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Integration of wind power for optimal power system black-start restoration

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Abstract: Integration of wind farms into power systems may increase the risk of power system blackouts due to the uncertain nature of their output power. In the meantime, wind turbines have relatively short starting time when compared to non-black-start (NBS) generating units. For this reason, wind farms need to participate in power system restoration after blackouts. The decision of restoring a wind farm depends on its output power and the characteristics of the power system. The power system restoration should be accomplished as soon as possible. For complete power system restoration, three stages must be completed: generation restoration, transmission system restoration, and load pick up. To achieve a faster restoration process, an optimal schedule for the black-start units to crank the NBS units is required with optimal transmission path selection. During the restoration process, to maintain the stability of the system and satisfy the system's operational constraints, an optimal load pick up sequence is required. In this paper, the firefly optimization algorithm is used to find the optimal final sequence of NBS unit restoration, the optimal transmission paths, and the optimal load pick up sequence with and without integration of wind farms in the system. The objective is to minimize the overall restoration time and the unserved load, which maximizes the energy capability and improves the sustainability of the system. The proposed algorithm is applied successfully to the IEEE 39-bus system.

Key words: Wind power, power system restoration, black-start, generation capability, firefly optimization algorithm

1. Introduction

Recent development in utility-scale wind farm control increased their integration into power systems. The integration of large-scale wind farms to power systems increased the risk of blackouts due to the uncertainty in the wind power supply. However, most wind turbines normally start automatically about 10 min after getting stable voltage following a blackout, which encourages power system dispatchers to include them earlier in the power system restoration process to control the high reactive power resulting from unloaded high-voltage long transmission lines. In addition, wind farms can contribute in faster load pick up by ramping up in a fast manner when the load is stepping up. This will lead to an improvement in load restoration time, which helps in the reduction of the unserved load during restoration. However, at the beginning of a black-start restoration process, the restored generators are not yet located in the stability domain and the network is not completed; hence, it is not strong enough to allow the restoration of wind farms. The restoration of wind farms at that stage may lead to blackout again in the case of large fluctuations of wind farm output power. That is why it is recommended to restore a wind farm when the network is relatively complete and all constraints are met where the grid is strong enough to sustain a slight disturbance. Wind farm restoration depends on many factors other

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than the network characteristics, such as the power output. To calculate the wind farm output power, wind power forecasting is required [1,2].

In this paper, the time of restoration of wind farms is determined according to the optimal generator restoration sequence where it is selected to be the moment at which the network is completely reconstructed and all buses and lines are energized. At that moment the wind farm restoration will depend only on the output power of the wind farm. A sensitivity analysis is carried out to study the effect of wind output power on the sequence of load pick up and hence on the amount of unserved load energy.

System restoration after a complete blackout is one of the most important tasks for power system planers and operators. The major task is to return the system back to normal operating conditions. Determination of the restoration sequence of a power system after a major blackout is a complicated problem with many stages and constraints to satisfy. This problem can be formulated as a nonlinear optimization problem. Restoration plans are prepared offline for dispatchers' guidance. Through the assessment of system conditions, the restoration plans describe the sequence to start black-start (BS) units, the way to establish the transmission paths to crank non-BS (NBS) generating units, and the sequence to pick up necessary loads to maintain the stability of power system [3]. In [4], the restoration process was divided into three stages: preparation, system restoration, and load restoration, depending on the generation availability at each stage. The objective was to maximize the generation capability during the system restoration period through optimal use of the available BS capabilities.

Many studies have addressed this problem either by partitioning the systems into subsystems and carrying out the restoration in stages [5] or by treating the restoration process as a multilayer problem (network layer and plant layer) and dealing with each layer individually [6]. In [3], the authors dealt with the generation restoration separately from the transmission paths search. In addition, they only tried to find the initial restoration sequence and, according to the operating conditions of each system, they started to manually modify the initial guess to reach the final sequence after many trials, which is not suitable for large-scale systems. The authors of [7] used the enumerative algorithm to search the combination of all possible starting times, which may lead to global optimality but limits the real-time application due to the extremely high computational burden. To overcome this drawback, the problem was divided into stages in [8] and dynamic programming was used to optimally link these stages together. Although the computation problem was solved, the introduced restoration procedure was very complicated to apply to large-scale systems. A two-step algorithm using mixed integer quadratically constrained programming was introduced in [9] to solve the problem for discretized times with optimality guaranteed at each step. However, the quadratic components that exist in both objective functions and constraints cannot guarantee the global optimality. On the other hand, other methods required knowledge bases that become very complicated when dealing with large-scale systems.

