# Reconfiguring A Radial Distribution Network to Reduce Losses and Enhance Voltage Profile

**Vishal Chaudhari[1], Dr. Rahul Mishra[2]**

[1]M. Tech Scholar in Dr. A.P.J Abdul Kalam University, Indore, Madhya Pradesh, India
[2]Associate Professor in Dr. A.P.J Abdul Kalam University, Indore, Madhya Pradesh, India

## Abstract

Power loss and voltage instability are major problems in distribution systems. However, these problems are typically mitigated by efficient network reconfiguration, including the integration of distributed generation (DG) units in the distribution network. In this regard, the optimal placement and sizing of DGs are crucial. Otherwise, the network performance will be degraded. This study is conducted to optimally locate and sizing of DGs into a radial distribution network before and after reconfiguration. A multi-objective particle swarm optimization algorithm is utilized to determine the optimal placement and sizing of the DGs before and after reconfiguration of the radial network. An optimal network configuration with DG coordination in an active distribution network overcomes power losses, uplifts voltage profiles, and improves the system stability, reliability, and efficiency. For considering the actual power system scenarios, a penalty factor is also considered, this penalty factor plays a crucial role in the minimization of total power loss and voltage profile enhancement. The simulation results showed a significant improvement in the percentage power loss reduction (32% and 68.05% before and after reconfiguration, respectively) with the inclusion of DG units in the test system. Similarly, the minimum bus voltage of the system is improved by 4.9% and 6.53% before and after reconfiguration, respectively. The comparative study is performed, and the results showed the effectiveness of the proposed method in reducing the voltage deviation and power loss of the distribution system. The proposed algorithm is evaluated on the IEEE-33 bus radial distribution system, using MATLAB software.

***Keywords:*** *Radial distribution system, Distribution network reconfiguration, voltage deviation, Voltage stability, Distributed Generation.*

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## 1. INTRODUCTION

The electric power supply chain consists of generating station, transmission network, distribution system and end users load. The distribution network's main concern is to ensure delivering power to customers. In order to achieve continuity in power supplying; system stability and load balancing have to be observed. The radial distribution networks (RDN) mostly suffers from voltage instability problems. Voltage reduction caused by power losses could drop under the accepted limits and block the power delivered to the network. Distributed Generation (DG) is a small generation unit directly connected to the distribution network to enhance the network performance. DG optimum placement and sizing achieve minimum power losses and improve the voltage profile of the system [1]. Network reconfiguration is considered an operational technique to achieve minimum power losses. By changing the Sectionalizing Switches' (S.S) and Tie Switches' (T.S) status between on and off, the load flow starts to change. The optimal operating conditions are obtained to minimize the power losses and balance the load of each feeder [2]. In recent years, the use of Artificial Intelligence (AI) based techniques for network reconfiguration has proved to achieve enhanced network operation, as mentioned in [3-6]. The Genetic Algorithm (GA) was used in the meshed distribution network configuration to achieve minimum losses [3]. Numerous researchers focused on Partial Swarm Optimization (PSO) as optimizing technique because it is easy to set parameters and costs less time than GA. Traditional PSO adopts continuous encoding, but reconfiguration of distribution feeders is a discrete issue, so Binary Particle Swarm Optimization (BPSO) encoding was used. The hybrid algorithm of PSO with Ant Colony Optimization (ACO) has been applied for optimum system configuration in the study which aims to decrease the system losses and improve the voltage profile. In Harmony search Algorithm (HAS) was used to get the optimal configuration of RDN to achieve minimum losses. Using renewable DG systems as Photovoltaic (PV) plants and wind turbines (WT) plants are considered a modern effective solution to meet the demand load. Different researches developed diverse optimization strategies to decide the optimal penetration of the DG. Both the analytical approach and the PSO algorithm are proposed for the long term and short-term planning for the optimal DG units' management. (GA),(PSO) and biogeography-based optimization (BBO) technique has been used to determine the optimal placement and sizing of different types of DGs consider a single or multi objective function to minimizing the power and energy losses while improving the overall voltage stability index.

