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Distributed Generation Approach for Single Step System Restoration During Cold Load Pickup

منهج التوليد الموزع لاستعادة النظام فى خطوة واحدة خلال اعادة توصيل الاحمال الباردة

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ملخص

عندما يتم استعادة النظام بعد انقطاع طويل، يكون التحميل أكبر من ذلك الذي كان عليه قبل الانقطاع و ذلك بسبب اعادة توصيل الاحمال الباردة (CLPU). محاولة استعادة هذه الاحمال في الوقت ذاته سوف يسبب التحميل الزائد على عناصر الشبكة، بالإضافة إلى انتهاك حدود التشغيل. لهذه الأسباب تم اقتراح استعادة النظام خطوة بخطوة للتغلب على هذه المشاكل. ومع ذلك ، هذه الطريقة في التشغيل تتطلب وقتا طويلا لعودة النظام متكاملا الى الخدمة. في هذه الورقة ، تم اقتراح خوارزمية سرب الجسيمات الأمثل (PSO) لتحديد المواقع و السعة المثلى لوحدات التوليد الموزعة (DG) لاستعادة التوصيل فى خطوة واحدة لكل من شبكات النقل والتوزيع في وقت واحد. الهدف من هذه الخوارزمية المقترحة هو الحد من الفقد في العمر الافتراضى لمحولات التوزيع بسبب الحمولة الزائدة وتقليل الحمل المفقود وبالتالي الطلب على الطاقة الإضافية. تم تطبيق الخوارزمية المقترحة على شبكة النقل ٦٦ كيلوفولت في مدينة الاسكندرية بما في ذلك مغذيات التوزيع الأولية ١١ كيلوفولت ذات ٣٣ و ٦٩ نقاط تجميع.

Abstract

When a system is restored after an extended outage, the demand is greater than that was before the outage. The increase in the demand is due to the cold load pickup (CLPU) condition. The attempt to restore such load simultaneously will cause an excessive loading on the network elements in addition to limits violation. For these reasons, step-by-step restoration was suggested to overcome such problem. However, this way of restoration requires a long time for the complete system to be back to service. In this paper, a particle swarm optimization (PSO) algorithm is introduced to find the optimal sizing and siting of distributed generation (DG) units for simultaneous single step restoration of transmission and distribution networks. The aim of the proposed DG allocation algorithm is to reduce the distribution transformer loss of life due to overloading and to reduce the lost load and hence the additional power demand caused by CLPU. The capacity of the DG required is determined on the basis of additional power demand and the load diversity preserved. The proposed algorithm is applied to the Egyptian 66 kV transmission network in the city of Alexandria including a 33-bus and a 69-bus, 11 kV primary distribution feeders.

Keywords: Single step restoration; Distributed generation; Black-out; intentional islanding; Particle swarm optimization.

List of Symbols

α	Time constant of CLPU model.
σ_i	Binary decision variable for load $S_i(t)$, 1='ON'; 0='OFF'.
MVA_i	Power flow through branch i.
I_V	Sum of the ratios of line-current violations to its thermal limit in the main network.
K_D	Load diversity factor.
N	Total no. of buses in the system.
NG	No. of installed DG units.
S(t)	Load demand with respect to time for $t \geq t_0$.
S_D	Diversified value of the load.
S_{Di}	Diversified value of load at bus i.
$S_i(t)$	Load demand with respect to time for $t \geq t_0$ at bus i.
S_T	Substation transformer capacity.
S_U	Undiversified value of load
S_{Ui}	Undiversified value of load at bus i
S_{UG}	Required utility owned DGs (UGs) capacity
$C_i(P)$	Operation cost ith DG unit.
P	Active power generated by the DG unit in pu.
a, b, c	Fuel cost coefficients of DG units.
t_0	Initiation of restoration process
t_I	Initiation of load decay towards S_D in CLPU model.
t_R	Time instance for roll-back of UGs.
u(t)	Unit step function.
V_i	Voltage at bus i.
V_V	Sum of the ratios of bus-voltage violations to the limiting value in the main network
W_{IV}	Weight for I_V
W_{Load}	Weight for ratio of lost load over total load
W_T	Weight for transformer loss of life (LOL)
W_{VV}	Weight for V_V
W_{OC}	Weight for operation cost (OC)
A, B	are the transformer life expectancy curve constants

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ΔT_o	the top-oil temperature rise over ambient, °C
ΔT_{ofl}	the top-oil temperature rise over ambient, °C
ΔT_g	the hottest-spot winding temperature rise over top-oil temperature, °C
ΔT_{gfl}	the hottest-spot temperature rise over top-oil, °C
$K(t)$	the loading ratio, $K(t) = S_L(t)/S_N$
m	the winding exponent
n	the oil exponent
R	the ratio of copper to iron losses
$S_L(t)$	the transformer load in time t
S_N	the transformer rated load
T_{hs}	the winding hottest-spot temperature, °C
T_a	the ambient temperature, °C
T_o	the top-oil temperature
τ_{ofl}	the oil time constant at rated load, hours
τ_{gfl}	the winding time constant at rated load, hours.

