

# Chapter 6

## Coordinated Planning and Scheduling of DER and SOP in Active Distribution Network

### 6.1 Introduction

Due to the shortage of fossil fuels and environmental concerns, distribution system (DSs) experiences rapid growth of penetration of distributed energy resources (DERs), particularly photovoltaics (PVs), wind generators (WGs), and battery energy storage (BESs) all over the world [95]. On other side, utilities are paying renewed interest in the operational techniques such as distribution network reconfiguration (DNR) [132] and conservation voltage reduction (CVR) [100], due to their ability of loss reduction, energy savings and peak demand reduction. The proper installation and operation of DER in conjunction with DNR and CVR techniques can postpone the system upgrades, reduce the losses, improve voltage profile and enhance the system reliability. In the view of above, a new coordinated planning and operation model of active distribution network (ADN) has been introduced in this chapter to determine sizes, sites and types of DERs considering DNR and CVR impact.

To the author's best knowledge, the coordinated planning and operation of DER in ADN considering DNR and CVR simultaneously has not been reported so far. To fill this gap, the present chapter incorporates both DNR and CVR to develop a new DER planning methodology in ADN. The contribution of this chapter is as follows.

- Proposed a new two-layer coordinated optimization framework for planning and operation of DERs and soft open point (SOP) in active distribution network (ADN).
- Proposed an integrated long-term planning model for DER that addresses the economic, operational, and environmental issues of DER; for which the uncertainties of renewable-based DG units and load demands are entirely taking into account by using a proposed stochastic module.
- Combined impact of DNR and CVR techniques in conjunction to smart inverter and SOPs on DERs planning has been studied .
- Introduced a hybrid optimization solver to solve the large scale non-convex mixed integer nonlinear programming (MINLP) problem without linearization or relaxation.
- Validation of proposed algorithm on large scale (118 bus test system) distribution system.

## 6.2 Framework of Proposed Two-Layer coordinated optimization model

In proposed two layer coordinated optimization model, optimal planning of DER and SOP in ADN is not only determine the type, location and capacity of DER but also simulate the optimal operation and management of DER, SOP and VVC devices . It consists of outer and inner layer optimization model, where the outer and inner layer

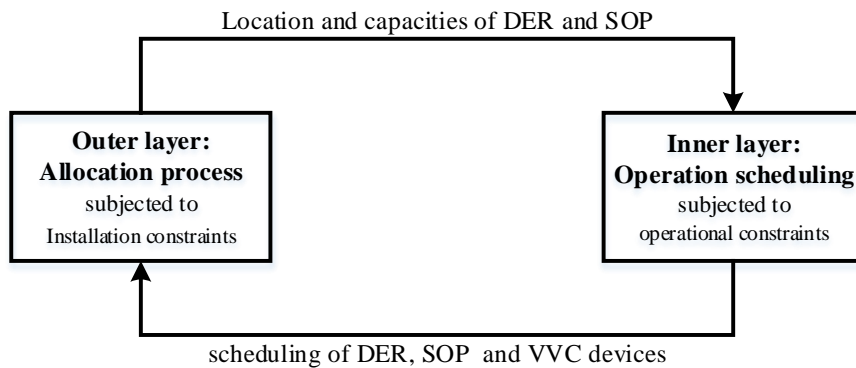


Figure 6.1: Framework of Proposed two layer model

corresponding to the decision-making in the planning and operation levels respectively. The outer-layer performs the planning of DER (i.e. PV, wind-based DG, BES) and SOP devices. In this layer, decision variables are the locations and capacities of DER and SOP to be installed. For coordinated purpose, all the candidate planning proposals would be transferred to the inner layer, where optimal scheduling of DER, SOP and VVC devices over a day have been performed considering uncertainties of solar irradiance, wind speed and loads. Meanwhile, the feasibility of outer layer decisions has also been checked in these simulations, where the technically infeasible solutions are recognised and rejected. After this step, the posted scheduling of DERs, SOPs and VVC devices will be fed back to revise previous planning scheme in the upper layer. With on-going simulations, these procedures would finally arrive at the optimal solution. The proposed framework has been depicted in Fig. 6.1.

### **6.2.1 Stochastic Variable Module (SVM) for uncertainties**

Stochastic Variable Module (SVM) has been introduced in order to model the uncertainties of variables such as wind speed, solar irradiance and electrical load as illustrated in Fig.6.2. Historical data of variables (wind speed, solar irradiance and load) have been collected for a specified time period and determine the mean and variance of each variable with help of the collected data. Generate several numbers of scenarios with the help of probability distribution function (PDF) using Monte Carlo simulation (MCS) method within specified mean and variance. In this chapter, Weibull distribution, Beta distribution and Normal distribution have been employed to exhibits the uncertainty of wind speed, solar irradiance and load [106]. Then convert the wind speed and solar irradiance into wind power generation and PV power generation based on the wind turbine performance curve and PV module characteristics respectively. It is noteworthy to mention that as the number of scenarios increases; the computational time will also increase. Distribution operator must decide the settings of control variables as fast as possible, since operation approach for 24- hour scheduling. Therefore, an efficient scenario reduction method is required to decrease the computation time. Thus, K-mean clustering algorithm [137] has been employed to reduce the number of scenarios. The aim of this algorithm is to arrange original scenarios of solar irradiance, wind speed and loads in to clusters according to their likenesses. The centroid of each cluster is defined as the