Firefly algorithm (FA) is used to decide the optimal sizing of DG unit and placement to enhance the voltage stability by minimizing the network losses. Antlion inspired algorithm (ALIA)has been utilized to optimize the RDN performance integrated with different types of DGs by minimizing the losses and mitigate the voltage stability index considering the daily loading profile. Modified flower pollination algorithm (MFPA) has been presented to determine the optimal location of a DG to minimize the network losses in the study. In Improved Versions of Genetic Algorithm (IGA), Improved Particle Swarm Optimization (IPSO) and Improved Cat Swarm Optimization (ICSO) manage the problem of the allocation of DG units and shunt capacitor. Quantum particle swarm algorithm (QPSO) has been suggested to determine (PV)and (WT) to minimize the power losses in the study. Multiple objective NSGA-II method along with fuzzy satisfying method (FSM) has been used to determine the optimal DG sitting and sizing considering active power loss index (APLI), line loading index (LLI) and voltage deviation index (VDI).

In, hybrid Particle Swarm Optimization in addition to a Gravitational Search Algorithm (PSOGSA) and Moth-Flame Optimization (MFO) are proposed to realize the location and the size of (PV) and (WT) based on minimizing the power losses and the operation cost. Aiming to improve the voltage stability and reduce the network losses, new methodologies of reconfiguration networks integrated with DGs have been proposed in recent researches. Different techniques as (PSO), (FA), gravitational search algorithm and (GA) with respect to dynamic time-varying loads are suggested to solve the problem of feeder reconfiguration with distributed generations.

The distribution network reconfiguration problem in the existence of different DGs using the modified PSO algorithm is presented. Improved binary PSO (IBPSO) algorithm indicated that the optimal configuration of the distribution network with DG is capable of reducing power loss and improving the voltage profile and reliability of the network significantly. Methodology for distribution system feeder reconfiguration considering a different model of DGs based on Decimal coded quantum PSO (DQPSO) was applied. Reconfiguration of the smart distribution network in the existence of renewable DG's using Grey Wolf Optimizer (GWO) Algorithm has been proposed. Multi-objective approach NSGA-II method along with fuzzy and bacterial foraging optimization (BFO) accompanied by fuzzy are recently involved in solving the stochastic modeling of using simultaneous reconfiguration and optimal DGs sizing and shunt capacitors in a distribution system.

This paper presents different scenarios of incorporations between system reconfiguration and DG integration to improve RDN's performance. The proposed strategy optimizes the sizing of DG and clarifies the optimal placement using PSO technique. Also, BPSO is used to submit the required network reconfiguration. Different scenarios are applied to study the case of real RDN to minimize the power losses and achieve voltage stability enhancement.

## 2. PROBLEM FORMULATION

**Modeling of DGs**

For load flow studies, DGs can be model as either PV mode or PQ mode. In this paper, DG is modeled as PQ mode. In this type of modeling, DG is modeled as a generating source (negative load model) with constant active power output (PDG) and reactive power output (QDG). In this type of modelling, active power and power factor (PF) of the DG is mentioned. Reactive power of the DG is calculated by using Eq. 1.

(1) QDG=PDG∗(tan(cos−1PF))

The effective load at any bus with the integration of DG unit can be expressed as

(2) Peff,load=Pload−PDG

(3) Qeff,load=Pload−QDG

Where $P_{load}$, Qload active and reactive power demands at the bus are, $P_{eff,\ load}$, Qeff, load are the effective active and reactive power demands at the bus after the placement of DG.

## 3. OBJECTIVE FUNCTION

In this paper, a weighted multi-objective function (OF) is formulated which addresses daily active power loss reduction and voltage deviation index reduction.

(4) min{OF}=(w1∗PLRI)+(w2∗VDIRI)

Where, *w1* and *w2* are weighting factors, *PLRI*- Power loss reduction index and *VDIRI*- voltage deviation index reduction index. The range of weighting factors is 0 to 1, which are user-defined. The sum of the weighting factors should always be equal to one.

## 4. POWER LOSS REDUCTION INDEX (PLRI)

The daily power loss of the system can be reduced by minimizing *PLRI* which is taken as the ratio of system daily active power loss after placement of DGs $(P^{DG}_{loss,daily})$ to the system daily active power loss before placement of DGs $(P_{loss,\ daily})$.

$$PLRI = \frac{P^{DG}_{loss,daily}}{P_{loss,daily}} = \frac{\sum_{j=1}^{24} P^{DG}_{jloss}}{\sum_{j=1}^{24} P_{jloss}}$$

Where P $_{jiloss\ is}$ the j[th] hour system active power loss before placement of DGs $P^{DG}_{jloss}$ is the j[th] hour system active power loss after placemen the t of DGs.