1. Introduction

Increasing exposure of electrical power systems to extensive blackouts in the world in the last years is a consequence of heavier system loading and revolutionary changes in industry structure. Distribution systems with large concentration of thermostatically controlled loads may result in loads significantly higher than normal loads during restoration after a prolonged outage due to cold load pickup. During normal conditions, diversity exists among the loads served by a substation, so that the maximum coincident demand is less than the sum of the individual maximum demands. However, following an outage, a distribution substation has to supply power for simultaneous starting of all ON connected loads, of which the thermostatically controlled ones (such as air conditioners, heaters and refrigerators) constitute the largest portion. CLPU condition results in excessive substation transformer(s) and feeders overloading and unacceptable voltage drops though feeders. In addition, CLPU needs to be included as one of the considerations when protective relay set points are selected for distribution feeder protection [1-5]. Electric power system (EPS) planners are concerned by improving the network profits while minimizing their investment risk to meet the growth in demands. For these reasons, EPS planners try to implement new planning strategies to meet such growth in load economically so as to get a competitive edge. They are seeking to achieve such goals by introducing new alternatives for solving the power system planning problem in addition to the traditional options. Distributed generation (DG) technologies are one of the new alternatives that play a major role in the power system planning [6-10]. Many researchers have attempted to include CLPU in system design. It was evident that simultaneous restoration of the network due to violation of the steady state operational constraints was not possible. Therefore, step-by-step restoration of the system was adopted [1-3], [11-16]. The goal was to find the optimum restoration sequence to minimize a multi-objective function without violating the system operational constraints. Some researchers aimed to minimize the restoration time [1, 2, 11, 12, and 16] or to prevent overheating of substation transformers [1, 3, 13, and 14]. Other researchers tried to minimize a total annual cost function including the cost of transformers and sectionalizing switches, the cost of energy interruption or lost load and the cost of transformer loss of life due to overloading [3,13]. Different solution algorithms were suggested to solve the optimal restoration problem. Some of them were based on conventional analytical methods [1-3, 12]. Others were based on evolutionary algorithms such as genetic algorithm (GA), ant algorithm and expert systems [13-16].

Due to the increasing improvement in the DG technologies, DG was considered as an alternative solution of the power system restoration including CLPU. In [8], authors utilized DG units to maintain load diversity for quick restoration of distribution system in a single step with the reduction of additional power demand caused by CLPU. They used the genetic algorithm (GA) to determine the optimal size and location of the required DG to achieve minimum load curtailment during CLPU. However, they neglected the transformer loss of life and operation cost of DGs while performing their problem in addition to considering reduced loading when verifying the bus voltage and line loading profiles. In [17,18], a deep build-together strategy was suggested for simultaneous restoration of transmission and distribution networks with the aid of DG units but without including the CLPU.

In this paper, the problem of optimal sizing and location of DG to help in simultaneous restoration of transmission and distribution system in a single step during CLPU is formed as a multi-level, multi-objective optimization problem. The allocated DG units in the transmission and distribution networks are treated as black-start units. The transmission system is already equipped with DG units optimally placed as in [19]. These previously located units in addition to the newly located units are used to pick up loads during the restoration process instead of staying in black till the EPS would be restored. DG units could provide the local service continuity and energize the grid as large as possible in an "intentional islanding" manner. This way the restored load by the main EPS is reduced (un-served load) and the collapsed time is shorter.

The optimization problem is solved using particle swarm optimization (PSO) technique which is capable of finding global or near global optimum solution in addition to its very short simulation time compared with other evolutionary algorithms such as genetic algorithm (GA), tabu search (TS) or simulated annealing (SA). Although GA, for example, is very sufficient in finding global or near global optimal solution of the problem, it requires a very long run time that may be several minutes or even several hours depending on the size of the system under study [20-22]. Particle swarm optimization (PSO), first introduced by Kennedy and Eberhart, is one of the modern heuristic algorithms. It was developed through simulation of a simplified social system, and has been found to be robust in solving continuous nonlinear optimization problems [20, 21]. The PSO technique can generate a high quality solution within shorter calculation time and stable convergence characteristic than other stochastic methods [22]. PSO has been motivated by the behavior of organisms, such as fish schooling and bird flocking. Generally, PSO is characterized as a simple concept, easy to implement, and computationally efficient. Unlike the other heuristic techniques, PSO has a flexible and well-balanced mechanism to enhance the global and local exploration abilities.

This paper is extended also to include the distribution substation transformer loss of life due to overloading and the operation cost of DG units which were neglected in [8]. The proposed algorithm is applied to the Egyptian 66 kV transmission network in the city of Alexandria including a 33-bus and a 69-bus, 11 kV primary distribution feeders. The results show the effectiveness of the proposed algorithm to achieve minimum loss of load and minimum transformer loss of life with no violation of system operational constraints even under full load conditions.

2. CLPU Model and DG Operation

CLPU condition is the additional demand in power during restoration of distribution system after a prolonged outage. This condition is caused by the loss of diversity among the thermostatically connected loads. Therefore, the simultaneous restoration of the network is restricted by the excessive loading conditions due to the violation of the steady state operational constraints. With the availability of very acute measured data on CLPU, researchers have proposed various types of models to predict the behavior of CLPU such as physical based models [23] and regression based models [24]. However, the resultant CLPU characteristics are in much closed agreement with a delayed exponential model [25] and expressed mathematically as (1). The corresponding model is shown in Fig.1 [8].

$$S(t)=\{[S_D+(S_U-S_D)e^{-\alpha(t-t_1)}]u(t-t_1)+S_U[1-u(t-t_1)]u(t-t_0)\} \quad (1)$$

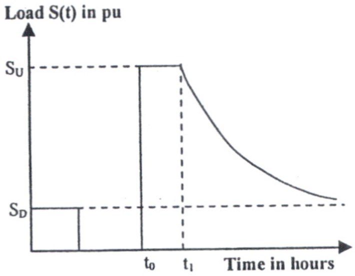


Fig.1. CLPU condition modelled as a delayed exponent.

