# Stepwise Restoration of DG-integrated Distribution Network under Cold Load Pickup

Vishal Kumar*, Rohith Kumar. H.C., I. Gupta and H.O. Gupta

***Abstract—*** *A scheme for step-by-step restoration of a power distribution network under Cold Load Pickup condition has been presented in this paper. The proposed scheme uses the optimal load shedding at each step of restoration process while taking into account the effects of dispersed generation (DG). The load diversity conserved by DG has been effectively utilized for quicker restoration of the network. The optimization is performed to achieve multiple objectives of minimum load curtailment and minimum switching operations while satisfying all the network constraints. Genetic Algorithm has been utilized to search the optimal solution. A considerable amount of improvement in the reliability has been observed in case of DG incorporation. The proposed scheme has been illustrated on a 33-bus radial distribution network.*

***Keywords—*** **Cold load pickup, Distributed generation, Optimal load shedding, Power distribution network restoration.**

## 1. INTRODUCTION

Loss of diversity among electrical loads during the restoration following an extended outage can lead to heavy loading on system during post-outage period. This loss of diversity is mainly due to thermostatically controlled loads connected in the system being switched ON simultaneously at the instant of supply restoration, causing post-outage load-demand to reach 2 to 5 times the diversified load, such a high load condition is known as 'Cold Load Pickup' (CLPU) [1]. The proportion of thermostatically controlled loads is increasing at a high rate and these loads constitute the major portion of the load on the system today. Such a raise has made the CLPU problem a prevalent feature of distribution system restoration, especially in the power deficient countries where scheduled and forced power outages are frequent.

CLPU has more than sixty years old history, however low percentage of thermostatically controlled loads at that time did not make the problem so severe. It was first recognized as inrush phenomenon in 1952, and change of relays settings were proposed [2]-[4]. In the recent past, researchers started paying attention towards CLPU problem, and several efforts have been made to model the connected loads and also the interconnecting elements under this condition [5]. During last few years much of research in this area has been oriented towards optimal designing of the distribution network and development of better restoration techniques under CLPU [3], [6]-[9]. A critical survey has been conducted recently to highlight various aspects of CLPU problem [2].

The CLPU condition mainly depends on several factors such as the duration of outage, type of connected load, weather condition, living habits of the user, and thermal characteristics of the building. Researchers have divided CLPU condition in to four phases: Inrush, motor starting current, motor accelerating current, and enduring current phase [10]-[12]. Initial three phases are transient in nature and die out within few seconds, whereas the enduring phase can last for long duration thereby causing significantly high loading on the distribution network elements, thereby violating voltage and current limits of the feeder [2]. Hence, all the connected loads can not be switched ON simultaneously during the initiation of restoration. However, the aggregated load decreases with time, and allows more loads to be switched ON as the network regains diversity gradually.

As evident from the literature, extensive research in the area of CLPU has been carried out to restore network in minimum duration. Several heuristic and non-heuristic approaches have been used to obtain the optimal sequence of restoration. Ucak and Pahwa [6] aimed at minimizing the total restoration time and customer interruption duration by making use of derived function between restoration time and restoration order. Further, the authors determined the optimal switching order to minimize customer average interruption duration index (CAIDI) by using adjacent pair wise interchange method [7]. Walkilesh and Pahwa [8] performed a cost optimization to determine the size of substation transformer and number of sectionalizing switches that minimize the total annual cost. The same authors also applied Genetic Algorithm (GA) for optimal restoration of an actual feeder. The capacitor banks were used for

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boosting the voltage to meet the under-voltage permissible limit [9]. As the restoration time is based on the order in which sections are restored, for sequencing the switches, GA [10] and Ant Colony algorithm [13] have also been exploited. The issues like voltage and current constraints of buses and branches, and location for placement of sectionalizing switches have been addressed in a recent paper by Gupta and Pahwa [14], they have taken the base of voltage drop to find the location of sectionalizing switches and optimal size of transformer and feeder, while minimizing the restoration time. Therefore, it is evident from the above references that rigorous work has been carried out on transformer overloading and cost minimization for cold load pickup condition.