## 5. VOLTAGE DEVIATION INDEX REDUCTION INDEX (VDIRI)

Voltage profile through the day can be improved by minimizing VDIRI which is the ratio of voltage deviation index with DGs to the voltage deviation index without DGs.

$$VDIRI = \frac{VDI^{DG}}{VDI^{WODG}} = \frac{\sum_{j=1}^{24} \max\left(1 - |U^{DG}_{j,i}|\right)}{\sum_{j=1}^{24} \max\left(1 - |U_{j,i}|\right)} i = 1, 2 \ldots\ldots. nb$$

Where, $|U_{i,\ i}|$ the voltage magnitude of ith bus is during jth hour in p.u before placement of DGs |UDGj,i| is the voltage magnitude of $i^{th}$ bus during $j^{th}$ hour in p.u after placement of DGs.

## 6. CASE STUDY

Overview of Harmony Search Algorithm (HSA) and Improved Harmony Search Algorithm (IHSA)

### A. Harmony Search Algorithm

In recent years, nature inspired heuristic and meta – heuristic optimization algorithms find widespread use in providing optimal solution for optimization problems of industrial and scientific importance. The harmony search (HS) developed by Geem et al. is an emerging meta– heuristic optimization technique conceptualized from the music improvisation process where a group of musicians collectively tune their musical instruments' (population members) pitches developing a perfect state of pleasing harmony (global optimum solution) as determined by aesthetic standard (fitness function). In comparison to other optimization techniques, HSA is easy to implement, better robustness, and reduces the number of iterations for converging towards optimal solution.

The analogy between improvisation and optimization is shown in the tabular form as follows:

**Table 1. Analogy between improvisation and optimization**

| Improvisation | Optimization |
|---|---|
| Musician / Music Player | Decision Variable |
| Musical Instrument Pitch Range | Decision Variable Range |
| Harmony | Solution Vector |
| Audience Aesthetics | Objective Function |

The major steps in implementing HSA are explained as follows:

**Step 1: Optimization Problem**

Description and HSA Parameters Initialization Initially, the optimization problem with constraints is formulated in terms of the objective function f (x ) : Minimize f(x) subject to $x_L \le x_i \le x_U$ in which i ∈{ 1, 2,3,......,D,} $x_L$ and $x_U$ are the lower and upper bounds for the decision variables, and D is the number of decision variables. The control parameters that govern the performance of HSA: Harmony Memory Considering Rate (HMCR), Harmony Memory Size (HMS), Pitch Adjustments Rate (PAR), Adjusting Distance Bandwidth (bw), and Stopping Criteria (i.e., number of improvisation (NI) are also initiated in this step. Here, HM is the repository of solution vectors; HMCR and PAR are used to improve the j solution vector. Step 2: Harmony Memory Initialization In this step, Harmony Memory (HM) matrix, is filled with randomly constructed HMS solution vectors.

**Step 2: Harmony Memory Initialization**

In this step, Harmony Memory (HM) matrix, is filled with randomly constructed HMS solution vectors.

$$HM = \begin{bmatrix} x_1^1 & x_2^1 & \cdots & x_{N-1}^1 & x_N^1 \\ x_1^2 & x_2^2 & \cdots & x_{N-1}^2 & x_N^2 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_1^{HMS-1} & x_2^{HMS-1} & \cdots & x_{N-1}^{HMS-1} & x_N^{HMS} \\ x_1^{HMS} & x_2^{HMS} & \cdots & x_{N-1}^{HMS} & x_N^{HMS} \end{bmatrix}$$

**Step 3: New Harmony Improvisation**

In this stage, a new solution $x' = (x'_1, x'_2, \ldots\ldots\ldots\ldots, x'_N)$ termed as harmony vector is generated based on memory consideration, random initialization, and pitch adjustment. The generation of new harmony memory is known as improvisation. The memory consideration, the value of each component is updated as follows:

$$
\begin{aligned}
&\text{if } (rand() < HMCR) \\
&\quad x_i' \leftarrow x_i' \in \{x_i^1, x_i^2, x_i^3 \ldots\ldots\ldots, x_i^{HMS}\} \\
&\text{else} \\
&\quad x_i' \leftarrow x_i' \in X_i \\
&\text{end}
\end{aligned}
$$

Where rand ( ) is a random number uniformly distributed in the range of 0 and 1, and $Xi$ is the value space of the $i$ th variable. HMCR, which lies in the range [0,1], is the rate of selecting one value from already stored historical value in the HM whereas the ratel of randomly selecting one value from the possible range of values is denoted by (1 – HMCR).