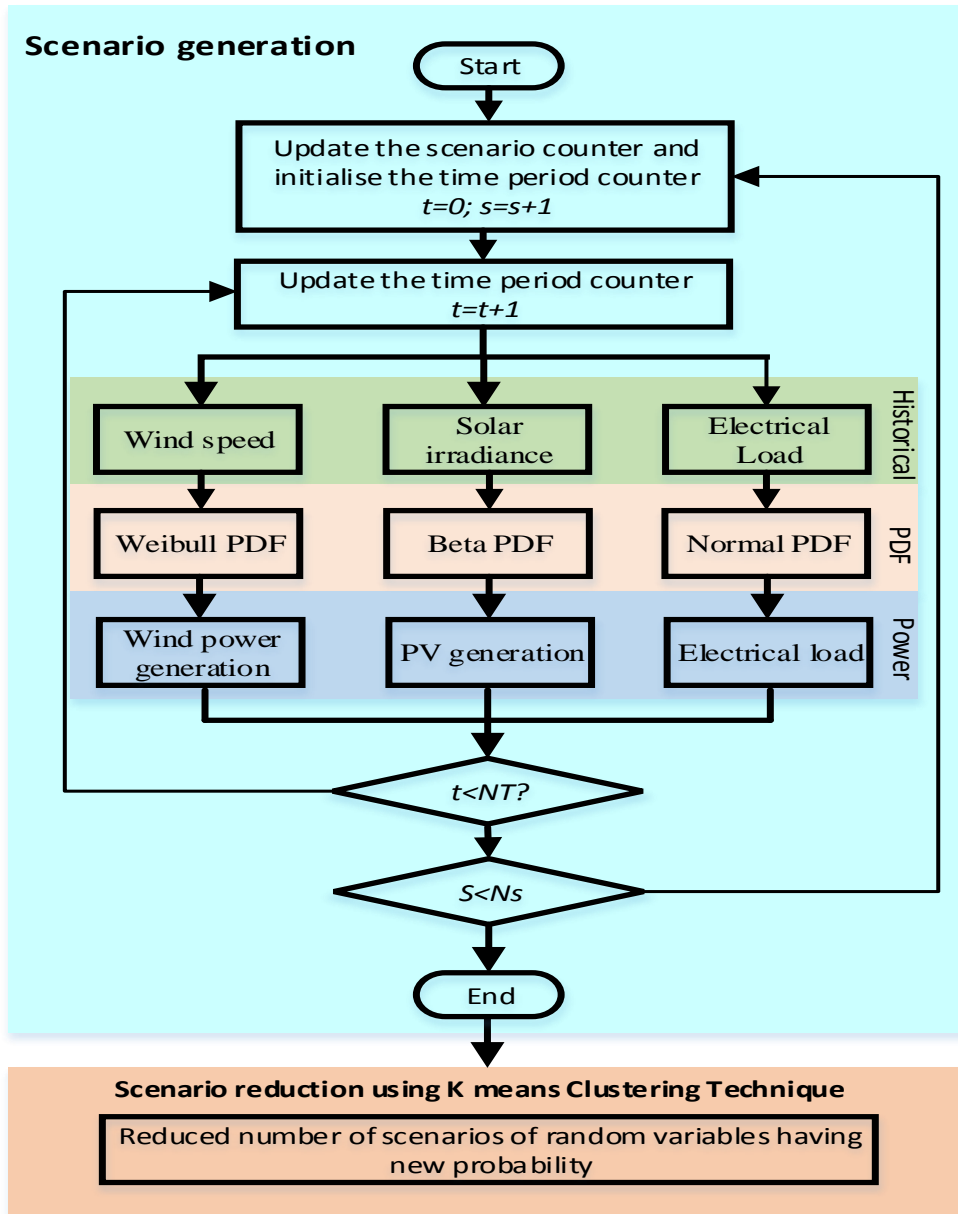


Figure 6.2: Stochastic Variable Module (SVM) for uncertainties

mean value of wind speed, solar irradiance and loads allocated to each cluster. After implementing the scenario reduction technique, the probability of the achieved scenarios is normalized as follows

$$\pi_s^n = \frac{\prod_{k=1}^{Nv} \text{Pr } ob_{k,s}}{\sum_{s=1}^{N_s} \prod_{k=1}^{Nv} \text{Pr } ob_{k,s}} \quad (6.1)$$

## 6.2.2 Voltage dependant loads

In medium/low voltage distribution network, most of the loads exhibit the voltage dependant behaviour [133]. These loads are highly dependent on the voltage magnitude. There are two voltage dependant loads namely exponential and polynomial loads. In this chapter, polynomial load voltage dependents have been chosen to represent the load-to-voltage sensitivities in this study.

$$P_{L,i}^t = P_{L,i}^{n,t} \left[ Z_i^p \left( \frac{V_i^t}{V_n} \right)^2 + I_i^p \left( \frac{V_i^t}{V_n} \right) + P_i^p \right] \times (1+r)^y \quad (6.2)$$

$$Q_{L,i}^t = Q_{L,i}^{n,t} \left[ Z_i^q \left( \frac{V_i^t}{V_n} \right)^2 + I_i^q \left( \frac{V_i^t}{V_n} \right) + P_i^q \right] \times (1+r)^y \quad (6.3)$$

where,  $Z_i^p + I_i^p + P_i^p = 1$  and  $Z_i^q + I_i^q + P_i^q = 1$

## 6.3 Proposed Problem formulation

### 6.3.1 objective function

The objective function of the present problem is to minimize the total cost (TC) over the entire planning horizon as given in (6.4), which can be expressed as

$$TC = \sum_{y=1}^{Ny} \left[ \frac{(C_{inv,y}^{tot} + C_{om,y}^{tot} + C_{sub,y}^{tot} + C_{ENS,y}^{tot} + C_{emis,y}^{tot})}{(1+d)^{(y-1)}} \right] \quad (6.4)$$

The calculation of each term in equation as follows

- Investment cost of wind, solar plant, BES and SOP device for each year ( $C_{inv,y}^{tot}$ )

$$C_{inv,y}^{tot} = \left[ \begin{array}{l} A^{wd} \sum_{i \in \Omega_{wd}} C_{wd}^{inv} P_{wd,i}^{rated} + A^{pv} \sum_{i \in \Omega_{pv}} C_{pv}^{inv} P_{pv,i}^{rated} + \\ A^{bes} \sum_{i \in \Omega_{bes}} (C_{P,bes}^{inv} P_{bes,i}^{rated} + C_{E,bes}^{inv} E_{bes,i}^{rated}) \\ + A^{sop} \sum_{i \in \Omega_{sop}} C_{sop}^{inv} S_{sop,i}^{rated} \end{array} \right] \quad (6.5)$$

where

$$A^x = \frac{d(1+d)^{y_x}}{(1+d)^{y_x} - 1}; x \in \{wd, pv, bes, sop\} \quad (6.6)$$

- Yearly operational and management cost of DER and SOP ( $C_{om,y}^{tot}$ )

$$C_{om,y}^{tot} = \sum_{s=1}^{N_{s,y}} days_y \times \pi_{s,y}^n \times OM \quad (6.7)$$

$$OM = \sum_{t=1}^T \left[ \begin{array}{l} \sum_{i \in \Omega_{wd}} C_{wd}^{OM} P_{wd,i,s,y}^t + \sum_{i \in \Omega_{pv}} C_{pv}^{OM} P_{pv,i,s,y}^t \\ + \sum_{i \in \Omega_{bes}} (C_{bes}^{OM} P_{bes,i,s,y}^t + C_{bes}^{EOM} E_{bes,i,s,y}^t) \\ + \sum_{i \in \Omega_{sop}} C_{sop}^{OM} S_{sop,i,s,y} \end{array} \right] \quad (6.8)$$

- Yearly cost of power purchased from the substation ( $C_{sub,y}^{tot}$ )

$$C_{sub,y}^{tot} = \sum_{s=1}^{N_{s,y}} days_y \times \pi_{s,y}^n \times \sum_{t=1}^T C_y^{sub,t} \times P_{sub,s,y}^t \quad (6.9)$$

- Yearly cost of emission from the substation ( $C_{ENS,y}^{tot}$ )

$$C_{emis,y}^{tot} = \sum_{s=1}^{N_{s,y}} days_y \times \pi_{s,y}^n \times \sum_{t=1}^T C_y^{emis,t} \times P_{sub,s,y}^t \quad (6.10)$$

- Yearly cost of energy not served

$$C_{ENS,y}^{tot} = \sum_{s=1}^{N_{s,y}} days_y \times \pi_{s,y}^n \times \sum_{t=1}^T C_y^{ENS,t} \times P_{sub,s,y}^t \quad (6.11)$$

### 6.3.2 constraints

The following constraints should be satisfied

- Maximum penetration of DERs at each bus

$$\left. \begin{aligned} 0 &\leq P_{wd,i,s,y}^t \leq P_{wd,i,y}^{\max} \\ 0 &\leq P_{pv,i,s,y}^t \leq P_{pv,i,y}^{\max} \\ 0 &\leq P_{BES,i,s,y}^t \leq P_{BES,i,y}^{\max} \end{aligned} \right\} \quad (6.12)$$

- Power flow equations for each scenario

$$\left. \begin{aligned} P_{i,s,y}^t &= V_{i,s,y}^t \sum_{j=1}^{Nbus} V_{j,s,y}^t (G_{ij,y} \cos \theta_{ij,s,y}^t + B_{ij,y} \sin \theta_{ij,s,y}^t) \\ Q_{i,s,y}^t &= V_{i,s,y}^t \sum_{j=1}^{Nbus} V_{j,s,y}^t (G_{ij,y} \sin \theta_{ij,s,y}^t - B_{ij,y} \cos \theta_{ij,s,y}^t) \end{aligned} \right\} \quad (6.13)$$