The main reason for occurrence of CLPU condition is the loss of diversity among the loads. However, in the modern days of integrated power system, most of the high priority loads such as hospitals, and commercial complexes etc. prefer to have their own DG plants to meet their demand during outages. These non-utility-owned generators (NUGs) are operated in rollover mode and they conserve load-diversity during CLPU condition, thereby reducing the total load requirement during restoration. This paper studies the effect of presence of such NUGs in distribution network during restoration under CLPU condition, and proposes a scheme to restore the network quickly by making use of the diversity conserved by NUGs. The scheme is demonstrated on a 33 bus, 12.66kV radial distribution system. The results obtained for the network with and without incorporation of NUG are compared, and quicker restoration of the network was achieved.

***CLPU Model***

Variety of models for CLPU condition with various approaches is available in the literature [15]-[21]. However, in the present work, the delayed exponent model has been considered [21]. The model characterizes CLPU condition as an exponential function with delay.

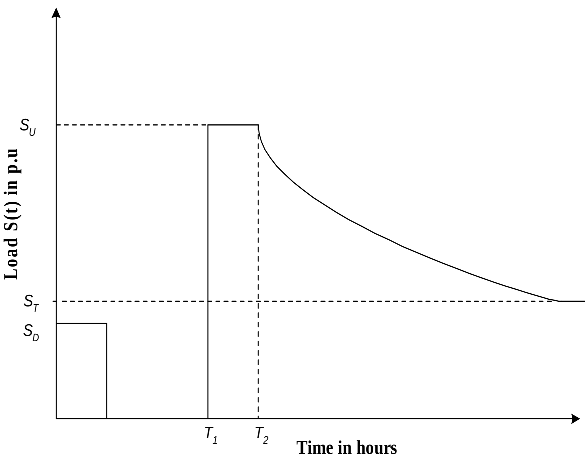


**Fig.1. CLPU model represented as a delayed exponent**

In the delayed exponential model, un-diversified load $S_U$ remains constant from restoration time $T_1$ to $T_2$, showing delay, and after $T_2$ it decreases exponentially to diversified level $S_D$ as shown in the above Fig 1. Mathematically, this model can be expressed as (1) [14].

$$S(t) = \left\{ \begin{array}{l} [S_D + (S_U - S_D) e^{-\alpha(t-T_2)}] u(t-T_2) \\ \qquad + S_U [1-u(t-T_2)] u(t-T_1) \end{array} \right\} \quad (1)$$

## 2. AIM AND APPROACH

The aim of the present work is to study the effect of presence of NUGs on the restoration of network under CLPU in a DG-integrated distribution system.

The approach adopted in the proposed scheme for restoration of a network under CLPU is based on load curtailment. The loads are curtailed to restart the network and then are restored in step-by-step manner as the loading of the network elements decays with time. It is assumed that all the loads follow the delayed exponent model of CLPU [21] except the loads with NUG, which are supplied during outage and maintain their diversity. Some predetermined step-points are considered on the load profile, and corresponding locations for optimal load shedding/restoring at each step are determined with the help of GA. Main objective is to determine the optimal locations for load curtailment, and the sequence of restoration of loads as to achieve maximum utilization of the existing network capacity.

***Methodology***

The enduring phase of CLPU condition persists for much longer period and causes excessive loading on substation transformer, current violation in the feeders, and voltage violation at the buses. Hence, loads are picked up in an optimal sequence so that all the operational constraints could be satisfied [3]. However, loads connected to NUG are being supplied during the outage, and they maintain their diversity, hence contribution of such loads to the total load demand remains constant during pre and post outage period. Here, the methodology is to determine the optimal load shedding locations and restore the network in steps, besides the inclusion of effects of NUG.