Several methods were also used to solve this optimization problem, such as genetic algorithms [6], mathematical programming [10], expert system method [11], vague set theory [12], back tracing algorithm [13,14], and ant colony search [15]. Some of these studies addressed the stage of generation restoration alone and managed to find an optimal but not final generation restoration sequence. Others addressed the three stages of system restoration, but separately. However, the optimal power system BS restoration in the presence of renewable energy sources such as wind farms was not addressed. In [1], some aspects of power system restoration considering wind farms were presented, but the restoration problem was not solved. In [2], a restoration sequence with the participation of wind farms was suggested without optimizing this suggestion.

In this paper, the three stages of power system restoration are combined into one optimization problem to be solved simultaneously considering the presence of wind farms in the system. The firefly optimization algorithm (FA) is used to solve this optimization problem. The FA is used to determine the optimal and final sequence of NBS units restoration, the most optimal transmission paths to deliver cranking power from BS units to NBS units, and the optimal load pick up sequence with and without the presence of wind farms in the system. The objective is to maximize the energy capabilities and restored energy of the system through minimizing both the overall restoration time of generators and loads and the unserved load energy. The proposed algorithm is efficient in the case of large-scale systems because it is very simple and does not need any knowledge bases. The simulation time of the FA compared to other methods is relatively short, as will be shown by the results. The proposed algorithm is tested using the IEEE 39-bus system.

2. Firefly optimization algorithm

The FA is a metaheuristic algorithm inspired by the phenomenon of bioluminescent communication and the flashing behavior of fireflies. Some assumptions were made to formulate the FA. These assumptions are [16,17]:

i) All fireflies are unisex, which allows any one firefly to be attracted to any of the other fireflies.

ii) Attractiveness is proportional to the brightness of the fireflies. This means that, for any two fireflies, the less bright one will be attracted to the brighter one, taking into consideration that the brightness can decrease as their distance increases.

iii) If there are no fireflies brighter than a given firefly, it will move randomly.

In an optimization problem solved by FA, each individual represents a firefly and its fitness value is determined by association of fireflies' brightness with the objective function.

A firefly moves by comparing its light intensity with another brighter firefly. The attractiveness of a firefly (β) is proportional to its light intensity as seen by a neighbor firefly and it depends on the distance between these two fireflies (z). In this case, the movement of firefly i to another more attractive (brighter) firefly j can be expressed as

$$X_i = X_i + \beta(X_j - X_i) + \alpha\left(r - \frac{1}{2}\right), \quad (1)$$

and the attractiveness function of a firefly can be formulated as

$$\beta = \beta_0 \cdot e^{-\gamma z_{ij}^2}, \quad (2)$$

where X_i is the position of firefly i in the d-dimension space,

X_j is the position of firefly j in the d-dimension space,

α is a randomization parameter,

r is a random number between 0 and 1,

z_{ij} is the distance between firefly i and firefly j,

- is light absorption coefficient,

β_o is the attractiveness at z = 0.

The steps of implementing the classical FA can be listed as shown in Figure 1.

```
Generation initial population of m fireflies X_i (i = 1,2,......,m) through uniform distribution in search space
Evaluate objective function J
Light intensity I_i at X_i is evaluated by J
Define light absorption coefficient γ
Generation = 0
while (Generation < Maximum of generations)
  Generation = Generation + 1
  for i = 1 to m
    for j = 1 to i
      if (I_j < I_i) in case of a minimization problem
        Move firefly i towards j in d − dimension
      end if
      Attractiveness varies with distance z as in equation (2)
      Evaluate new solutions and update light intensity
    end for j
  end for i
  Rank the fireflies and find the current best
end while
```

Figure 1. Implementation steps of classical FA.

3. Problem formulation

The restoration process has been divided into stages. The primary stages are generation capability maximization, transmission path search, constraint checking, and distribution system restoration (load pick up) [8]. These stages have been addressed separately before as previously mentioned. However, in this paper an FA-based method is proposed to consider all these stages simultaneously. The FA is used to find the optimal restoration sequence of generators, the optimal transmission path for BS units to deliver cranking power to NBS units, and the optimal load pick up sequence while satisfying the system constraints.

