated with minimizing the total generation capacity which is not available after blackout as formulated in (1) [1]:

$$\begin{cases} \min f_1(x) = \sum_{j=1}^M (P_{j\max} - P_{jstart})t_{jstart} \\ S.t : \\ T_{j\min} \leq t_{jstart} \leq T_{j\max} \\ t_{jpath-opt} \leq t_{jstart} \\ P_{igen-opt}(t) \geq P_{jstart}(t), j = 1, 2, \dots, M \end{cases} \quad (1)$$

Minimizing the active power loss is formulated as the second objective function in (2) [20]:

$$\begin{cases} \min f_2(x) = \sum_{i=1}^n P_{g_i} - \sum_{j=1}^k P_{l_j} \\ S.t : \\ P_{g_i\min} \leq P_{g_i} \leq P_{g_i\max}, i = 1, 2, \dots, n \\ P_{l_j\min} \leq P_{l_j} \leq P_{l_j\max}, j = 1, 2, \dots, k \\ P_{g_i} - P_{l_i} - V_i \sum_{j \in NB_i} V_j (g_{ij} \cos \delta_{ij} + b_{ij} \sin \delta_{ij}) = 0 \\ Q_{g_i} - Q_{l_i} - V_i \sum_{j \in NB_i} V_j (g_{ij} \sin \delta_{ij} + b_{ij} \cos \delta_{ij}) = 0 \end{cases} \quad (2)$$

The third cost function aims to decline the voltage violation in all PQ buses as given in (3) [20]:

$$\begin{cases} \min f_3(x) = \sum_{i=1}^k |V_{ref} - V_i| \\ S.t : \\ V_{i\min} \leq V_i \leq V_{i\max}, i = 1, 2, \dots, k \end{cases} \quad (3)$$

It is impossible in multi-objective design to achieve a better answer when all fitness functions are simultaneously being minimized or maximized, because of incompatibility of different cost functions. Accordingly, the system operator as a decision maker selects an efficient option as a best solution [21]. In this research, a fuzzy technique is employed for three different fitness functions (f_1 , f_2 , f_3) because of their approximate amounts. To do this process, a membership function based on fuzzy logic is modelled for finding the best answer. For all answers stored in storage, equation (4) is formulated [22]:

$$\mu_{f_i(X)} = \begin{cases} 0 & f_i(X) \geq f_i^{\max} \\ \frac{f_i^{\max} - f_i(X)}{f_i^{\max} - f_i^{\min}} & f_i^{\min} \leq f_i(X) \leq f_i^{\max} \\ 1 & f_i(X) \leq f_i^{\min} \end{cases} \quad (4)$$

In Eqn (4), f_i^{\max} and f_i^{\min} respectively show high value and low value of limitation for all cost function. These limitations are computed in single objective planning of each fitness function.

Then, the obtained membership of stored answers will be normalized by computing Eqn. (5) [23]:

$$N_{\mu}(X_i) = \frac{\sum_{k=1}^h w_k \mu_{f_k}(X_i)}{\sum_i^d \sum_k^h w_k \mu_{f_k}(X_i)} \quad (5)$$

In Eqn.(5) h, d , w_k respectively imply the number of cost functions, the total number of Pareto front solutions in storage and the weight of K -th fitness function. At the final step, the most compromise answer is selected to the answer with the most value of N_{μ} .

The CSA has been employed to optimally solve the multi objective design problem according to the following given steps. It is worth to note that a clustering method based on fuzzy logic is carefully utilized to set the capacity of the storage in this paper [24]. For this purpose, each answer of the storage is determined as a cluster with certain distance. Adjacent clusters are unified until the suitable capacity of storage is significantly acquired. In unifying stage, the candidate with the more membership amount of unified clusters is selected to be stored in the storage. The stages of proposed plan are addressed below:

- Stage 1:** Enter the necessary parameters of algorithm including N , f_l , AP , maximum iteration, and the size of Pareto storage.
- Stage 2:** Create the first random set of crow's location and related memories.
- Stage 3:** Calculate the amount of fitness functions for each individual.
- Stage 4:** Verify the mentioned constraints of the MOP by Eqs. (1)–(3).
- Stage 5:** Check and find the non-dominated answers between the extracted answers and archive them in the Pareto storage by Eqs. (4) and (5).
- Stage 6:** Verify the capacity of storage. If it's capacity exceeds the high limitation, eliminate the extra candidate with clustering technique based on fuzzy logic.
- Stage 7:** Produce the modified set of candidate's location.
- Stage 8:** Investigate the feasibility of updated set of candidate's location. If updated location is satisfied, stage 9 is followed. Otherwise, stage 7 is followed.
- Stage 9:** Evaluate the amount of cost functions for each updated candidate.
- Stage 10:** Assess the constraints of the proposed MOP by Eqs. (1), (2) and (3).
- Stage 11:** Update the storage by recording new non-dominated answers by considering Eqs. (4) and (5).
- Stage 12:** Verify the capacity of storage. If the dimension of storage exceeds the high value of predefined amount, eliminate the extra candidate with clustering method based on fuzzy logic.