There are two types of DG that are installed in the distribution network. The first type is the standby power generating units usually of dispersed generation type owned by the customers. These non utility owned DGs (NUGs) are operated in a rollover operation in which they are immediately switched 'ON' when the supply fails. These units maintain the diversity of the loads they supply until the loads are reconnected back to grid on restoration. Although the operation of NUGs is not under the control of the electric utility distribution companies (DISCOs), they quicken the restoration of the network and thereby improve the reliability of the system [8].

The second type of DGs is that entirely owned and operated by the DISCOs (UGs), with being connected or isolated from the grid. During outage, UGs supply only a part of the total demand or the loads connected to nearby locations to UGs. However, both types of DGs are considered as black-start units. As the outage is over, the main supply from the grid is restored, and the UGs continue to operate either in synchronization with the main supply or in rollover mode which is used in this paper. The load under CLPU condition decreases lower than its undiversified value (S_U) at t_1. Therefore, the loads supplied by UGs can be reconnected back to the main network as the substation load decreases at least by an amount equal to that load (at t_R). The roll-back condition is explained by (2) as follows,

$$\sum_{\forall i} S_i(t_1)-\sum_{\forall i} S_i(t_R)\geq \sum_{\forall j} S_j \quad (2)$$

Considering (1), the initial value of t_R is given by

$$t_R^I=-\frac{1}{\alpha}\ln\left[\left(\frac{\sum_{\forall i} S_i(t_1)-\sum_{\forall j} S_j-\sum_{\forall i} S_{Di}}{\sum_{\forall i} S_i(t_1)-\sum_{\forall i} S_{Di}}\right)\right]+\Delta t \quad (3)$$

Where

$i \in$ {Loads of main network}
$j \in$ {Loads of sub-networks}
Δt = Un-diversified load duration (i.e. t_1-t_0).

At t_R^I computed by (2) and (3), the rollback may not be performed due to constraints violation. It is just used as an initial guess from which the search for t_R has started. The search for t_R starts by making attempts on some discrete time instants corresponding to next reduced value of supplied load or at some fixed interval. In this paper, the second way of search is used. To roll-back the loads of the distribution feeders, the operational constraints in both the distribution network and the transmission network must be satisfied.

In the transmission network, the remaining connected loads are also partially supplied by distributed generation. All the DG units in the transmission network are assumed to be utility owned units. Some of them are black-start units and the others are not.

Generally, DG units are placed for many purposes such as power generation support, reduction of power losses, operating during the period of high-price grid power, improvement of voltage profiles and load factors and enhancement of system reliability. UGs also improve the reliability of the supply [19, 26].

3. Particle Swarm Optimization

In this paper a PSO technique is developed to find the best solution of the multi-objective, optimization problem of placing and sizing of multiple DG units to help the single step restoration of distribution network.

PSO is one of the optimization techniques and belongs to the evolutionary computation techniques [20-22]. The method has been developed through a simulation of simplified social models. The features of the method are as follows:

(1) The method is based on researches on swarms such as fish schooling and bird flocking.

(2) It is based on a simple concept. Therefore, the computation time is short.

According to the research results for bird flocking, birds are finding food by flocking (not by each individual). It leaded the assumption that information is owned jointly in flocking. According to observation of behavior of human groups, behavior pattern on each individual is based on several behavior patterns authorized by the groups such as customs and the experiences by each individual (agent). The assumptions are basic concepts of PSO.

PSO is basically developed through simulation of bird flocking in two-dimension space. The position of each individual (agent) is represented by XY axis position and the velocity is expressed by vx (the velocity of X axis) and vy (the velocity of Y axis). Modification of the agent position is realized by the position and velocity information.

An optimization technique based on the above concept can be described as follows: namely, bird flocking optimizes a certain objective function. Each agent knows its best value so far (pbest) and its XY position. Moreover, each agent knows the best value so far in the group (gbest) among pbests. Each agent tries to modify its position using the following information:

- the current positions (x,y),
- the current velocities (vx,vy),
- the distance between the current position, and pbest and gbest.

This modification can be represented by the concept of velocity. Velocity of each agent can be modified by the following equation:

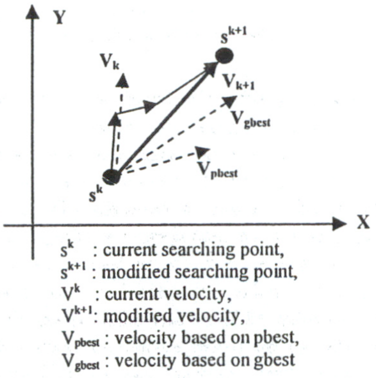
$$v_i^{k+1} = w v_i^k + c_1 rand \times (pbest_i - s_i^k) + c_2 rand \times (gbest - s_i^k) \tag{4}$$

where, v_i^k : velocity of agent i at iteration k,
w : weighting function,
c_j : weighting factor,
rand : random number between 0 and 1,
s_i^k : current position of agent i at iteration k,
$pbest_i$: pbest of agent i,
gbest : gbest of group.