Consider load at bus $i$, switched ON at time step $T_j$, if this load is not connected with NUG during outage period, then it follows CLPU profile given by (2.a) on restoration, else the load diversity is conserved (2.b), and this aids the process of network restoration.

$$S_i(t) = [S_{D_i} + (S_{U_i} - S_{D_i}) e^{-\alpha(T_j - \Delta T)}] u(t - \Delta T) \quad \forall j = 1...m \qquad (2.a)$$

$$S_i(t) = S_{D_i} \quad \forall j = 1...m \qquad (2.b)$$

Here, $m$ is the total number of distinct discrete step-points considered on the CLPU load profile, and the corresponding timing instants can be evaluated from (3).

$$T_j = -\frac{1}{\alpha}\ln\left[\left(\frac{S^j - S_D}{S_U - S_D}\right)\right] + \Delta T, \quad \forall j = 1...m \quad (3)$$

The $S^j$ is loading corresponding to predetermined step point j considered on CLPU model as shown in Fig. 1.

Here, in the case study presented in next section these are considered as given in Table 1.

***Problem Formulation***

The main objective here is to minimize the load curtailed at each step while restoring the network along with minimum switches being operated. This is a case of nonlinear combinatorial problem with multiple objectives. This multi-objective optimization problem is converted to a single objective problem with the help of suitable weights, and the mathematical formulation of the problem is expressed as (5).

$$Min \quad f = W_{Load}\frac{\left[S_{Total} - S_{Supplied}\right]}{S_{Total}} + W_{IV}I_V + W_{VV}V_V + W_{TV}S_{TV} + W_{SW}SW \quad (5)$$

Objective function given by (5) is subjected to operational constraints as mentioned below.

- All the power flow equations of the network should be satisfied
- The utility voltage at each load bus should be within permissible limit (Utility's standard ANSI Std. C84.1-1989) (±5%).

$$V_{\min} \le V_i \le V_{\max}, \quad \forall i \in \{buses\ of\ the\ network\} \quad (6)$$

- In a feeder or conductor, current cannot be increased beyond a specified limit, which is decided by thermal capacity of the conductor.

$$I_i \le I_i^{Rated}, \quad \forall i \in \{branches\ of\ the\ network\} \quad (7)$$

Here, $I_i^{\ Rated}$ is current permissible for branch *i* within safe limit of temperature.

- The total power supplied to the network must be within the substation transformer capacity limit. In the proposed scheme for network restoration, maximum loading of the transformer is considered as the loading limit of transformer for no additional loss of life.

$$S_{T_{Max}} < K_{TM} \times S_T \quad (8)$$

Loading limit of the forced air-cooled transformer for a delayed exponential CLPU model has been explained for different outage-duration, and pre-outage and post-outage loading conditions. The maximum un-diversified load for different diversified loads and outage duration is also reported, and the maximum supplying limits for one-hour outage with different pre and post outage load conditions have also been determined [6], [22].

Weights considered in (5) reflect the relative priority of each term present in the objective function. The weights act as the penalty to be imposed in case of violation of constraints. However in the present work, the weight is also used to convert multi-objective optimization problem to a single objective problem. Since the main objective is to achieve a small quantity of loss of load, heavy penalty is imposed to the first term. The second and the third terms in the objective function are steady state security constraints, and heavy penalties are applied in case if these limits are violated. Fourth term is of slightly lesser significance in comparison with second and the third, as the distribution transformers are rated for a short period of overloading with no or a very nominal loss of life. Varying these weights can lead to alternative solutions.

***Genetic Algorithm***

Genetic algorithms are the computerized search and optimization algorithms based on the mechanism of natural genetics and selection [23], [24]. These algorithms work with a population of possible solutions, rather than a single point as in conventional optimization techniques. The population of possible solution continuously undergoes the process of natural changes such as selection, crossover and mutation finally to arrive with a global optimum solution. In the present research work, binary encoding system has been successfully adopted owing to its simplicity of representation and ease of understanding. The length of the encoded string is equal to the total number of buses in the system, and each bit of this string represents the status of the load connected at that bus. GA here uses roulette wheel selection, one-point crossover and bit-wise mutation along with elitism preserving mechanism [23], [24]. Maximum number of generations is used to terminate GA.

The algorithm designed for the determination of the optimal locations for load curtailment/restoration is explained as follows.