- Nodal voltage constraint for each scenario

$$V_i^{\min} \leq V_{i,s,y}^t \leq V_i^{\max} \quad (6.14)$$

- Branch capacity constraint for each scenario

$$0 \leq S_{l,s,y}^t \leq S_l^{\text{rated}} \quad (6.15)$$

- Reactive power constraint of wind generation for each scenario

$$\left. \begin{aligned} Q_{wd,i,s,y}^t &= P_{wd,i,s,y}^t \tan(\varphi_{wd,i,s,y}^t) \\ \varphi_{wd,i}^{\min} &\leq \varphi_{wd,i,s,y}^t \leq \varphi_{wd,i}^{\max} \end{aligned} \right\} \quad (6.16)$$

- Reactive power constraint of PV for each scenario

$$\left. \begin{aligned} Q_{pv,i,s,y}^t &= \sqrt{(S_{pv,i}^{\max})^2 - (P_{pv,i,s,y}^t)^2} \\ -Q_{pv,i}^{\max} &\leq Q_{pv,i,s,y}^t \leq Q_{pv,i}^{\max} \end{aligned} \right\} \quad (6.17)$$

- Operation constraint of OLTC transformer

$$OLTC_{trans}^{\min} \leq OLTC_{trans,y}^t \leq OLTC_{trans}^{\max} \quad (6.18)$$

- Radial structure constraint

$$\text{rank}(\text{BBIM}_y) = Nbr \quad (6.19)$$

- BES operation constraints:

$$SOC_{BES,i,s,y}^{t+1} = SOC_{BES,i,s,y}^t + \left( \eta_i^c P_{BES,i,s,y}^t + P_{BES,i,s,y}^t / \eta_i^d \right) \Delta t \quad (6.20)$$

$$|P_{BES,i,s,y}^t| \leq P_{BES,i}^{rated} \quad (6.21)$$

$$SOC_{BES}^{\min} \leq SOC_{BES,i,s,y}^t \leq SOC_{BES}^{\max}; i \in \Omega_{bes} \quad (6.22)$$

- SOP operation constraints

$$P_{sop,i,s,y}^t + P_{sop,j,s,y}^t + P_{sop,i,s,y}^{t,loss} + P_{sop,j,s,y}^{t,loss} = 0 \quad (6.23)$$

$$Q_{sop,i}^{\min} \leq Q_{sop,i,s,y}^t \leq Q_{sop,i}^{\max} \quad (6.24)$$

$$Q_{sop,j}^{\min} \leq Q_{sop,j,s,y}^t \leq Q_{sop,j}^{\max} \quad (6.25)$$

$$\sqrt{(P_{sop,i,s,y}^t)^2 + (Q_{sop,i,s,y}^t)^2} \leq S_{sop,i,y} \quad (6.26)$$

$$\sqrt{(P_{sop,j,s,y}^t)^2 + (Q_{sop,j,s,y}^t)^2} \leq S_{sop,j,y} \quad (6.27)$$

### 6.3.3 Implementation of proposed solution methodology

The problem formulated in the previous section is a large-scale mixed integer nonlinear programming (MINLP) problem, which is difficult to solve by a conventional optimization techniques. In this section, the model is decomposed into the planning and operation models. These models are solved by using outer and inner layer optimization as said previous section. These outer and inner layers are controlled by the decision variable sets, D1 and D2, respectively. The set D1 consists of candidate solutions for installations of DER and SOP. Set D2 consists of operational scheduling of DER, SOP and Volt/VAR control devices. In this chapter, the outer and inner layers have been solved concurrently with help of the evolutionary algorithms and GAMS optimization tool respectively.

In outer layer, candidate solution of the each individual has been illustrated in Fig.6.3. In this chapter, a proposed modified binary grey wolf optimization (MBGWO) [130] evolutionary algorithm has been employed to generate the candidate solutions D1 subject to the constraints given in (6.12)-(6.27) under MATLAB environment.

Each candidate solution of upper layer D1 transferred to GAMS environment through GAMS data exchange (GDX) files. For each candidate solution D1, an inner layer MINLP

optimization problem relating the operation scheduling of transformer taps, DERs, BESs and SOPs has been solved dynamically for each hour for each possible scenarios. The candidate solution is represented as shown in Fig.6.4. Note that, to reduce computational burden, discrete variable present in inner layer (i.e. transformer taps) has been relaxed and treated as continuous variable. Thus MINLP problem has been transformed to non-linear program (NLP) problem, which can be efficiently solved by using CONOPT3, NLP solver under GAMS environment [146]. The NLP optimization problem subject to the constraints given in (6.13)-(6.27). Here, the objective is to recursively minimize the daily operation costs representing the entire year at the candidate installation variables provided from the MBGWO solver. The solution of the inner layer yields the set of decision variables for the operation scheduling, i.e. D2 for each scenario  $s$  at hour  $t$ .

Above process has been repeated until maximum number of iterations has reached, and the best individual is stored. Figure 6.5 illustrates the proposed hybrid optimization solver.