Using the above equation, a certain velocity, which gradually gets close to pbest and gbest can be calculated. The current position (searching point in the solution space) can be modified by the following equation:

$$s_i^{k+1} = s_i^k + v_i^{k+1} \tag{5}$$

Fig. 2 shows a concept of modification of a searching point by PSO.



s^k : current searching point,
s^{k+1} : modified searching point,
V^k : current velocity,
V^{k+1}: modified velocity,
V_{pbest} : velocity based on pbest,
V_{gbest} : velocity based on gbest

Fig. 2. Concept of modification of a searching point by PSO.

4. Problem Formulation

The main objective is to restore the entire network in a single step. It is required to do so with minimum transformer loss of life due to overloading, minimum operating cost of UGs and minimum load curtailment during CLPU while meeting the network steady state operational constraints.

4.1 Objective Function

The objective function consists of the following terms:

- Loads to be curtailed due to constraints violations.
- Operation cost of UGs.
- The distribution substation transformer loss of life.
- Bus voltage and line flow violations.

Each term contributes a penalty term and is considered as ratio for dimensional uniformity and normalization.

Therefore, the final objective function given in (6) is the weighted sum of all these penalized terms.

$$Min f = W_{load}\left[\frac{S_{total} - S_{supplied}}{S_{total}}\right] + W_T\, LOL + W_{I_V} I_V + W_{V_V} V_V + W_{OC} OC \tag{6}$$

Where

$$\begin{aligned} S_{total} &= \sum_{i=1}^{N} S_i(t_0) \\ &= \left[\sum_{\substack{i=1\\ i\neq j}}^{N} K_D S_{Di}(t_0) + \sum_{\forall j} S_{Dj}(t_0)\right] \end{aligned} \tag{7}$$

$$\begin{aligned} S_{supplied} &= \sum_{i=1}^{N} S_i(t_0)\sigma_i \\ &= \left[\sum_{\substack{i=1\\ i\neq j}}^{N} K_D S_{Di}(t_0)\sigma_i + \sum_{\forall j} S_{Dj}(t_0)\right] \end{aligned} \tag{8}$$

With

$\forall j \in$ {buses with DG} and $K_D = [S_{Ui}/S_{Di}]$ [8].

To calculate the transformer loss of life due to overloading, the differential equations for top-oil temperature over ambient and hottest-spot temperature over top-oil are solved. These differential equations are given in (9) and (10), respectively [13].

Differential equation for top-oil temperature over ambient

$$\begin{aligned} \frac{d\Delta T_o}{dt} &= \frac{\Delta T_{ofl}}{\tau_{ofl}} \frac{P_{loss}(t)}{P_{loss_N}} - \frac{\Delta T_o}{\tau_o} \\ &= \frac{\Delta T_{ofl}}{\tau_{ofl}} P_t(t) - \frac{P_t(t) - P_{ti}}{P_t^n(t) - P_{t_i}^n} \frac{\Delta T_o}{\tau_{ofl}} \end{aligned} \tag{9}$$

$$P_t(t) = \frac{K^2(t)R + 1}{R + 1} \quad , \quad T_o = \Delta T_o + T_o$$

Differential equation for hottest-spot temperature over top-oil

$$\begin{aligned} \frac{d\Delta T_g}{dt} &= \frac{\Delta T_{gfl}}{\tau_{gfl}} P_w(t) - \frac{P_w(t) - P_{wi}}{P_w^m(t) - P_{wi}^m} \frac{\Delta T_g}{\tau_{gfl}} \\ &= \frac{\Delta T_{gfl}}{\tau_{gfl}} K^2(t) - \frac{K^2(t) - K_i^2}{K^{2m}(t) - K_i^{2m}} \frac{\Delta T_g}{\tau_{gfl}} \end{aligned} \tag{10}$$

$$T_{hs} = \Delta T_g + T_o = \Delta T_g + \Delta T_o + T_a$$

Transformer loss of life due to overloading is calculated as given in (11) [13],

$$\%LOL \text{ in } (t_f - t_o) \text{ hrs} = 100\sum_{i=0}^{pts} 10^{-\left(\frac{A}{T_{hs}(i)+273}+B\right)}.h \qquad (11)$$

where h is the step size when solving the two differential equations (9) and (10) using points (pts) in the time interval $[t_o,t_f]$, $h=(t_f - t_o)/pts$.

The operation cost of UGs is calculated as,

$$OC = \sum_{i=1}^{NG} C_i(P) \qquad (12)$$

Where

$$C_i(P) = a\,P^2 + b\,P + c \qquad (13)$$

4.2 Constraints

While solving the optimization problem explained before, the following constraints must be met [8]:

- The network power flow equations must be satisfied.
- The voltage at every bus in the network should be within the acceptable range
  $$V_{min} \le V_i \le V_{max} \qquad (14)$$
- Power flow in a feeder or a conductor must be within the maximum loading capacity of the conductor
  $$MVA_i \le MVA_i^{rated} \qquad (15)$$
- Radiality constraint of the distribution feeders: the load curtailed for the restoration should be in the form of a radial sub-network so that it could be supplied by the UGs installed.
- The total installed capacity of UG in the system has been limited to less than 30% of total load similar to [6].
  $$S_{UG} \le 0.3\,S_T \qquad (16)$$

5. Application of PSO Algorithm

The PSO based algorithm for optimal sizing and siting of UGs to accomplish single step system restoration is described by the following steps.