***Algorithm***

Some load-points are considered on the CLPU profile; these load points actually represent the steps of restoration. Following is the computational flow for designed algorithm using GA, applied for a load-point, which determines the load shedding locations corresponding to that load-point. The application of the algorithm for each restoration step enables to know the optimal sequence of restoration of the loads.

```
INPUT : P_SIZE , Ge_MAX , P_C , P_M , N
Generate random population P_0 of P_SIZE
for (i = 1 : i ≤ Ge_MAX )
      set: j=1;
        While( j ≤ P_SIZE )
          set: k=1;
            While(k ≤ N )
                Update P_i^k (j) by eq. (2.a); //if bus k
                                 not connected to NUG//
                Update P_i^k (j) by eq. (2.b); //if bus k
                                 connected to NUG//
                k++;
            end While
            Evaluate  P_i(j) from eq. (5)
            j++;
       end While
       /* Apply genetic operators as below */

     Select(P_i);   //Subroutine for Roulette wheel
                     selection //
     Xover(P_i);    //Subroutine for one-point
                     crossover //
     Mutate(P_i);   //Subroutine for bit-wise
                     mutation //
     Elite(P_i,P_i-1);  //Subroutine for elitism //
     i++; //Increment generation counter //
end for
OUTPUT : Optimal Switching locations
```

## 3. CASE STUDY

The proposed scheme is illustrated on a 33-bus, 12.66 kV radial distribution network [25] with a substation transformer capacity of 5MVA. Under CLPU condition, most of the system buses violate the lower voltage limit, and hence to effectively utilize the permissible range of the utility voltage, the substation voltage has been considered as 1.045 p.u.. It is considered that the network is initially compensated for reactive power through the optimal placement of capacitors at buses, and the corresponding values are given in Appendix-I [26]. In order to illustrate the effects of presence of NUGs, It is assumed that NUGs are present at buses 14, 17, 25 and 30.

**Table 1. Values of time elapsed for the step-points**

| Step-point ($j$) | Time Elapsed in Minutes | Description of Step-point/($S^j$) |
|---|---|---|
| -1 | -120 | Outage duration |
| 0 (Restart) | 0 | Start of Restoration 2.50 x $S_D$ |
| 1 | 54.33 | 2.0 x $S_D$ |
| 2 | 95.92 | 1.50 x $S_D$ |
| 3 | 137.51 | 1.25 x $S_D$ |
| 4 | 192.48 | 1.10 x $S_D$ |
| 5 | 234.07 | 1.05 x $S_D$ |

The typical values of weights applied in the objective function for the present case-study are: 75.0 for the lost load, 500.0 for the current violation, 10000.0 for the voltage violation, 50.0 for the transformer violation, and 10.0 for number of switching operations.

The proposed scheme utilizes a delayed exponential model as explained in section-1. The associated parameters to the model are taken as $\alpha$ =1 hr$^{-1}$, $\Delta T= T_2-T_1$=30 minutes, $S_U$= 2.5 p.u., and $S_D$=1.0 p.u., and $K_{TM}$ =1.50. Time instances and loadings corresponding to each step of stepwise restoration of the network are illustrated in Table 1.

## 4. RESULTS AND DISCUSSION

The current restoration problem is a nonlinear combinatorial problem and GA has been used to obtain the optimal solution. GA is applied with different population size: 60, 80, 100 and 150, and the best result obtained has been reported here. The corresponding GA convergence curve for step-point-0 is shown in Fig.2. The following are the considered GA parameters

| | |
|---|---|
| Population size: | 100 |
| Crossover rate: | 0.8 |
| Mutation rate: | 0.05 |
| Maximum no of generations: | 50 |