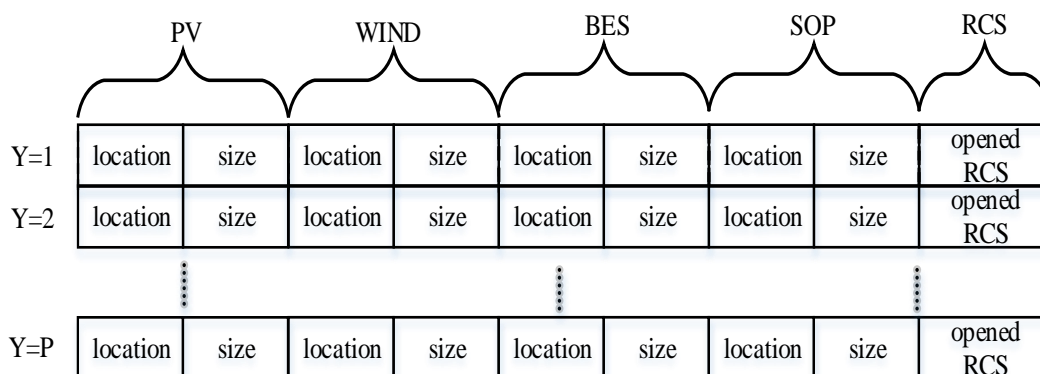


Figure 6.3: Candidate solution of upper layer D1

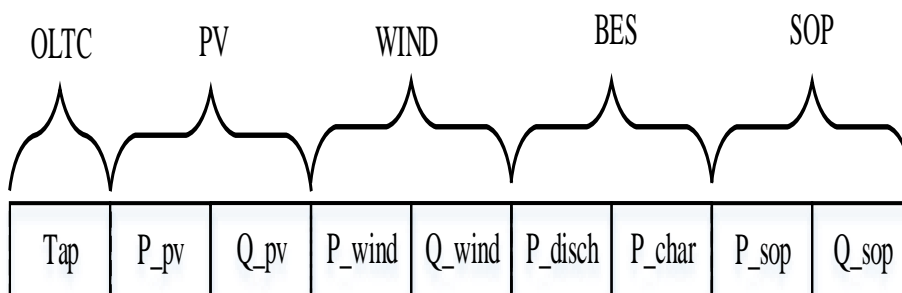


Figure 6.4: Candidate solution of lower layer D2

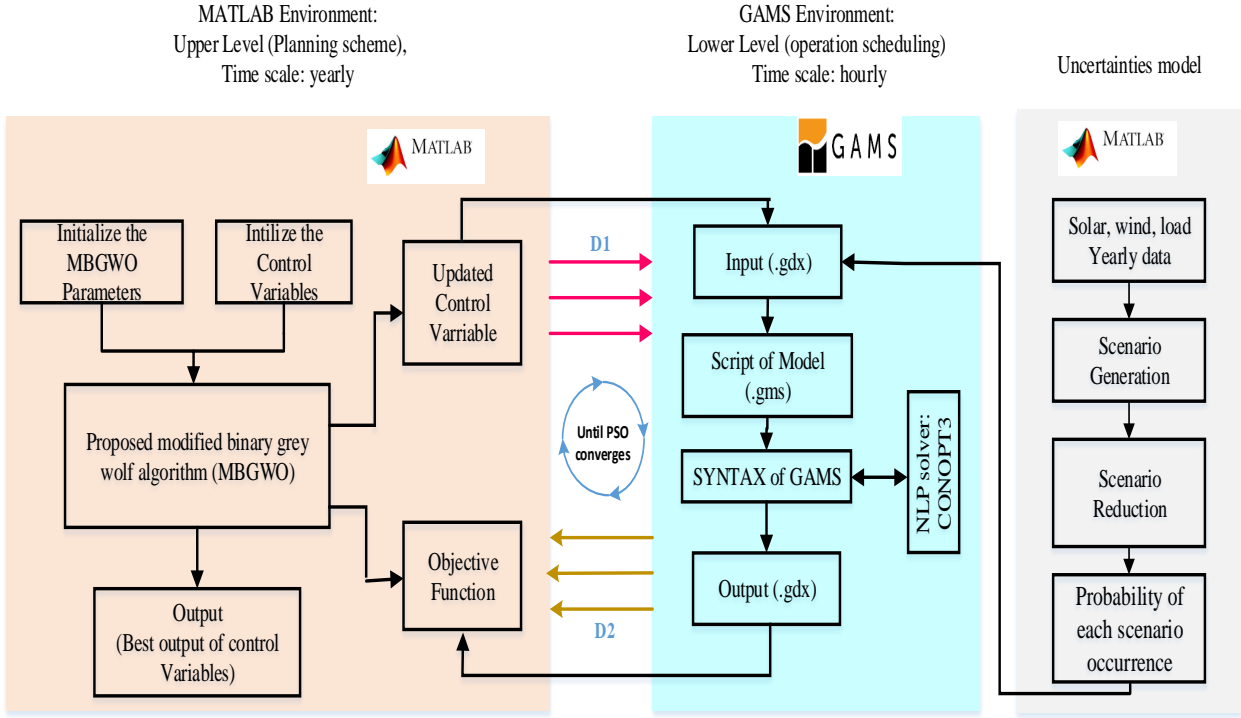


Figure 6.5: schematic of the proposed hybrid optimization solver

## 6.4 Simulation results and discussions

### 6.4.1 Simulation platform

The proposed coordinated planning and operation methodology has been implemented on MATLAB-GAMS environment. GAMS and MATLAB interfacing has been utilised to solve the given problem. Detailed explanation interfacing GAMS and MATLAB has been given in [144].

### 6.4.2 Data and assumptions

The performance of the proposed methodology has been tested on standard IEEE 119-bus distribution system. The detailed line data and load data of 119-bus system has been taken from [132]. In modified test system, it is assumed that OLTC transformer is connected between substation and node 1. The single line diagram of modified 119-bus distribution system has been shown in Fig. 6.6. Typical load profile, active energy price purchased from grid, PV generation and wind generation output over 24 hours have been plotted in Fig. 6.7. The cost parameters of PV, wind has been taken from [106]. The cost parameters of BES and SOP has been taken from [95] and [102] respectively. The

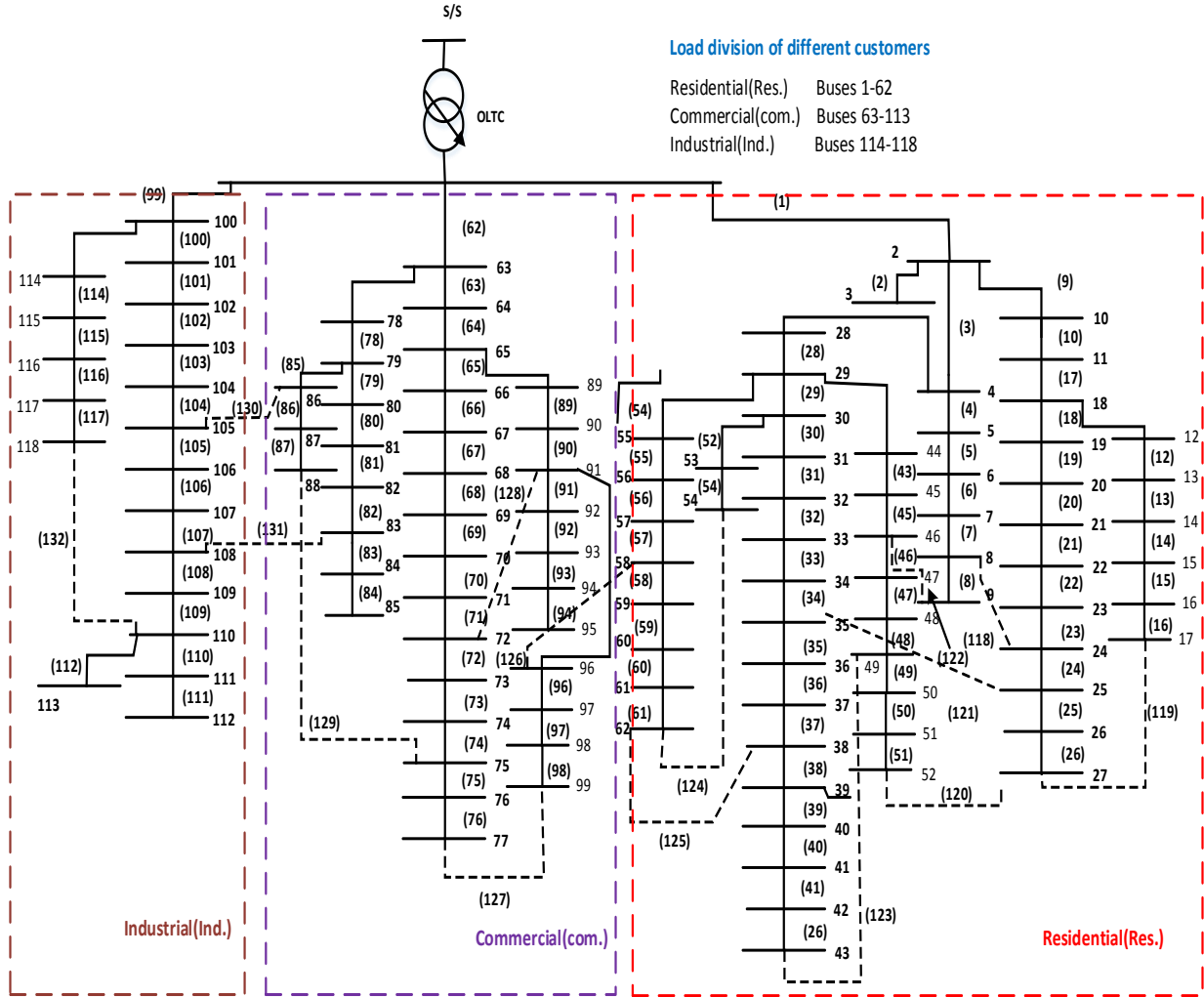


Figure 6.6: modified 119 bus distribution system

load growth is taken as a 7% for each year. The cost of unserved energy is taken as 2000 \$/MWh. The emission rate of purchased power from grid is taken as  $0.4 \text{ tCO}_2\text{e}/\text{MWh}$  and the emission price in the five year plan is set as 40, 60, 80, 100 and 120 \$/tCO<sub>2</sub>e respectively.