1. For a current individual in a swarm, which include the candidate buses for UG installation, determine the loading at each bus, total loading using (7) and the supplied load using (8) taking into consideration the radiality constraint.
2. Determine the load served by each UG and check that the installed capacity constraint given by (16) is not violated. If violated, the solution is refused and another one is generated till the constraint is satisfied.
3. Perform power flow calculation to determine I_V and V_V in both distribution and transmission network during the initiation of the restoration process (t_0).
4. For rollback time (t_R) computation, determine t_R^1 from (3) as an initial t_R.
5. Repeat the following steps till the constraints are satisfied:
    - Run power flow algorithm and determine the constraints (I_V, V_V).
    - If no constraint is violated, exit loop and determine t_R, else go to the next step.
    - Select the next search point.
6. Calculate the transformer loss of life due to overloading from (9), (10) and (11).
7. Evaluate the objective function value from (6).
8. Repeat steps 1 to 7 till the stopping criterion of the PSO is satisfied.

To validate the proposed PSO method, it was applied to the same test system given in [8]. The same objective function of [8] was adopted under the same constraints and assumptions, which consists of the following terms:

- The loads that cannot be supplied and have to be curtailed due to constraint violations.
- Bus voltage violations.
- Branch current violations.
- Substation transformer overloading.

In addition, the same penalty weights were used. The PSO parameters were set equal to that of GA in [8] as follows:

Population size = 100

Maximum number of generations = 150

The location and size of UGs obtained from PSO compared with those obtained in [8] from GA are given in Table 1.

TABLE 1

COMPARISON OF RESTORED LOADS EVALUATED FROM PSO AND GA

	Substation		Utility owned UGs	
Load served in kVA	GA	PSO	GA	PSO
	6724.6	6767.3	1049.2	1031.59
Buses served	1-9 , 19-30	1-11, 19-21, 23-30	10-18, 31-33	12-18, 22, 31-33

A comparison between the minimum objective function values (Min f), the rollback time (t_R), the computation time (t_c) and the total DG installed capacity (S_{UG}) in case of PSO and in case of GA algorithms is given in Table 2.

TABLE 2

A COMPARISON BETWEEN RESULTS IN CASE OF PSO AND GA

	Min f	t_R (min)	t_c (sec)	S_{UG} (kVA)
GA	496.09	71.59	496.09	1200
PSO	52.59	66	300	1200

As shown in Table 2, the PSO method proved to be efficient in solving the addressed optimization problem. PSO method was able to give better results considering the minimum objective function value (mainly less bus voltage and branch current violations) and rollback time with less computational time.

6. Case Study

The proposed algorithm is applied to the Egyptian 66 kV transmission network in the city of Alexandria including a 33-bus and a 69-bus, 11 kV primary distribution feeders. For the three test systems, the set of penalizing weight used in the objective function, guided by [8], are: W_{Load}=75, W_{VV}=10000, W_{IV}=500, W_T=1000 and W_{OC}=50. The PSO parameters applied are as follows: swarm size = 50 and maximum number of iterations=100. As an example of the PSO fitness conversion, Fig. 3 shows the PSO fitness conversion in case of the 33-bus system.

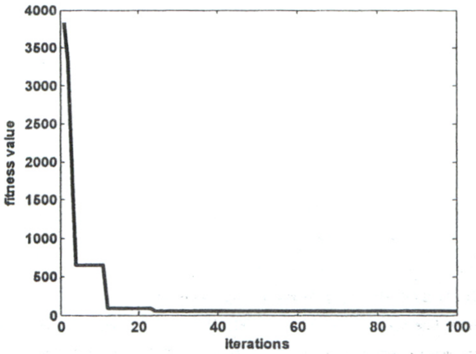


Fig. 3. The PSO fitness conversion in case of the 33-bus system.

6.1 The 33-bus distribution system

The system is an optimally compensated 11 kV, 33-bus test system with an assumed substation transformer rating of S_T=400 MVA. The network details are available in [8] but with its loads re-scaled to be inserted at bus 4 of the 66 kV systems. The network is facing severe low voltage problem during restoration under CLPU condition. A load connected with a NUG and operating in rollover mode is assumed at bus 25. The delayed exponential model of CLPU uses the following parameters: α=1 hr^{-1}, Δt=30 minutes and K_D=2.5. A minimum objective function was attained at the 24th iteration. The load and buses served by the substation and by the UGs during restoration are given in Table 3.

TABLE 3
THE LOAD AND BUSES SERVED BY THE SUBSTATION AND THE UGS DURING RESTORATION IN CASE OF 33-BUS SYSTEM

	Substation	Utility owned UGs
Load served in MVA	527.85	80.46
Buses served	1-11, 19-21, 23-30	12-18, 22, 31-33

The graphical representation of the single step restoration is presented in Fig. 4. As shown in Fig. 4, at t_0=0, restoration is initiated and at t_R=90 min, the rollover operation of the sub-networks take place. The figure also illustrates the duration and amount of load supplied by substation, NUG and UGs.