Stage 13: Survey the finalizing law. If the high limitation of iteration is carefully satisfied, leave the implementation of the proposed algorithm. Otherwise stage 7 is followed.

III. RESULTS AND DISCUSSION

In this segment, the presented MOP is considered to be utilized for a typical test system to show its efficient performance during restoration and normal conditions.

The 39-bus power grid is completely considered as a test network [25]. This grid is carefully divided into two segments in restoration plan [1], and each partition must consist of at least one BSU [26]. Accordingly, the number of main BSUs is optimally determined to be 2 (G6 and G10) [1, 3]. Besides, it is essentially vital that the BBSUs (GTs) be selected for each power grid, and their best places are achieved.

The proposed plan is orderly done in two parts. Firstly, the single objective plan is run to evaluate and to utilize the limit amount of three cost functions f_1, f_2 and f_3 (Eqs. (1)–(3) for the next part (multi-objective plan). In the second part, the multi-objective plan is fulfilled to quickly find the best answer including the begin times of NBSUs and the places of GTs. The important data of units for black-start phase are completely addressed in Table I [3]. In this Table, T_{cp} shows the time of power cranking for a NBSU to start and to ramp up for joining with grid, and R_r implies the ramp rate of a NBSU.

A. Single objective planning

The objective function f_1 (Eq. (1)) is minimized using CSA to extract all best begin times of NBSUs and the optimal places of GTs (BBSUs) and the outcomes are shown in Table II. The last row of Table II gives the more desirable amount of the cost function f_1 employed for the margins chosen in multi-objective plan. Moreover, the best start-up sequences of NBSU units are obtained as given in Table II. In this regard, each subsystem includes one redundant BSU and four NBSUs.

TABLE I. CHARACTERISTICS OF GENERATING UNITS

unit	Type	P_{max} (MW)	P_{start} (MW)	R_r (MW/hr)	T_{max} (min)	T_{min} (min)
G1	Coal	572.9	5.5	215	-	40.
G2	Nuc.	650	8	246	-	-
G3	Nuc.	632	7	236	120	-
G4	Coal	508	5	198	-	70
G5	Coal	650	8	244	60	-
G6	Nuc.	560	0	214	-	-
G7	Coal	540	6	210	-	-
G8	Nuc.	830	13.2	346	-	-
G9	Nuc	1000	15	384	-	-
G10	Hyd.	250	0	162	-	-

It should be noted that the size of each GT (BBSU) is chosen to be 50 MW because the total demand of starting power of all NBSUs in each subsystem is 50 MW. The best highlighted path of restoring energy for large NBSUs is given in Fig. 1. In this figure, the rout of restoration for large NBSUs is individualized by a different line.

TABLE II. THE BEST SINGLE OBJECTIVE PLAN USING CSA

Island 1	Unit	10	1	2	8	9	BBSU
	BBSU	-	-	-	-	-	Ok
	NBSU	Ok	Ok	Ok	Ok	Ok	-
	t_{start} (min)	25	40	40	30	40	15
	Place of BBSU	-	-	-	-	-	Busbar 3
Island 2	Unit	4	3	5	6	7	BBSU
	BBSU	-	-	-	-	-	Ok
	NBSU	Ok	Ok	Ok	Ok	Ok	-
	t_{start} (min)	70	40	30	30	35	15
	Place of BBSU	-	-	-	-	-	Busbar 16
Value of UEC (p.u. . min)		2334.9					