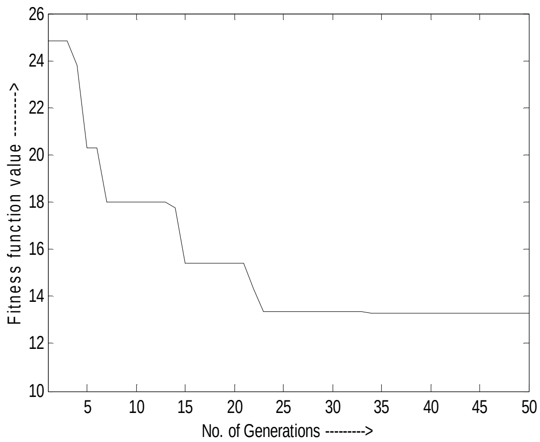


**Fig.2. Convergence curve of GA for step-point-0 of case-2**

Table 2 shows the results obtained for stepwise restoration of the network in both the cases, without NUGs (Case-1) and with NUGs (Case-2). It is clear that during step-wise restoration of Case-2, restoration of network takes place in step-point 3 against step-point-4 for Case-1. Also, the number of loads being disconnected is lesser in all the steps in Case-2. This is mainly because of the reduction in the total load demand owing to conservation of diversity of loads connected with NUG during outage period. The graphical view of step-wise restoration under both the cases has been presented in Fig.3 and 4; the load supplied by NUG during the outage is also shown in the figure. The expected load represents the required load to be restored for the complete restoration of the network corresponding to the load-points. The analysis was conducted by self developed codes written in MATLAB-R2006a package, on PC with Intel P-IV processor of 2.0 GHz clock frequency, and the average CPU execution time pertaining to Case-1 and

Case-2 has been reported in Table 3.

**Table 2. Results of step-wise restoration of network**

| | **Case 1** With out NUGs | **Case 2** With NUGs |
|---|---|---|
| **Step-point: 0** | | |
| Total load served in MVA | 7.1292 | 7.0541 |
| Load at the buses to be disconnected | 7,8,12,13,17,18,31,32,33 | 14,16,18,29,32 |
| Total number of switching operation | 9 | 5 |
| **Step-point: 1** | | |
| Total load served in MVA | 6.6940 | 6.2166 |
| Load at the buses to be disconnected | 12,13,17,18,31,32,33 | 14,18,32 |
| Total number of switching operation | 7 | 3 |
| **Step-point: 2** | | |
| Total load served in MVA | 5.7207 | 5.2726 |
| Load at the buses to be disconnected | 17,18,32 | 14,18 |
| Total number of switching operation | 3 | 2 |
| **Step-point: 3** | | |
| Total load served in MVA | 4.8092 | 4.7846 |
| Load at the buses to be disconnected | 17,32 | Nil |
| Total number of switching operation | 2 | Nil |
| **Step-point: 4** | | |
| Total load served in MVA | 4.6994 | 3.7631 |

**Table 3. Average CPU Time per Step-point**

| | **Case-1** | **Case-2** |
|---|---|---|
| CPU Time (in sec./step) | 231.03 | 217.43 |

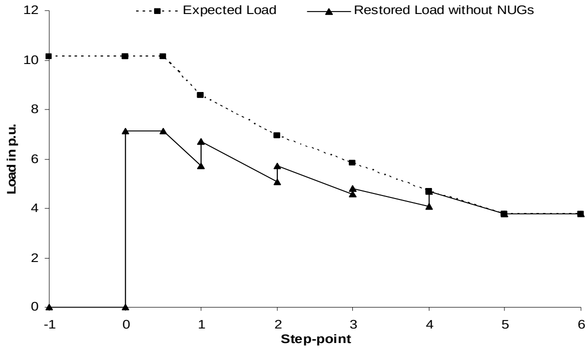


**Fig.3. Step-wise restoration of network in case-1**

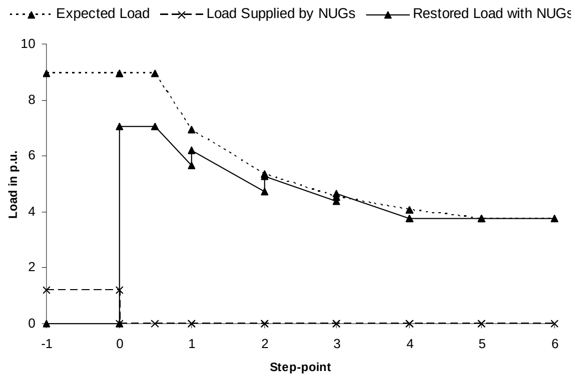


**Fig.4. Step-wise restoration of network in case-2**

The presence of DG in distribution network also improves the reliability indices of supply. For the purpose of illustration, a case has been considered where the total connected load is equal to substation transformer capacity. An average load per customer of 2kW is assumed and reliability indices are evaluated. The number of customers restored under both the cases is presented in Fig.5, it is evident that more number of customers are restored in Case-2.