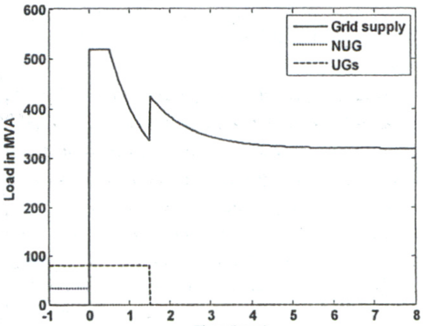


Fig. 4. The graphical representation of the single step restoration of the 33 bus network.

Results obtained from PSO algorithm proposed the installation of three DG units for the purpose of single step restoration under CLPU condition. The UGs of 50 MVA, 10 MVA and 40 MVA capacity are to be installed at buses 12, 22 and 31, respectively. The total DG installed capacity is accounting for 25% (100 MVA) of the total load which is well within the considered limit of 30%.

Fig. 5 shows the division of the network into a main network and three sub-networks. During the outage, sub-networks are supplied by UGs while NUG supplies the load connected to it and the main network remain unenergized. During restoration, the sub-networks continue to be supplied by the UGs while NUG loads are connected back to substation supply. The sub-networks are then connected back to substation after t_R minutes, when the main network gains sufficient diversity.

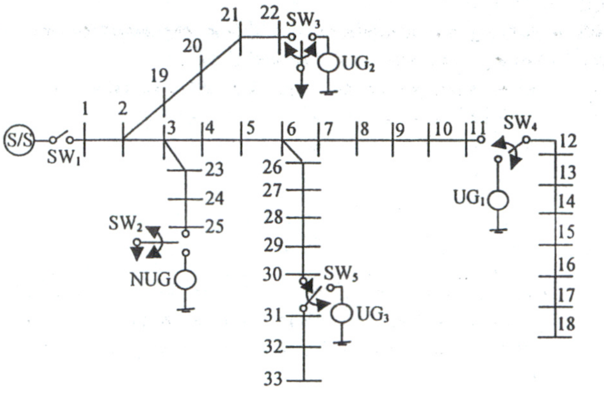


Fig. 5. The 33-bus radial test system operation during CLPU condition.

The sub-networks attained by PSO are checked for normal load condition. Voltages at all buses and line loading of all lines are found within the permissible limits. The improvement in voltage and line loading in case of presence of DGs at initiation of restoration under CLPU condition is observed. Fig. 6 and Fig. 7 show the improvement in voltage profile and line loading, respectively, between the cases of presence and absence of DGs. As shown in Fig. 6, a minimum voltage of 0.8404 pu was observed at bus 18 before installing UGs. After the installation of UGs, the voltage at bus 18 was improved to 0.9943 pu and a minimum voltage of 0.95 pu was observed at bus 30, which is within the permissible voltage limits (0.95 pu $\leq V_i \leq$ 1.05 pu). Fig. 7 shows also how the line loading of almost all lines was greater than the rated value before installing UGs. After the installation of UGs, all line loadings were improved and reduced to be less than their rated values.

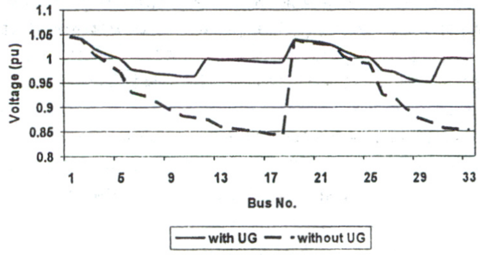


Fig. 6. Voltage profile under CLPU condition on initiation of restoration.

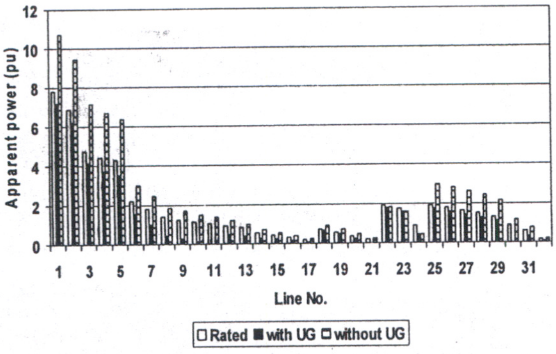


Fig. 7. Line loading under CLPU condition on initiation of restoration.

The operation cost of the three DG units was found to be 121.5 \$/h. Considering the transformer heating and loss of life, the PSO resulted in a maximum top-oil temperature of 76°C, a maximum hottest-spot temperature of 92°C and a transformer loss of life during restoration of 0.0127%. Fig. 8 shows the transformer temperature during single step restoration.

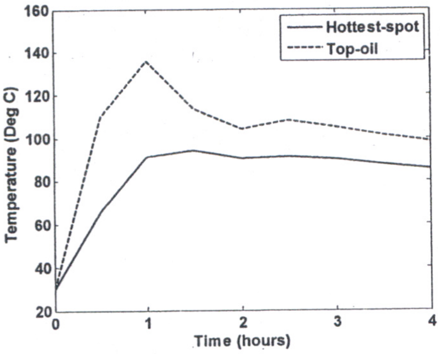


Fig. 8. Transformer temperature during single step restoration.

6.2 The 69-bus distribution system

The system is an 11 kV, 69-bus test system with an assumed substation transformer rating of S_T=250 MVA. The network details are available in [26] but with its loads re-scaled to be inserted at bus 38 of the 66 kV system. The network faces severe low voltage problem during restoration under CLPU condition. A load connected with a NUG and operating in rollover mode is assumed at bus 50. The delayed exponential model of CLPU uses the following parameters: α=1 hr^{-1}, Δt=30 minutes and K_D=2.5.