3.1. Objective function

The indirect objective is to maximize the overall system energy capability (MWh) through the maximization of the system MW generation capability during a specified system restoration period. The system energy capability E_{sys} is the difference between the total system MWh capability and the NBS generators' start-up requirements over the restoration period [3] as given by Eq. (3):

$$E_{sys} = \sum_{i=1}^{N} E_{igen} - \sum_{j=1}^{M} E_{jstart}, \tag{3}$$

where E_{igen} and E_{jstart} are the MW capability of generator i and start-up requirement of NBS generator j, respectively, over the system restoration horizon T,

M is the number of NBS units,

N is the total number of generation units.

Simplifying Eq. (3) as in [3] leads to:

$$\max\ E_{sys} \Leftrightarrow \ \min \sum_{j=1}^{M} (P_{j\max} - P_{jstart}) * t_{jstart}, \tag{4}$$

where P_{jmax} is the maximum MW generation of NBS unit j,

P_{jstart} is the start-up power of NBS unit j,

t_{jstart} is the starting time of generator j.

However, as long as P_{jmax} and P_{jstart} of each generator are constants, the objective function can be further reduced to:

$$\min \sum_{j=1}^{M} t_{jstart}. \tag{5}$$

As considered in this paper, maximizing the generation capability during the restoration period can be achieved by minimizing the restoration time of each NBS unit and hence minimizing the total restoration time of the whole system and the unserved energy in accordance.

Considering also the minimization of the unserved load energy, the objective function can be expressed as follows:

$$\min\ [\sum_{j=1}^{M} t_{jstart} + \sum_{t=1}^{T} (P_{load-total} - P_{load}(t)) * t], \tag{6}$$

where T is the total restoration time,

$P_{load-total}$ is the total load power of the system,

$P_{load}(t)$ is the total restored load at time t.

3.2. Transmission path search

The optimal transmission path connecting a BS unit to a NBS unit or connecting an energized bus to an unenergized bus can be selected from a number of possible paths. To determine the possible paths, the system incidence matrix is used. When a branch connects to a bus, the branch and bus are said to be incident [18]. A tree of a network is formed by those branches of the network that interconnect all the buses of the network without forming closed paths. In general, there are many possible trees of a network since different combinations of branches can be chosen to connect the buses. A network can be described in terms of the incidence matrix. The branch-to-bus incidence matrix **A**, which has one row for each branch and one column for each bus, is used in this paper. For the six-bus network shown in Figure 2, the incidence matrix is given in Figure 3. For example, one of the paths from G1 to G3 is marked on Figure 2 and the way to find it using the **A** matrix is marked on Figure 3. To complete that path, three buses and two branches need to be energized. The buses are bus 1, bus 2, and bus 3, and the branches are branch 1-2 (b5) and branch 2-3 (b2).

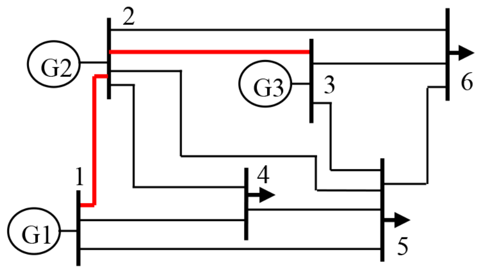


Figure 2. The six bus system with a path marked on it.

$$A = \begin{matrix} b1 \\ b2 \\ b3 \\ b4 \\ b5 \\ b6 \\ b7 \\ b8 \\ b9 \\ b10 \\ b11 \end{matrix} \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 & 0 \end{bmatrix}$$

Figure 3. The **A** matrix of the six-bus system with a path marked on it.

3.3. Constraints

To decide whether to restore wind farms or not, two constraints must be satisfied. The first constraint is the completion of network reconstruction and the second one is the availability of wind power.

The starting times of NBS generators and their start-up power requirements must satisfy certain constraints. During restoration, some NBS units are not ready to receive cranking power until after a certain time interval ($T_{j\,min}$), while others need to start within a certain interval ($T_{j\,max}$) or they will become unavailable for a considerable time delay. In addition, all NBS units have their start-up power requirements ($P_{j\,start}$) that must be supplied by the system for the units to start.