### 6.4.3 Discussions on numerical results

The developed optimization has been solved considering six different cases (i.e. namely case A to case F) as given Table 6.1 . Case A is corresponding to base case scenario, where no investments of DER are made. Case B corresponds to scenario, where investment of DER (i.e. PV, wind and BES) are made. Case B can be referred as traditional planning scheme. Case C is similar to Case B but considers the distribution network reconfigura-

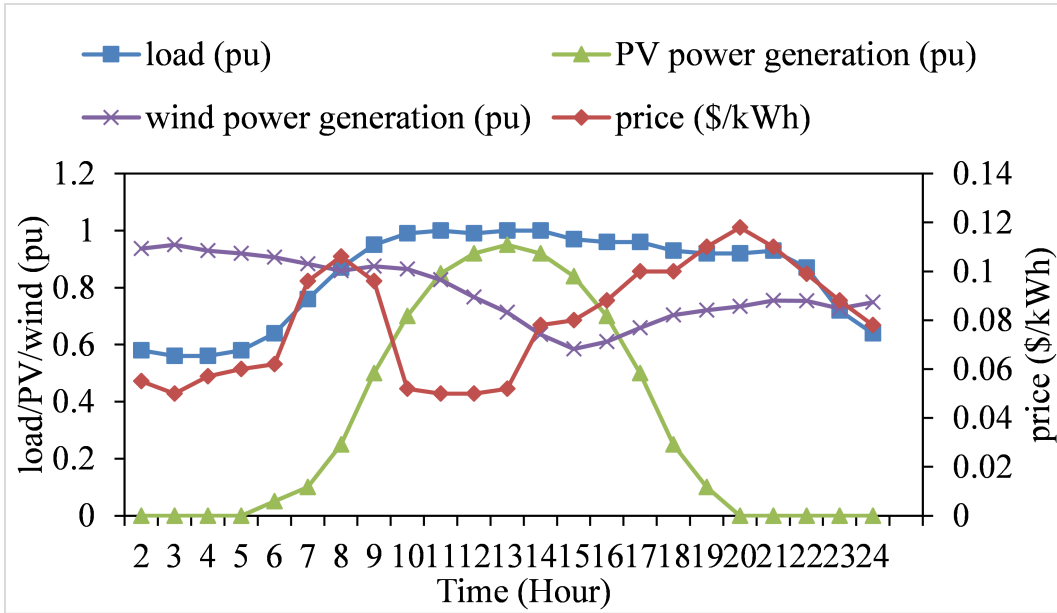


Figure 6.7: Typical PV, wind, load and its price profile

Table 6.1: Different cases studied

Cases	RES	BES	DNR	SOP	CVR
case A	✗	✗	✗	✗	✗
case B (method in [108])	✓	✓	✗	✗	✗
case C (method in [105])	✓	✓	✓	✗	✗
case D (method in [101])	✓	✓	✗	✓	✗
case E (proposed method 1)	✓	✓	✗	✓	✓
case F (proposed method 2)	✓	✓	✓	✓	✓

✗- indicates not considered, ✓- indicates considered

tion (DNR) operation. Case D is similar to Case B but considers the investment of soft open point (SOP). Case E is similar to Case D but considers the conservation voltage reduction (CVR) operation. Finally, case F corresponds to scenario, where investment of DER (i.e. PV, wind, BES) and SOP are made considering DNR and CVR operations.

Table 6.2 shows the most relevant variables such as investment cost, operation & maintenance (O & M) cost of DER (PV, wind, BES) and SOPs, energy purchased cost from the grid, energy not served (ENS) cost and  $CO_2$  emission cost of different cases over the five-year planning horizon. The results of case B to Case F shows a significant benefit compared with the base case (i.e. case A). The optimal planning and operation of DERs in distribution system can minimize the total cost up to 56.34% as seen in case B compared

Table 6.2: Results of different cases over planning horizon

Costs (millions \$)	Case A	Case B	Case C	Case D	Case E	Case F
Investment cost	—	4.226	4.240	4.351	4.401	4.408
O &M cost	—	30.272	30.222	30.327	30.368	30.348
Energy purchased cost from grid	73.73	17.556	17.340	16.867	15.351	15.106
ENS cost	59.80	16.364	10.923	6.155	6.124	5.941
Emission Cost	45.32	9.656	9.580	9.380	8.462	8.362
Total cost	178.84	78.074	72.305	67.079	64.707	64.164
Savings in Total cost	—	100.766	106.535	111.761	114.133	114.676
Total reduction cost (%)		56.34	59.57	62.49	63.82	64.12

with that of case A. With the optimal operation of DNR, additional 3.23% reduction has been achieved as seen in case C. However, with the simultaneously installation and operation of DERs and SOPs, the total cost has been reduced by 62.49% as seen in case D compared with that of case A. Further, 1.33% more reduction has been achieved with the association of CVR operation as seen in case E. Finally, simultaneously installation and operation of DERs and SOPs considering CVR and DNR operations, the total cost of the system has been reduced to 64.12% compared with that of case A.

Table 6.3 show the percentage of power share of RES and grid to meet the load demand of the distribution system in different cases. With the help of the optimal planning and operation of DERs and SOPs, the power share from the grid drastically reduced from 100% to 19.33% as seen in Table 6.3. This shows that proposed methodology encourages the DER penetration.

Table 6.3: Percentage power share between RES and grid in different cases

parameters	Case A	Case B	Case C	Case D	Case E	Case F
Wind	—	56.45	56.35	56.35	57.52	57.74
Solar	—	22.30	22.26	22.30	22.88	22.93
Imported	100	21.25	21.39	21.35	19.60	19.33

Table 6.5 summarizes the optimal location and size of installed PV based DGs, wind based DGs, BESs, and SOPs in different cases in initial year. As problem is formulated on five-

Table 6.4: Optimal location and size of DER and SOP for different cases at initial year

Cases	DER Type	(Location, size in MVA)* , (Location, size in MW; MWh)**, (Location,size in MVA)#	Total capacity (MVA;MWh)
case B	Wind*	(14,1.94); (32,0.32); (37,1.06); (42,0.72); (53,1.07); (56,0.47); (61,1.11); (71,0.87); (85,0.46); (93,0.79); (96,0.71); (116,0.17); (110,2.00); (69,0.45); (75,1.23)	13.38
	PV*	(25,1.86); (35,1.77); (43,0.17); (52,0.93); (77,0.41); (84,1.18); (100,2.00); (106,2.00); (112,0.20); (114,1.07); (116,0.56); (70,0.62); (73,0.36)	13.13
	BES**	(62,0.12;0.03); (71,0.85;0.21); (105,1.54;0.39); (108,0.65;0.16); (112,0.34;0.09); (56,0.23;0.06); (61,0.10;0.02); (66,0.06;0.02); (77,0.95;0.24); (83,1.03;0.26)	(5.85;1.46)
case C	Wind*	(14,1.93); (32,0.32); (37,1.01); (42,0.93); (53,1.32); (56,0.31); (61, 1.1); (71,0.54); (85,0.94); (93,1.43); (96,0.95); (116,0.21); (110,0.18); (69, 0.6); (75,1.62)	13.39
	PV*	(25,2); (35,0.65); (43,0.07); (52,1.06); (77,0.35); (84,0.92); (100,2); (106,1.34); (112,0.12); (114,1.02); (116,0.47); (108,0.46); (70, 0.4); (73,0.93); (74,0.75)	12.51
	BES**	(62,0.28;0.07); (71,0.83;0.2075); (105,0.66; 0.165); (108,1.23;0.3075); (112,0.42; 0.105); (56,0.21;0.0525); (66,0.36;0.09); (77,0.85;0.2125); (83,1.07;0.2675);	(5.91;1.48)
case D	Wind*	(14,2.00); (32,0.47); (37,0.95); (42,0.56); (53,1.50); (56,0.66); (61,1.11); (71,0.63); (85,0.60); (93,0.83); (96,0.83); (116,0.35); (110,1.69); (69,0.52); (75,0.71)	13.39
	PV*	(25,1.72); (35,1.53); (43,0.42); (52,0.82); (77,0.72); (84,0.79); (100,1.85); (73,0.51); (74,0.47); (106,2.00); (112,1.14); (114,0.25); (116,0.00); (108,0.20); (70,0.78)	13.20
	BES**	(62,0.13;0.03); (71,1.42;0.36); (105,1.46;0.36); (108,0.96;0.24); (112,1.56;0.39); (56,0.18;0.05); (61,0.10;0.02); (66,0.04;0.01); (77,1.22;0.30); (83,0.70;0.17)	(7.76;1.94)
	SOP#	(110-118, 0.50); (77-99, 0.45)	0.95