Each component obtained by the memory consideration is examined to determine whether it should be pitch adjusted. The PAR parameter is the rate of pitch-adjustment. This operation uses the rate of pitch adjustment as a parameter as follows:

if (rand ()PAR < PAR)

$$
\begin{aligned}
&x_i' = x_i' \pm rand() * bw \\
&\text{else} \\
&x_i' = x_i'
\end{aligned}
$$

End

Where bw is an arbitrary distance bandwidth for the continuous variable design and rand ( ) is a uniformly distributed random number (rand∈ [-1,1]).

**Step 4: Harmony Memory Updation**

If the fitness value of the new harmony vector $\overrightarrow{x'} = (x_1', x_2', \ldots\ldots\ldots\ldots, x_N')$ is better than the worst fit harmony, the worst harmony in HM is then substituted by the new harmony.

**Step 5: Check the Stopping Criterion**

If the termination criterion (i.e. maximum number of iterations) is reached, stop the computation. Otherwise, steps 3 and 4 are repeated.

**B. Improved Harmony Search Algorithm (IHSA)**

The performance of HSA reveals that although this algorithm is good in finding out the high performance regions of the solution space in a short time but weak in performing local search for numerical optimization applications. To improve the performance of HSA technique and overcome the drawbacks involved in the fixed values of PAR and bw, Mahdavi et al. [34] proposed an improved version of traditional HSA called as Improved Harmony Search Algorithm (IHSA). The IHSA uses variable PAR and bw values in the improvisation step to improve the performance of the HAS. The PAR and bw values change dynamically with the generation number expressed as follows:

$$PAR(gn) = PAR_{\min} + \frac{(PAR_{\max} - PAR_{\min})}{NI} * gn$$

$$bw(gn) = bw_{\max} * \exp\left(\frac{gn}{NI} * \ln\left(\frac{bw_{\min}}{bw_{\max}}\right)\right)$$

where PAR $_{min}$ and PAR $_{max}$ indicate the minimum and maximum pitch adjusting rates, respectively. gn and NI denote the generation number and the maximum number of iterations, respectively. Also, bw (gn) is bandwidth for each generation, $bw_{min}$ and $bw_{max}$ indicate the minimum and maximum bandwidths.

## 7. TEST SYSTEM IEEE 69- BUS RADIAL DISTRIBUTION SYSTEM

The IEEE 69 bus is a Standard 12.66 kV medium scale distribution system consists of 68 sectionalizing switches labelled from 1-68,5 tie switches from 69-73,69 nodes and 73 brances. The totel load demand foe this network are 3.082 MW and 2.694 MV Ar, respectively. Further, to evaluate the performance of proposed IHSA, three load levels: light load (0.5), norminal load (1.0) and overload load (1.5) are considerd while performing the simulation of network for optimized reconfiguration. The base case (i.e. before reconfiguration) network power loss calculated from the load flow at three load conditions are: 56.51 kW ( light load ), 224.95 kW (nominal load )665.32 kW ( heavy load). The initial nominal bus system voltage is 0.9091 p.u. The sectionalizing switches that are initially opened in normal operation are- SW1-69, SW1-70, SW1-71, SW1-72, SW1-73. The initial configuration of 69 – bus distribution system is depicted in Figure 1. and the results obtained by the proposed IHSA for two different scenarios are presented in Table 2.