In general, power systems can have more than one BS generator. The selection of the BS unit to crank a NBS unit depend on the length of the optimum transmission path between them and the generation capability of the BS unit at the time of the NBS unit starting. On the other hand, the sequence of load pick up depends on the value of the load to be picked up and the available generation capability of connected generators at the time of picking up that load.

Based on these definitions, the generators start-up constraints can be formulated as follows:

- Starting time constraints

  Considering the appropriate time interval to start the NBS unit, the starting time must satisfy the following constraints.

$$t_{jstart} \geq T_{j\,\min}, \qquad j = 1, 2, \ldots, M, if T_{j\,\min} exist \tag{7}$$

$$t_{jstart} \leq T_{j\max}, \qquad j = 1, 2, \ldots, M, ifT_{j\ \max}exist \tag{8}$$

To consider the time needed to energize the optimum path leading to the NBS unit j:

$$t_{jpath-opt} \leq t_{jstart}, \tag{9}$$

where t_{jstart} is the starting time of NBS unit j and $t_{jpath-opt}$ is the time taken to energize the buses and branches consisting of the optimal path to NBS unit j.

- Start-up power requirement constraints

$$P_{igen-opt}(t) \geq P_{jstart}(t) \tag{10}$$

for i=1,2,. . . ,Z and j=1,2,. . . .,M

Here, $P_{igen-opt}$ is the generation capability function of cranking unit i selected according the optimal transmission path found by the optimization algorithm, P_{jstart} is the start-up power function of NBS unit j, and Z is the number of BS units in the power system.

- Load pick up constraint

$$\sum_{i=1}^{NL} P_{iload}(t) \leq \sum_{j=1}^{NG} P_{jgen}(t) + P_{windfarm}(t) \tag{11}$$

Here, P_{iload} is the load power of the ith picked up load, P_{jgen} is the power generated by the jth connected generator, $P_{windfarm}$ is the wind power, NL is the number of picked up load nodes, and NG is the number of connected generators.

- The bus voltage constraint

$$V_i^{min} \leq V_i \leq V_i^{max} i = 1 \ldots nbus \tag{12}$$

- The branch power capacity constraint

$$S_{ij}(t) \leq S_{ij}^{\max} \qquad i = 1.\ldots nbus, j = 1 \ldots nbus, i \neq j \tag{13}$$

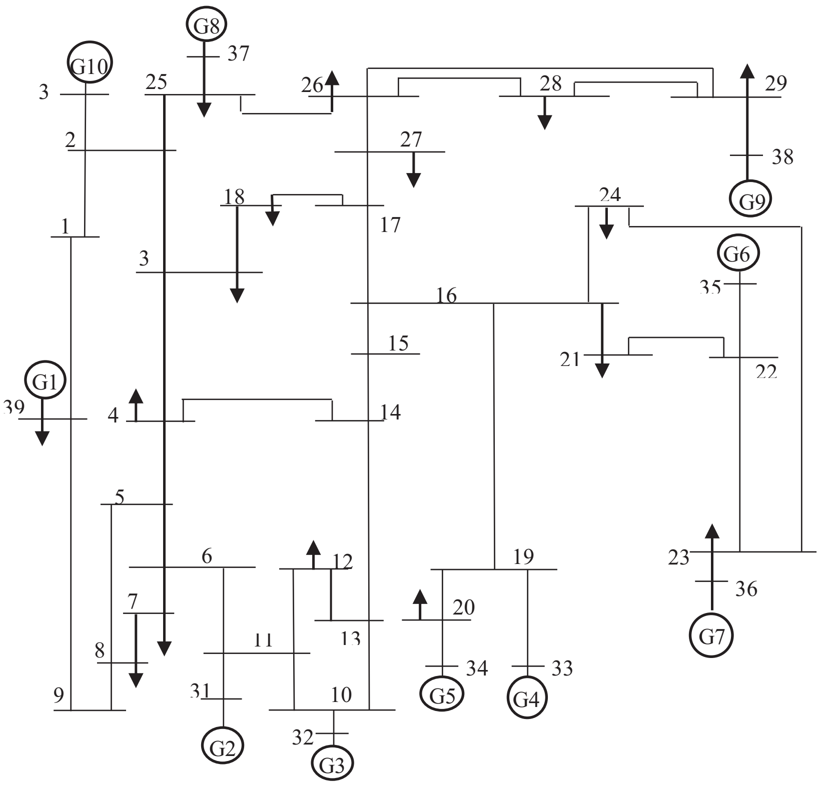


Figure 4. IEEE 39-bus system.