Table 6.5: Optimal location and size of DER and SOP for different cases at initial year

Cases	DER Type	(Location, size in MVA)* , (Location, size in MW; MWh)**, (Location,size in MVA)#	Total capacity (MVA;MWh)
case E	Wind*	(14,2.00); (32,0.50); (37,0.93); (42,0.54); (53,1.52); (56,0.68); (61,1.10); (71,0.64); (85,0.60); (93,0.80); (96,0.81); (116,0.35); (110,1.74); (69,0.52); (75,0.71)	13.43
	PV*	(25,1.72); (35,1.45); (43,0.41); (52,0.80); (77,0.70); (84,0.74); (100,1.77); (106,2.00); (112,1.02); (114,0.20); (116,0.00); (108,0.14); (70,0.71); (713,0.48); (74,0.43)	12.59
	BES**	(62,0.86;0.21); (71,1.32;0.33); (105,1.48;0.37); (108,0.90;0.22); (112,1.35;0.34); (56,0.14;0.03); (61,0.35;0.09); (66,0.06;0.01); (77,1.21;0.30); (83,0.66;0.16)	(8.31;2.08)
	SOP#	(110-118, 0.50); (77-99, 0.43)	0.93
case F	Wind*	(14,1.89); (32,0.37); (37,0.80); (42,0.71); (53,1.44); (56,0.35); (61,1.12); (71,0.87); (85,0.51); (93,1.35); (96,1.94); (116,0.30); (110,1.06); (69,0.46); (75,0.28)	13.44
	PV*	(25,1.85); (35,0.67); (43,0.44); (52,0.91); (77,1.04); (84,0.92); (100,2.00); (106,0.52); (112,1.26); (114,0.26); (116,0.27); (108,0.14); (70,0.40); (73,1.55); (74,0.34);	12.56
	BES**	(62,0.22;0.05); (71,1.54;0.39); (105,0.30;0.07); (108,0.35;0.09); (112,1.60;0.40); (56,0.59;0.15); (61,0.24;0.06); (66,0.45;0.11); (77,0.98;0.25); (83,0.94;0.24)	(7.23;1.81)
	SOP#	(110-118, 0.25); (77-99, 0.50)	0.75

year planning horizon, the aggregated capacities of installed DGs, BESs, and SOPs have been depicted in Table 6.6. As it can be seen in Table 6.6, majority of the investments are made in the initial year. Further, Table 6.7 depicts the optimal network topologies corresponding to the different cases over a five-year planning horizon.

#### 6.4.4 Effect of voltage profile

Figure 6.8. shows the average voltage profiles at each node for different cases. Figure 6.9. shows the cumulative distribution of the average voltage values for different cases. In both figures, it can be observed there is a significant improvement in voltages due to

Table 6.6: Optimal capacities of DER and SOP for different cases in each year

Cases	DER	Year 1	Year 2	Year 3	Year 4	Year 5	Total capacity
case B	Wind*	13.38	0.93	0.94	0.93	0.94	17.12
	PV*	13.13	0.91	0.91	0.9	0.9	16.75
	BES**	(5.85; 1.46)	(2.7; 0.67)	(3.11; 0.78)	(3.92; 0.98)	(4.6; 1.15)	(20.18; 5.044)
case C	Wind*	13.39	0.93	0.94	0.94	0.94	17.14
	PV*	12.51	1.54	0.91	0.91	0.9	16.77
	BES**	(5.91; 1.48)	(3.29; 0.82)	(3.42; 0.85)	(3.59; 0.89)	(4.29; 1.07)	(20.5; 5.12)
case D	Wind*	13.39	0.94	0.94	0.82	1.07	17.16
	PV*	13.2	0.91	0.92	0.77	1.04	16.84
	BES**	(7.76; 1.94)	(2.88; 0.72)	(3.49; 0.87)	(3.8; 0.95)	(4.69; 1.17)	(22.62; 5.65)
	SOP#	0.95	0	0.03	0.02	0	1
case E	Wind*	13.43	0.95	0.94	0.94	0.94	17.2
	PV*	12.59	1.47	0.94	1.26	0.71	16.97
	BES**	(8.31; 2.08)	(3.12; 0.78)	(3.57; 0.9)	(3.96; 1.0)	(4.6; 1.15)	(23.56; 5.89)
	SOP#	0.93	0.03	0.03	0.01	0	1
case F	Wind*	13.44	0.94	0.94	0.95	0.95	17.22
	PV*	12.56	1.28	1.16	1	0.95	16.95
	BES**	(7.23; 1.81)	(3.32; 0.83)	(4.00; 1.00)	(4.67; 1.16)	(5.1; 1.27)	(24.32; 6.08)
	SOP#	0.75	0.05	0	0	0	0.8

\*(Wind,PV in MW), \*\*(BES in MW; MWh), #(SOP in MVA)

the installation of DERs as seen in case B to case E. However, voltage profile in case E, and F are flatten and maintained at lower portion of permissible limit, this is due to the operation of CVR.

Table 6.7: optimal opened RCS\* of case C and case E in each year

Year	Case C	Case E
Year 1	(23), (26), (48), (34), (45), (40), (58), (125), (95),(97), (71), (74), (130), (131), (109)	(21), (25), (48), (32), (45), (40), (60), (125), (95),(97), (70), (73), (130), (131), (132)
Year 2	(23), (25), (50), (34), (44), (42), (61), (125), (95),(97), (71), (74), (130), (131), (109)	(21), (26), (48), (34), (45), (40), (58), (125), (95), (97), (71), (74), (130), (131), (109)
Year 3	(23), (25), (50), (34), (44), (42), (61), (125), (95),(97), (71), (74), (130), (107), (132)	(21), (26), (50), (34), (45), (40), (58), (125), (95),(97), (71), (74), (130), (131), (132)
Year 4	(23), (26), (48), (34), (45), (40), (58), (125), (95), (97), (71), (74), (130), (131), (109)	(21), (25), (48), (32), (45), (40), (60), (125), (95),(97), (70), (73), (130), (131), (132)
Year 5	(23), (25), (50), (34), (44), (42), (61), (125), (95), (97), (71), (74), (130), (131), (109)	(21), (26), (48), (34), (45), (40), (58), (125), (95),(97), (71), (74), (130), (131), (109)