**Table 2: Result of 69 – Bus System**

| Scenario | | Load Level | | |
|---|---|---|---|---|
| | | Light Load (0.5) | Nominal Load (1.0) | Heavy Load (1.5) |
| Scenario – I (i.e. Base Case) | Switches Opened | *SW -69, SW -70, SW -71, SW -72, SW -73* | *SW -69, SW -70, SW -71, SW -72, SW -73* | *SW -69, SW -70, SW -71, SW -72, SW -73* |
| | Power Loss (kW) | 56.51 | 224.95 | 665.32 |
| | Minimum Voltage (p.u) | 0.9576 | 0.9091 | 0.8454 |
| Scenario – II (i.e. Network Reconfiguration Implemented) | Switches Opened | *SW -14, SW -15, SW -61, SW -69, SW -70* | *SW -14, SW -15, SW -61, SW -69, SW -70* | *SW -14, SW -15, SW -61, SW -69, SW -70* |
| | Power Loss (kW) | 26.12 | 99.45 | 271.39 |
| | % Loss Reduction | 53.77 | 55.79 | 59.20 |
| | Minimum Voltage (p.u) | 0.9723 | 0.9495 | 0.9050 |

As seen from the results obtained in this table that after performing proposed reconfiguration problem based to on IHSA for IEEE 69 – bus system, switches: $SW_{14}$, $SW_{55}$, $SW_{61}$, $SW_{69}$, $SW_{70}$ are open and the network losses are reduced from 224.95 kW (i.e. base case) to 98.59 kW (i.e. scenario 2). For normal loading condition, the corresponding percentage of power loss reduction is 55.79%, and the voltage magnitude after reconfiguration raised to 0.9495 p.u.

Further, the voltage profile curves for both the scenarios obtained by proposed IHSA method for nominal load is shown in.

## 8. RECONFIGURATION WITH DGS

The PSO algorithm is implemented in the test system to find the optimal locations and sizing for the multi-DG units after reconfiguration. In scenario 2, after the optimal reconfiguration of the test system, the active power losses are reduced to 138.14 kW—an active power loss reduction of approximately 32%. The voltage magnitude is enhanced by 2.87%. Figures 1 and 2 show the voltage profile improvement and power loss reduction of the base and reconfigured test system, respectively. The lowest values of the voltage magnitude are measured as 0.9022 p.u. at bus-18 and 0.9281 p.u. at bus-32 for the system before and after reconfiguration, respectively.