4. Simulation results

The IEEE 39-bus system shown in Figure 4 is used for verification of the proposed algorithm. The system has 10 generators, among which 2 are BS units. The generator data are given in Table 1, where T_{ctp} is the cranking time for the generator to begin to ramp up and parallel with the system and R_r is the ramping rate of the generator. To consider the effect of the wind farm on load restoration, a wind farm of 250 MW is connected to bus 15. The objective function convergence is shown in Figure 5. The population size of the FA is selected to be n = 150.

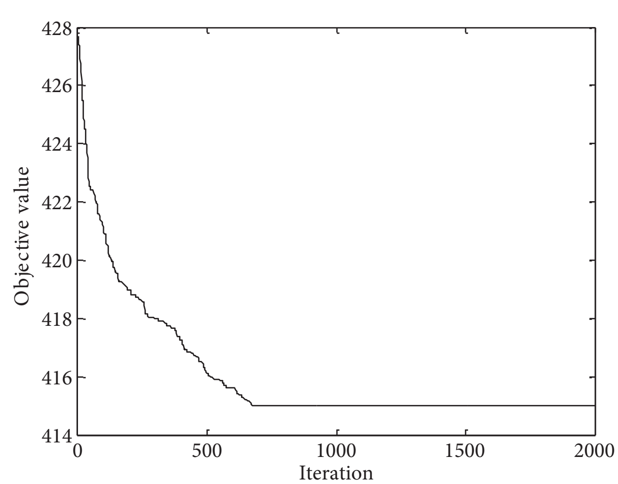


Figure 5. Convergence of objective function.

Table 1. Data of IEEE 39 bus system.

Gen.	Type	T_{ctp} (min)	T_{cmin} (min)	T_{cmax} (min)	R_r (MW/h)	P_{start} (MW)	P_{max} (MW)
G1	NBS	35	40	N/A	215	5.5	572.9
G2	NBS	35	N/A	N/A	246	8	650
G3	NBS	35	N/A	120	236	7	632
G4	NBS	35	70	N/A	198	5	508
G5	NBS	35	N/A	60	244	8	650
G6	BS	15	N/A	N/A	214	0	560
G7	NBS	35	N/A	N/A	210	6	540
G8	NBS	35	N/A	N/A	346	13.2	830
G9	NBS	35	N/A	N/A	384	15	1000
G10	BS	15	N/A	N/A	162	0	250

Applying the proposed algorithm resulted in the restoration sequence given in Table 2. As shown in Table 2, the last NBS generator started after 70 min. The actions needed to restore the whole system are given in Table 3. The optimal transmission paths are given in Table 4 and they are marked on Figure 6. As shown in Table 4, the entire generation and transmission systems are completely restored in 105 min, which is less

Table 2. Optimal generator restoration sequence.