\*RCS-remote-controlled switches

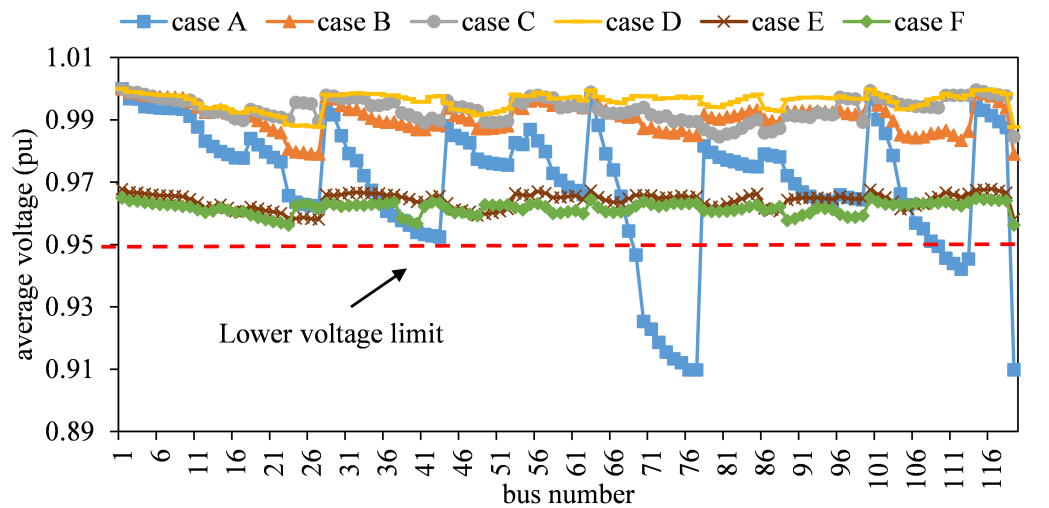


Figure 6.8: average voltage of each node in the system for different cases

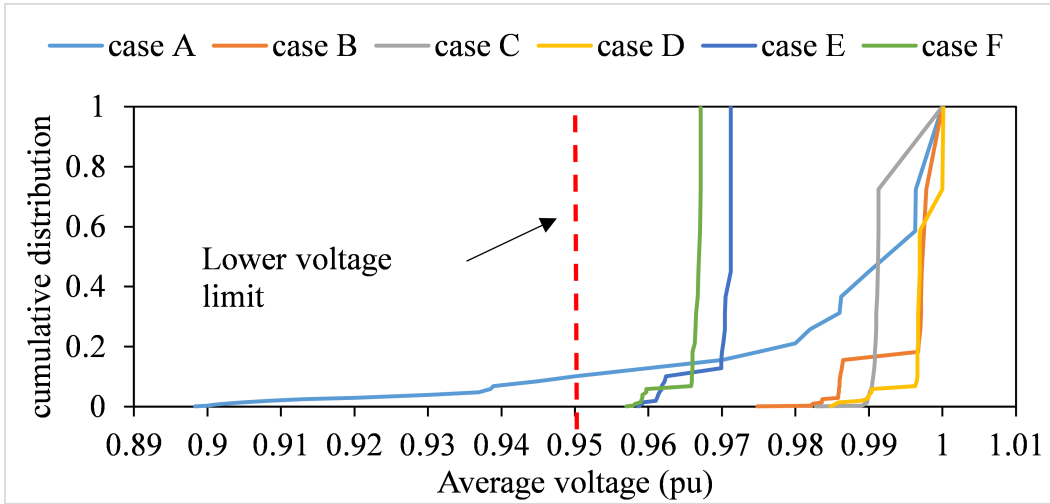


Figure 6.9: Cumulative probability distribution of nodal voltages in the system for different cases

#### 6.4.5 Effect of energy losses and consumption

Fig. 6.10 and Fig. 6.11 shows the total energy losses and energy consumption respectively for each year and for each case. With the proposed coordinated planning scheme (i.e. case F) approximately 63.71% average reduction in losses over a five year planning period has been achieved compared with traditional planning scheme (i.e. case B). On other hand, average energy consumption has been increased by 0.15% and 0.42% in case C and D respectively with respect to case B. This is due to increase in voltage would cause increase in energy consumption due to dependency of loads on voltage. Where as in case E and F, the average energy consumption has been reduced by 1.63% and 1.88% respectively. This happens due to the CVR operation.

#### 6.4.6 Effect of energy not served and carbon emissions

Fig. 6.12 and Fig. 6.13 shows the cost of  $CO_2$  emission and cost of energy not served (ENS) respectively for each year and for each case. As seen from case B to case F, It can be observed that carbon emissions has been decreased due the installation of RES. Further, in subsequent years, carbon emissions has been decreased due to addition of RES installation. On other hand, ENS in the system has been drastically decreased in case F, this is due the enhancement of controllability and flexibility operation of DER, SOP, RCS and VVC devices.

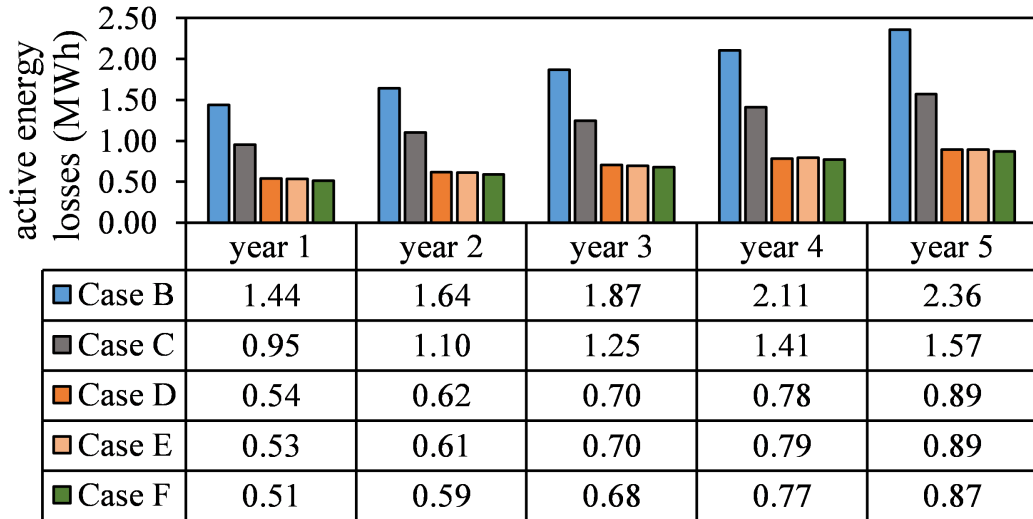


Figure 6.10: Energy losses of system in each year for different cases

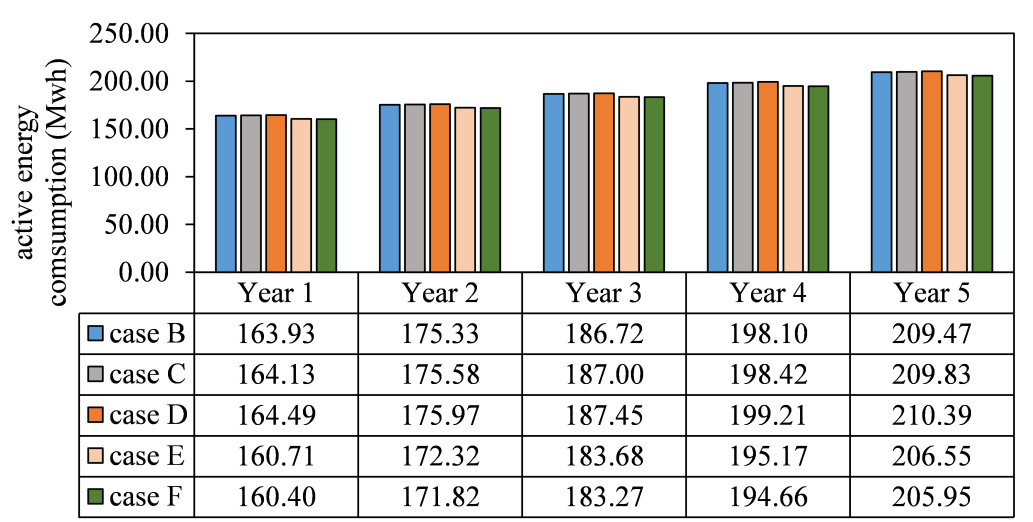


Figure 6.11: Energy consumption of system in each year for different cases

### 6.4.7 Performance of proposed hybrid optimization solver

In this section, the convergence performance and robustness of the hybrid optimization solver has been tested and also compared with the conventional GWO(CGWO) solver for case F. For this purpose, the simulation has been performed for 25 times with random initial data on Core i3 2.5GHz processor and 4 GB RAM. For both solvers, same number of initial population (i.e. 25), maximum iterations (i.e. 100) have been chosen. Fig. 6.14 shows the convergence pattern of both solvers. Further, Table 6.8 depicted the capability parameters such as best, worst, average and standard deviation of fitness value of both solvers.