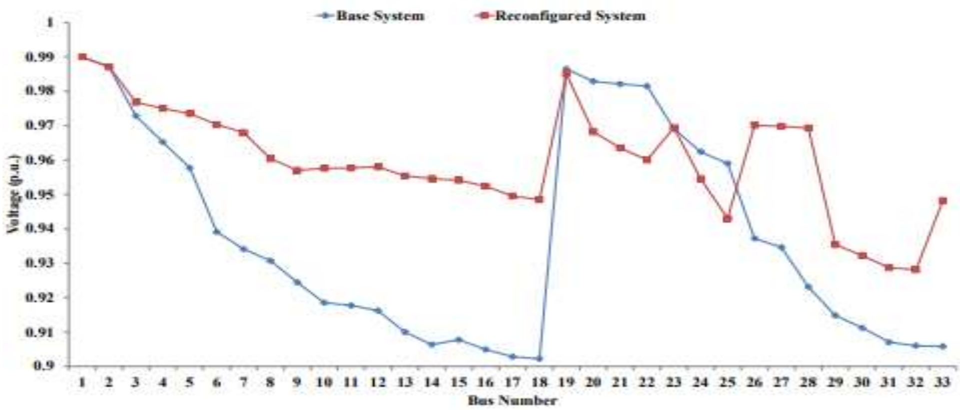


**Figure 1: Voltage profile of base and reconfigured distribution system.**

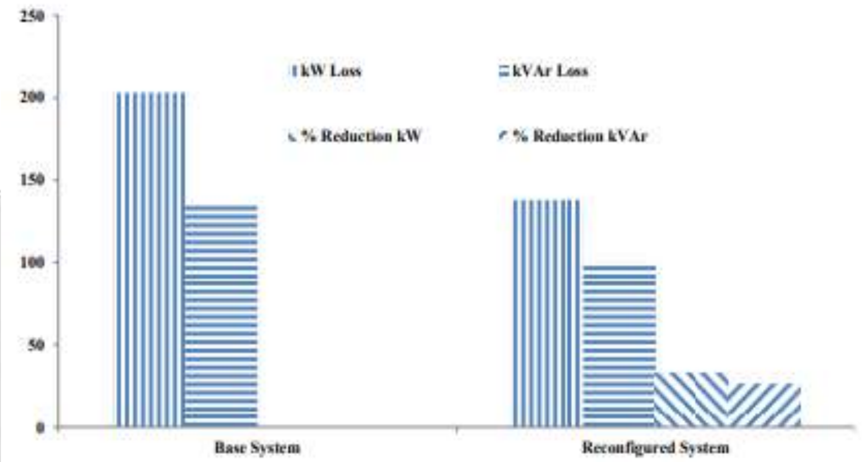


**Figure 2: Losses of base and reconfigured distribution system.**

when the three DG units are placed in the reconfigured distribution system, an outstanding reduction in power loss is observed. Multi-DG units with different sizes are installed at different locations. DG1 (1064.1 kW) is installed at bus 16, and DG1 and DG2 (1064.1 and 1215.5 kW, respectively) are installed at buses 16 and 29, respectively. Likewise, DG1, DG3 (1064.1, 1215.5, and 674.5 kW, respectively) are installed at buses number 16, 29, and 26, respectively, as shown in Table 1. Owing to the reconfiguration and DG installation in the network, the voltage profile increased by 6.53%, and the percent of loss reduction increased by 68.05%. The minimum voltage deviation is obtained. According to Table 2, four scenarios (1–4) for the IEEE-33 bus distribution system are presented.

**Table 3 Performance of proposed method on IEEE-33 bus radial distribution network**

| Methods | Base Network | Reconfigured Network | Base Network with DGs | Reconfigured Network with DGs |
|---|---|---|---|---|
| Active power loss (kW) | 203.17 | 138.14 | 82.77 | 64.91 |
| Reactive power loss (kVAr) | 135.17 | 99.85 | 58.39 | 47.03 |
| Min. voltage magnitude (p.u.) | 0.9022 | 0.9281 | 0.9464 | 0.9611 |
| Active power loss reduction (%) | | 32.00 | 59.26 | 68.05 |
| Reactive power loss reduction (%) | | 26.13 | 56.80 | 65.20 |
| Voltage deviation ($V_D$) | 0.0878 | 0.0619 | 0.0436 | 0.0289 |
| Voltage enhancement (%) | | 2.87 | 4.9 | 6.53 |

When we injected power, the active power losses were reduced in scenarios 1–4 by 203.17, 138.14, 82.77, and 64.91 kW, respectively, whereas the reactive power is also reduced from 135.17, 99.85, 58.39, and 47.03 kVAr, respectively. The percentage of active power loss reduction increased in scenarios 2–4 by 32%, 59.26%, and 68.05%, respectively. Similarly, the minimum bus voltage of the system in scenarios 2–4 improved by 2.87%, 4.9%, and 6.53%, respectively. This reveals that the NR and allocation of multi-DG units in scenario 4 are better than those in the other scenarios in terms of the voltage profile improvement and loss reduction. The voltage profile improvement, line current reduction, and total power loss reduction, respectively, by using the PSO algorithm to locate and size for multi-DG units before and after reconfiguration of the test system.

## 9. CONCLUSION

Inspired from musical harmony, an Improved Music Based Harmony Search Algorithm (IHSA) for solving distribution network reconfiguration problem for both medium scale and larger scale radial distribution system has been presented in the present paper. The proposed optimization algorithm establishes the optimized configuration of the network with main objective being active power loss minimization while considering operating constraints. The Distribution Network Reconfiguration of Radial Distribution Systems 355 IEEE 69 – bus and IEEE – 119 bus distribution systems at three different loading conditions namely light load, nominal load and heavy load have been considered to validate the efficacy of the proposed IHSA method. The power loss was 203.17 kW, and after the reconfiguration of the test system in scenario 3, the power loss decreased to 138.14 kW. PSO algorithm provided the best location and sizes for multi-DG units installation, and the active power losses were reduced from 82.77 to 64.91 kW before and after reconfiguration of the system, respectively. There were also significant improvements in the voltage profile and power loss reduction was achieved. The minimum voltage was 0.9022 p.u. at bus 18 for the base case. After adding 3 DGs with reconfigured system, the minimum voltage was enhanced to 0.9611 p.u. at bus 32. The overall simulation results showed that the proposed technique is comparatively efficient in terms of reducing the active and reactive power losses, voltage deviation, and boost-up voltage profile in the system.

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