Gen.	G1	G2	G3	G4	G5	G7	G8	G9
t_{start} (min)	50	50	60	70	55	40	40	50

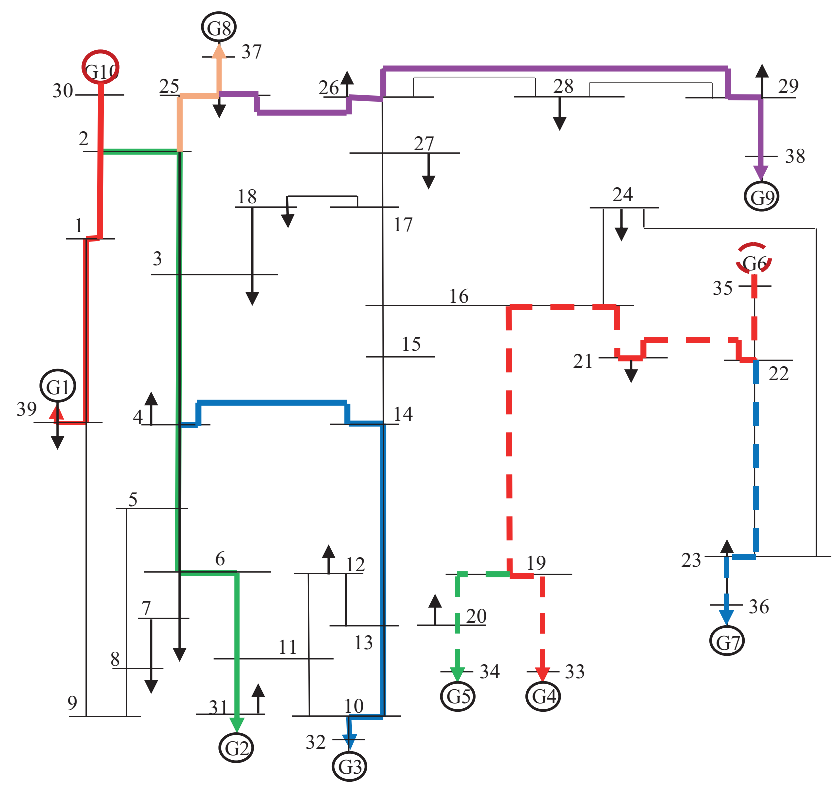


Figure 6. Optimal transmission paths of IEEE 39-bus system.

than any restoration times of the same system under the same conditions. The best restoration times recorded before for the same system under the same conditions were 110 min using the mixed integer linear programming (MILP) method [3] and 200 min using the ant colony search (AC) algorithm [15].

Table 3. Actions needed to restore the whole system.

Time (min)	Action	Target
15	Energize Parallel	Bus: 30, 35 G10, G6
20	Energize	Bus: 2, 22; Branch: 30-2, 35-22
25	Energize	Bus: 1, 3, 21, 23, 25; Branch: 2-1, 2-3, 2-25, 22-21, 22-23
30	Energize	Bus: 4, 16, 26, 36, 37, 39; Branch: 1-39, 3-4, 25-37, 25-26, 21-16, 23-36
35	Energize	Bus: 5, 14, 19, 29; Branch: 4-5, 4-14, 16-19, 26-29
Time (min)	Action	Target
40	Energize Crank	Bus: 6, 13, 20, 33, 38; Branch: 5-6, 14-13, 19-20, 19-33, 29-38 G7, G8
45	Energize	Bus: 10, 11, 34; Branch: 13-10, 6-11, 20-34
50	Energize Crank	Bus: 31, 32; Branch: 11-31, 10-32 G1, G2, G9
55	Crank	G5
60	Energize Crank	Bus: 7, 8, 9, 12, 15, 24; Branch: 6-7, 5-8, 39-9, 11-12, 14-15, 23-24 G3
65	Energize	Bus: 17, 18, 27, 28; Branch: 16-17, 3-18, 26-27, 26-28
70	Energize Crank	Branch: 8-9, 8-7, 28-29, 17-18, 17-27, 15-16, 16-24, 12-13, 10-11 G4
75	Parallel	G7, G8
85	Parallel	G1, G2, G9
90	Parallel	G5
95	parallel	G3
105	Parallel	G4

Table 4. Optimal transmission paths.

NBS gen.	Gen. providing cranking power	Optimal transmission path
G1	G10	Bus: 30→2→1→39
G2	G10	Bus: 30→2→3→4→5→6→11→31
G3	G10	Bus: 30→2→3→4→14→13→10→32
G4	G6	Bus: 35→22→21→16→19→33
G5	G6	Bus: 35→22→21→16→19→20→34
G7	G6	Bus: 35→22→23→36
G8	G10	Bus: 30→2→25→37
G9	G10	Bus: 30→2→25→26→29→38

A comparison of generation capability curves by using different methods, without considering wind power, is shown in Figure 7. As shown in Figure 7, the FA and MILP methods achieved approximately nearly the same generation capability and their results are better than that of AC method. In [3], the authors stated that the computational time of the MILP method was 8 s. However, those 8 s represented the time to reach an initial restoration sequence, not the final one. Afterwards, the starting times of the generators were manually altered several times before reaching the final restoration sequence, which may become very complicated and consume several minutes for large-scale systems. In this paper, the FA managed to reach the final optimal restoration sequence and the optimal transmission paths in 180 s.