A minimum objective function was attained at the 54th iteration. The load and buses served by the substation and by the UGs during restoration are given in Table 4.

TABLE 4
THE LOAD AND BUSES SERVED BY THE SUBSTATION AND THE UGS DURING RESTORATION IN CASE OF 69-BUS SYSTEM

	Substation	Utility owned UGs
Load served in MVA	247.74	46.02
Buses served	1-12, 47-61, 66-68	12-18, 22, 31-33

The graphical representation of the single step restoration is presented in Fig. 9. As shown in Fig. 9, at t_0=0, restoration is initiated and at t_R=210 min, the rollover operation of the sub-networks take place. The figure also illustrates the duration and amount of load supplied by substation, NUG and UGs.

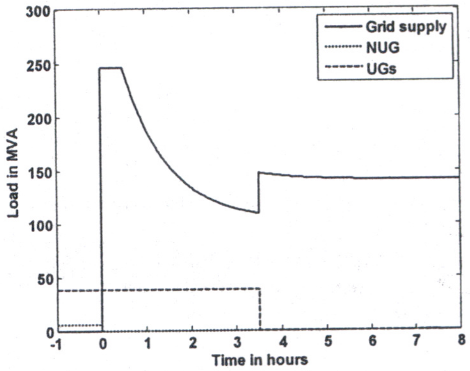


Fig. 9. The graphical representation of the single step restoration of the 69 bus network.

Results obtained from PSO algorithm proposed the installation of five DG units for the purpose of single step restoration under CLPU condition. The UGs of 15 MVA, 15 MVA, 15 MVA, 15 MVA and 5 MVA capacity are to be installed at buses 13, 28, 36, 62 and 69, respectively. The total DG installed capacity is accounting for 26% (65 MVA) of the total load which is well within the considered limit of 30%.

The sub-networks attained by PSO are checked for normal load condition. The improvement in voltage and line loading in case of presence of DGs at initiation of restoration under CLPU condition is observed. Voltages at all buses and line loading of all lines are found within the permissible limits. A minimum voltage of 0.7053 pu was observed at bus 64 before installing UGs. After the installation of UGs, the voltage at bus 64 was improved to 0.9972 pu and a minimum voltage of 0.951 pu was observed at bus 61, which is within the permissible voltage limits (0.95 pu $\leq V_i \leq$ 1.05 pu). The line loading of almost all lines was greater than the rated value before installing UGs. After the installation of UGs, all line loadings were improved and reduced to be less than their rated values.

The operation cost of the three DG units was found to be 287.8 \$/h. Considering the transformer heating and loss of life, the PSO resulted in a maximum top-oil temperature of 70°C, a maximum hottest-spot temperature of 86°C and a transformer loss of life during restoration of 0.011%.

6.3 The 66 kV transmission system

The system is the Egyptian 66 kV, 45-bus transmission system of the city of Alexandria with total load of 2826.42 MVA. The network details are available in the Appendix. There are three DG units that were optimally placed in the network to satisfy the conditions presented in [19]. The three DG units are of equal ratings of 0.63 pu. They were optimally placed at buses 21, 41 and 44. During blackout, these units work also in an islanding mode. However, even with the presence of these three units the network keep facing low voltage problem at some buses during restoration under CLPU condition. The delayed exponential model of CLPU uses the following parameters: $\alpha=1$ hr^{-1}, $\Delta t=30$ minutes and $K_D=2.5$.

The load and buses served by the grid and by the UGs during restoration are given in Table 5.

TABLE 5
THE LOAD AND BUSES SERVED BY THE GRID AND THE UGs DURING RESTORATION IN CASE OF 66 KV SYSTEM

	Grid	Utility owned UGs
Load served in MVA	4514.8	301.62
Buses served	1-6, 8-11, 13-15, 18-19, 22-31, 33, 35, 36,38, 42, 45	7, 12, 16, 17, 20, 21, 32, 34, 37, 39, 40, 41, 43, 44

The graphical representation of the single step restoration is presented in Fig. 10. As shown in Fig. 10, at $t_0=0$, restoration is initiated and at $t_R=60$ min, the rollover operation of the sub-networks take place. The figure also illustrates the duration and amount of load supplied by the grid and UGs.

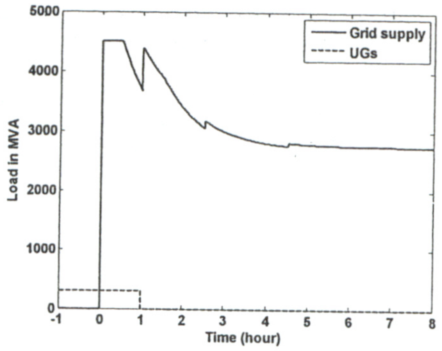


Fig. 10. The graphical representation of the single step restoration of the 66 kV network.

Results obtained from PSO algorithm proposed the installation of extra three DG units for the purpose of single step restoration under CLPU condition. The UGs of 55 MVA, 40 MVA and 50 MVA capacities are to be installed at buses 7, 12 and 34, respectively. The total DG installed capacity in addition to the previously installed ones is accounting for 12.4% (350 MVA) of the total load which is well within the considered limit of 30%.