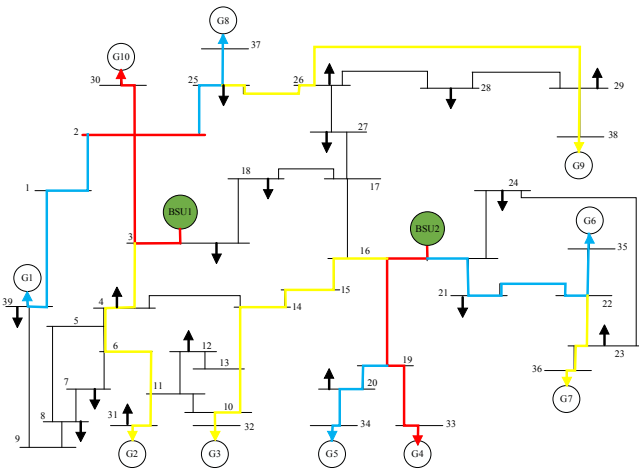


Fig. 1. Optimal generator start-up using redundant BSU

TABLE III. OPTIMAL MULTI-OBJECTIVE PLAN USING CSA

Island 1	Unit	10	1	2	8	9	BBSU
	BBSU	-	-	-	-	-	Ok
	NBSU	Ok	Ok	Ok	Ok	Ok	-
	Starting time (min)	35	40	30	35	55	15
	Place of BBSU	-	-	-	-	-	Busbar 5
Island 2	Unit	4	3	5	6	7	BBSU
	BBSU	-	-	-	-	-	Ok
	NBSU	Ok	Ok	Ok	Ok	Ok	-
	Starting time (min)	70	45	35	35	25	15
	BBSU Place	-	-	-	-	-	Bus 24
Amount of UEC (p.u. . min)		2522.37					

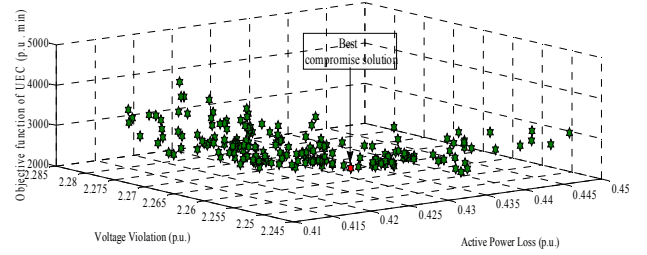


Fig. 2. Pareto curve of CSA-based multi-objective method

TABLE IV. COMPARISON OF DIFFERENT ANSWER IN GT PLACEMENT

Solution	Value of UEC (pu.min)	Voltage violation (pu)	Active power loss (pu)
$solution 1: \begin{cases} w_1=0.7 \\ w_2=0.15 \\ w_3=0.15 \end{cases}$	2500.5	2.284	0.456
$solution 2: \begin{cases} w_1=0.33 \\ w_2=0.33 \\ w_3=0.33 \end{cases}$	2522.3	2.257	0.426

B. Multi objective planning

In this segment, the multi-objective plan based on CSA is individually executed to extract the best efficient variables by simultaneous optimization of three cost functions and the outcomes are written in Table III. The Pareto optimization front is obviously illustrated in Fig. 2. Note that the red star is related to the best compromise solution.

Table III implies that the best amounts of cost functions are higher than the ones extracted in the mentioned single objective plan (Table II). This happens because all fitness functions are minimized together in multi-objective plan.

As well as, all the cost functions are considered by the alike factor ($w_1=w_2=w_3=0.33$). w_1 , w_2 and w_3 imply the weights of fitness functions of UEC, active power loss and voltage violation, respectively. In order to show the reason for choosing these weights, two various answers with various factor are and the outcomes are addressed in Table IV. As observed, the quantity of UEC for answer 2 (2522.3 pu.min) is very close to answer 1 (just 0.8% difference). But, the values of active power loss and voltage violation in solution 2 (0.426 pu. and 2.257 pu.) have been declined when compared with answer 1 by 7% and 1.2 % respectively. This results that considering alike weight factor for fitness functions in multi-objective plan desirably declined the active power loss and voltage violation in normal operation and also keep the amount of UEC about answers 1 and 2.

IV. CONCLUSION

In this article, a new MOP was presented to choose the best places of GTs (BBSUs). During the solving this problem, the best unit start-up process with the best cranking paths are also obtained.

Unavailable energy capability, energy loss and voltage change are addressed as the fitness functions and are minimized using CSA. The Pareto front technique was employed to solve the MOP and the Pareto optimal answers was extracted.

In the first stage of the design procedure, the cost functions f_1 , f_2 , and f_3 were separately optimized by employing CSA algorithm. These results are utilized for the limits considered in the next stage. In the second stage of design procedure, the Pareto optimization curve was extracted by simultaneously optimizing three fitness functions and using a fuzzy mechanism.

The graphical diagrams of the proposed design which shows the optimal subsystems and the optimal locations of BSUs corresponding to the best obtained solution were depicted for two systems. A numerical analysis of three criterion (Unavailable energy capability, energy loss and voltage change) is also given for IEEE 39 bus power system considering two different solution with different weights. These results implied considering of equal weights for three different criterion gives the better plan. Finally, outcomes implied that energy loss and voltage change are efficiently declined when BBSUs are connected to the system. As well as, the unavailable energy capability declined when the located GTs were applied as BBSUs.

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