This paper went further to include the optimal load pick up based on steady state analysis in the optimization problem and to study the effect of the wind farm power on load pick up sequence, where a wind farm of 250 MW is considered to be connected to bus 15. The forecasted wind power during an average day in April in Alexandria, Egypt, is used for simulation and is shown in Figure 8.

The proposed algorithm succeeded to find the optimal load pick up sequence while satisfying the constraint given by Eq. (11) as shown in Figure 9. The amount of restored load power compared to the restored generation power is shown in Figure 9. As shown in Figure 9, the load power closely follows the generation power, which satisfies the constraint of Eq. (11) and contributes in keeping the system stability while maintaining bus voltage and branch MVA within limits.

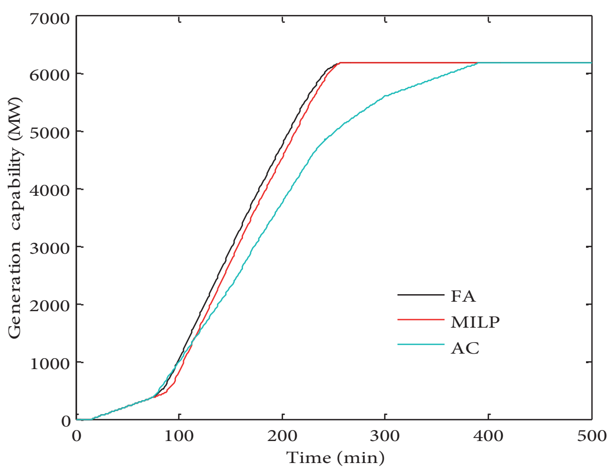


Figure 7. Comparison of generation capability curves by using different methods.

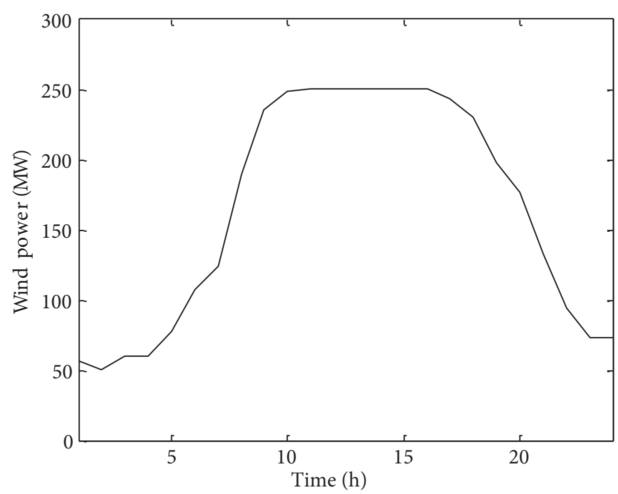
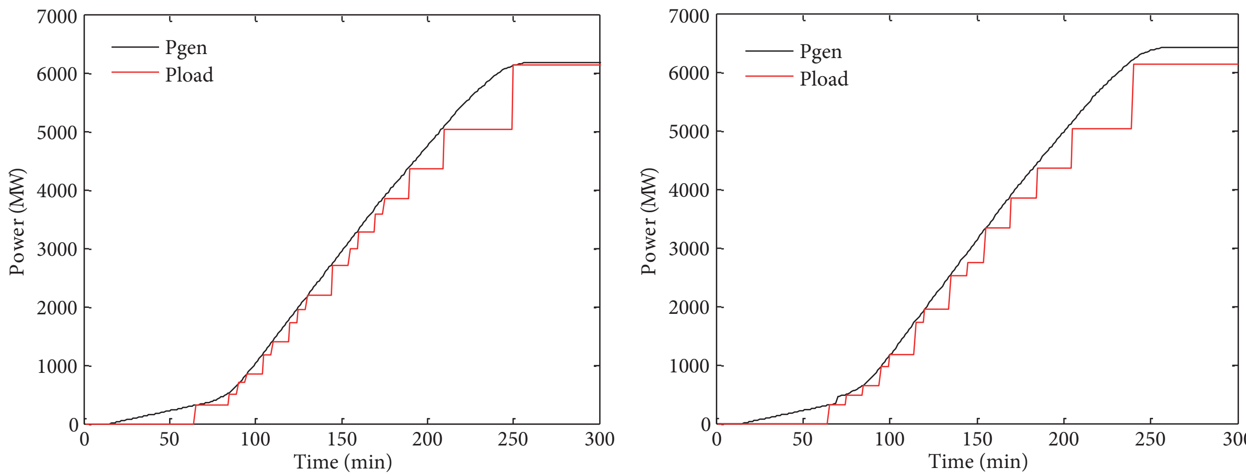


Figure 8. Forecasted wind power.