During the outage, sub-networks are supplied by UGs while the main network remains unenergized. During restoration, the sub-networks continue to be supplied by the UGs. The sub-networks are then connected back to substation after t_R minutes, when the main network gains sufficient diversity. As shown in Fig. 10, the load supplied by the grid at the initiation of restoration is 4514.8 MVA but that with the distribution feeders connected to buses 4 and 38 being partially supplied by its installed UGs as given in the previous sections. Without these UGs installed in the distribution networks the load supplied by the grid at the initiation of restoration will increase to 6312.1 MVA.

The sub-networks attained by PSO are checked for normal load condition. Voltages at all buses and line loading of all lines are found within the permissible limits. The improvement in voltage and line loading in case of presence of DGs at initiation of restoration under CLPU condition is observed. A minimum voltage of 0.9423 pu was observed at bus 16 before installing UGs. After the installation of UGs, the voltage at bus 16 was improved to 0.9996 pu and a minimum voltage of 0.9985 pu was observed at bus 35, which is within the permissible voltage limits ($0.95 \text{ pu} \le V_i \le 1.05 \text{ pu}$). After the installation of UGs, all line loadings were improved and reduced to be less than their rated values.

7. Conclusion

In this paper, a particle swarm optimization (PSO) algorithm was introduced for optimal sizing and siting of distributed generation (DG) units for single step restoration of the system. The aim of the proposed DG allocation algorithm was to reduce the lost load and hence the additional power demand caused by CLPU and in the same time to reduce the transformer loss of life in distribution substation due to overloading while satisfying the system operational constraints. The capacity of the DG required was determined on the basis of additional power demand and the load diversity preserved. The proposed algorithm is applied to the Egyptian 66 kV transmission network in the city of Alexandria including a 33-bus and a 69-bus, 11 kV primary distribution feeders. The results showed the effectiveness of the proposed algorithm to find the optimal installation scheme to minimize the lost load and the distribution transformer loss of life while satisfying the system operational constraints even with full load connected.

Appendix

Table A1. Bus data for Alex 66 kV network in pu (Base MVA=100 , Base kV= 66, Bus1 = slack bus).

Bus No.	Generation		Load		Bus No.	Generation		Load	
	P	Q	P	Q		P	Q	P	Q
1	0.46	0.4	0.1	0.08	23	0	0	0.22	0.09
2	5.31	3.98	0	0	24	0	0	0.04	0.15
3	0	0	0.8	0.5	25	0	0	0.34	0.19
4	0	0	2.6	2.07	26	0	0	0.48	0.28
5	2.18	1.64	0.34	0.18	27	0	0	0.04	0.018
6	0	0	0.6	0.24	28	0	0	0.76	0.403
7	0	0	0.08	0.03	29	0	0	0.38	0.205
8	0	0	2.45	1.4	30	0	0	0.55	0.321
9	1.04	0.79	0	0	31	0	0	0.4	0.5
10	0	0	0.08	0.03	32	0	0	0.5	0.31
11	0	0	0.04	0.01	33	0	0	0.7	0.42
12	0	0	0.08	0.03	34	0	0	0.48	0.29
13	0	0	0.7	0.36	35	0	0	0.34	0.19
14	0	0	0.25	0.113	36	0	0	0.04	0.018
15	0	0	0.3	0.16	37	0	0	0.3	0.15
16	0	0	0.8	0.5	38	0	0	1.2	0.65
17	0	0	0.3	0.15	39	0	0	0.48	0.3
18	0	0	0.3	0.15	40	0	0	0.08	0.03
19	0	0	0.7	0.34	41	0	0	1.3	0.8
20	0	0	0.8	0.4	42	0	0	0.6	0.37
21	0	0	0.52	0.25	43	0	0	0.26	0.12
22	0	0	0.23	0.1	44	0	0	0.8	0.36
					45	0	0	0.32	0.19

Table A2. Line data for Alex 66 kV network.

Bus code	Resistance (pu)	Reactance (pu)	Bus code	Resistance (pu)	Reactance (pu)
1-2	0.0004	0.003	6-26	0.003	0.014
1-3	0.0017	0.0085	7-16	0.006	0.025
1-36	0.01	0.014	7-40	0.046	0.131
1-31	0.006	0.01	7-17	0.006	0.026
1-44	0.021	0.07	8-27	0.002	0.004
1-9	0.009	0.026	9-41	0.005	0.008
1-10	0.052	0.064	9-28	0.008	0.019
2-3	0.0006	0.004	9-30	0.003	0.006
2-4	0.0002	0.0014	9-19	0.014	0.024
2-11	0.015	0.042	11-18	0.009	0.026
2-18	0.027	0.071	12-20	0.006	0.014
2-12	0.01	0.022	13-21	0.004	0.009
3-38	0.0004	0.001	14-22	0.004	0.006
3-29	0.004	0.006	15-24	0.002	0.005
3-13	0.002	0.006	15-25	0.001	0.002
4-5	0.0004	0.00212	21-32	0.003	0.007
4-33	0.01	0.022	23-26	0.009	0.016
4-22	0.002	0.004	28-35	0.002	0.003
4-15	0.003	0.005	34-39	0.005	0.02
5-6	0.0017	0.00912	36-45	0.01	0.014
5-8	0.0004	0.00212	37-41	0.006	0.008
5-34	0.007	0.014	38-42	0.01	0.015
5-26	0.016	0.038	43-44	0.007	0.009
6-7	0.0017	0.00912			

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