A considerable improvement in the reliability indices has been observed in Case-2. To support the previous statement, few of the basic customer oriented reliability indices such as System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI) are evaluated and given in Table 4.

**Table 4. Evaluated Reliability Indices**

| **Index** | **Case-1** | **Case-2** |
|---|---|---|
| SAIDI (min/customer) | 181.07 | 147.39 |
| SAIFI (int/customer) | 1.649 | 1.331 |

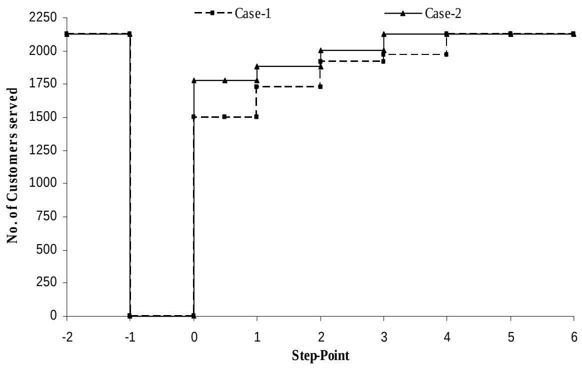


**Fig.5. Number of customers served in both cases**

## 5. CONCLUSION

In the present work, the effect of presence of NUGs on network restoration during CLPU condition has been investigated. A scheme has been proposed, to restore the network under CLPU with the utilization of diversity conserved by the NUGs. The proposed scheme for incorporation of NUGs restored the network quicker than the one without considering the NUG, moreover minimized the total number of switching operations required with maximum utilization of existing capacity of the system. It is concluded that the presence of NUGs also improves the reliability indices. The scheme is illustrated on a 33-bus 12.66kV distribution system. The subject matter discussed in this paper is of high relevance, as the amount of DG integrated network is rising, as to meet the customers supply requirement during outages, and the utilities seem to benefit under such scenario by being able to restore the network at a faster rate.

## NOMENCLATURE

| | |
|---|---|
| $\alpha$ | Rate of decay of load under CLPU |
| $Ge_{MAX}$ | Maximum number of generations |
| $I_V$ | Sum of the ratios of line-current violations to its thermal limit |
| $K_{TM}$ | Transformer maximum loading factor |
| $N$ | Total no of buses in the system |
| *NUG* | Non Utility-owned Generator |
| *NUGs* | Non Utility-owned Generator units |
| $P_C$ | Probability of crossover |
| $P_M$ | Probability of mutation |
| $P_{SIZE}$ | Population size |
| $P_i^k(j)$ | k^th^ bus of j^th^ chromosome during i^th^ generation |
| $S(t)$ | Load Demand with respect to time for $t \geq T_1$ |
| $S_D$ | Diversified Load in p.u. |
| $S_{Supplied}$ | Load supplied during CLPU |
| $S_T$ | Substation transformer rating |
| $S_{T\,Max}$ | Maximum transformer loading |
| $S_{Total}$ | Total connected load in the network |
| $S_{TV}$ | Transformer loading-limit violation |
| $S_U$ | Un-diversified load in p.u. |
| $SW$ | Number of switching operations |
| $T_1$ | Initiation of restoration |
| $T_2$ | Initiation of decay towards $S_D$ |
| $u(t)$ | Unit step function |
| $V_V$ | Sum of the ratios of bus-voltage violations to the limiting value |
| $W_{IV}$ | Weight for $I_V$ |
| $W_{Load}$ | Weight for ratio of lost load over total load |
| $W_{SW}$ | Weight for $SW$ |
| $W_{TV}$ | Weight for $S_{TV}$ |
| $W_{VV}$ | Weight for $V_V$ |

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## APPENDIX-I

Listing of the bus numbers and the amount of reactive power compensation provided [26].

| Bus No. | Capacitor Values in kVar |
|---|---|
| 9 | 100 |
| 14 | 300 |
| 19 | 100 |
| 21 | 100 |
| 23 | 100 |
| 24 | 100 |
| 25 | 100 |
| 29 | 200 |
| 30 | 500 |
| 31 | 100 |