To satisfy the two constraints of restoring wind farms, first the wind farm is restored after time t = 70 min from the start of restoration when the whole system is completely reconstructed. Second, for illustration, the wind farm is assumed to be restored at hour 6 while the wind power is rising. The load pick up sequence with and without considering the wind power is given in Table 5. As shown in Table 5, the load is picked up faster with the support of wind power supply. As a result, the total unserved load energy during the restoration period is reduced with the presence of wind power as given in Table 6. To consider the variation of wind power during the day, different wind farm restoration times are taken into consideration. The times are picked such that at hour 6 the wind power will be increasing during system restoration, at hour 10 the wind power will be constant, and at hour 16 the power is decreasing. As shown in Table 6, the unserved load energy with wind power included is less than that without wind power. In addition, the unserved load energy when the wind power is falling or constant is less than that when the power is rising.



(a) Without wind power (b) With wind power

Figure 9. Restored load power compared to restored generation power.

Table 5. Optimal load pick up sequence without and with wind power.

Time (min)	Bus no.	Power (MW)	Time (min)	Bus no.	Power (MW)
65	3	322	65	3	322
85	12	8.5	75	12	8.5
	18	158		26	139
	31	9.2		31	9.2
90	28	206	85	18	158
95	26	139	95	16	329
105	16	329	100	28	206
110	7	233.8	115	27	281
120	15	320		29	283.5
125	25	224	120	25	224
130	23	247.5	135	15	320
145	8	522		23	247.5
155	29	283.5	145	7	233.5
160	27	281	155	21	274
170	24	308.6		24	308.6
175	21	274	170	8	522
190	4	500	185	4	500
210	20	680	205	20	680
250	39	1104	240	39	1104

Table 6. Unserved load energy during restoration period with and without wind farm.

Without wind power	With wind power	
Energy (MWh)	Restoration time (h)	Energy (MWh)
16652	6	16167
	10	15891
	16	15926

To show the effect of the proposed restoration procedure on the bus voltages, the maximum value of bus voltage and the minimum value of bus voltage during restoration period compared with the upper and lower limits of bus voltage (V_i^{max} = 1.1 pu, V_i^{min} =0.9 pu) are shown in Figure 10. As shown in Figure 10, the bus voltages remained within their specified limits.

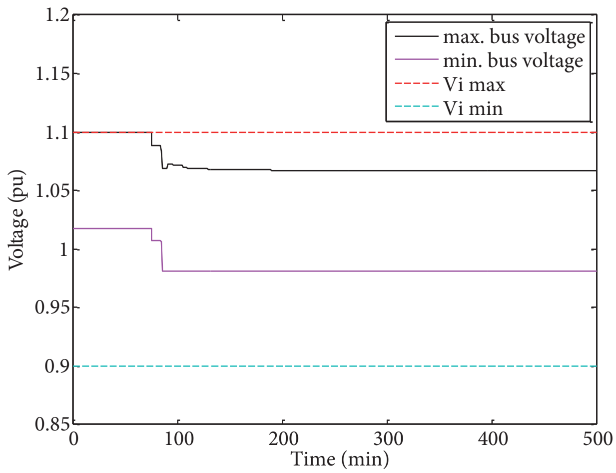


Figure 10. Bus voltages during restoration period.

5. Conclusion

The proposed FA was applied successfully to restore the IEEE 39-bus system after total blackout. Wind power was integrated to the system to improve the restoration time and reduce the unserved load energy during the restoration period. As shown by the results, the proposed algorithm achieved complete restoration of the system in a relatively short time, which maximized the energy capability during the restoration period and improved the sustainability of the system. The integration of wind farms in system restoration reduced the unserved load energy while satisfying the wind farm restoration constraints. In addition, the FA succeeded to reach the optimal solution within a very short simulation time, where 2000 iterations over a population of 150 fireflies were completed in 180 s on a Core i3 CPU, 2.53 GHz.

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