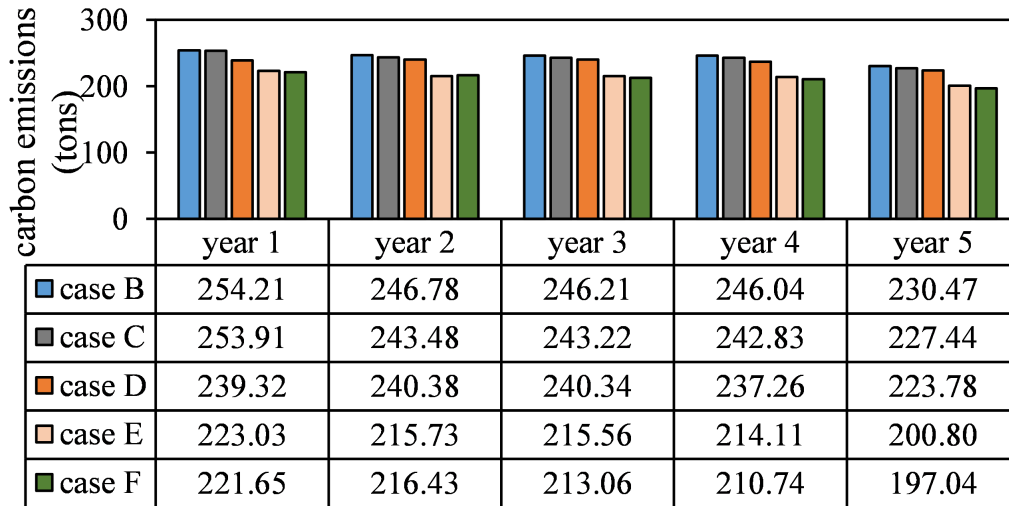


Figure 6.12: carbon emission from system in each year for different cases

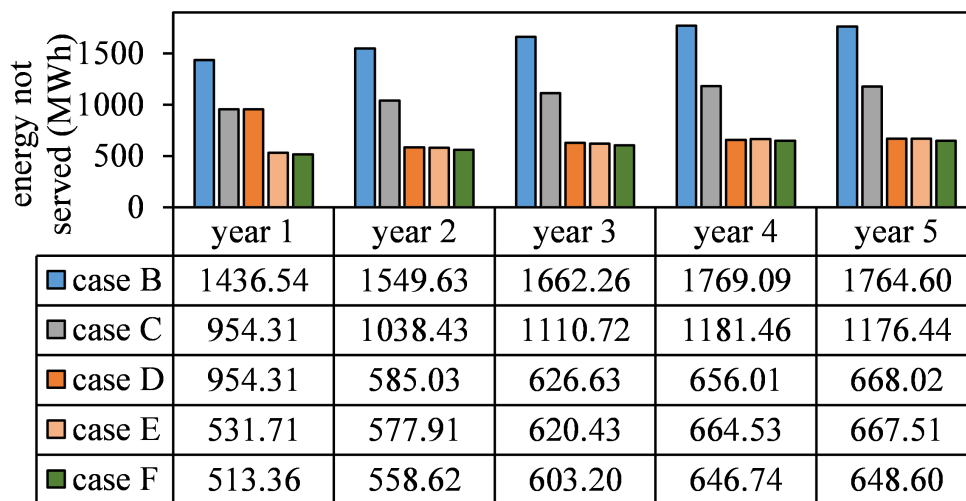


Figure 6.13: Energy not served of system in each year for different cases

With the comparison of CGWO, proposed hybrid optimization solver converges faster as seen in Fig. 6.14. Besides, it has achieved good capability parameters as seen in Table 6.8. It is note worthy mentioned that, more than 65% of computational time has been reduced using proposed hybrid solver compared with CGWO. Further, an attempt has made for solving the present MINLP problem using the DICOPT solver in GAMS [134].Where, the solving process has been stopped after 3 hours without converging.

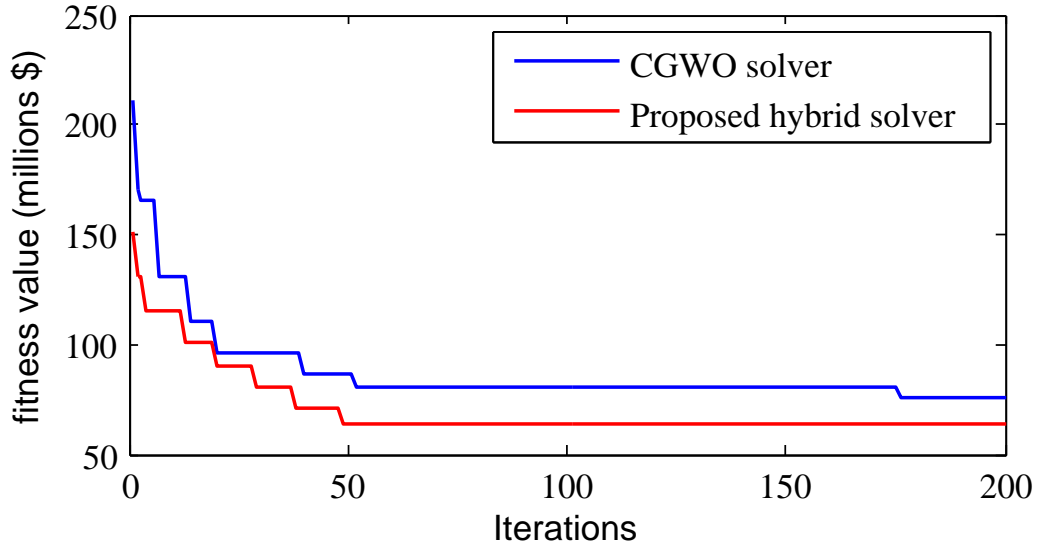


Figure 6.14: Convergence curve of different algorithms for case E

Table 6.8: Performance of proposed hybrid solver and CGWO for case E

Solver	Best value	Worst value	Average value	Standard deviation	Time (hours)
CGWO	75.654	210.54	87.31	19.11	2
Proposed hybrid	64.164	150.65	71.14	15.63	0.683

## 6.5 Conclusion

This work proposed a two-level coordinated optimization framework to optimally planning and operation of the distributed energy resources (DER) and soft open point (SOP) in an active distribution network (ADN). Besides, the proposed planning model incorporates the DNR and CVR techniques. Simulation results verify the efficiency and feasibility of the proposed planning model and hybrid optimization solver. Based on the numerical results following conclusions can be drawn

- The proposed method effectively coordinates the planning and operation schemes, which results in 64.12% reduction in total cost.
- The proposed method can improve and flatten the voltage profile without violating the permissible voltage limits.

- The proposed method can reduce energy losses and energy consumption by 64% and 1.88%, respectively, which is higher compared to the traditional planning scheme.
- The proposed method can reduce the energy not served and carbon emission by 63.71% and 13.48%, respectively, which is higher compared to the traditional planning scheme.
- The proposed solver could efficiently find the global optimum and also it reduced more than 65% of the computational time compared with CGWO.

It can be concluded that the proposed methodology can improve the economical, reliable and environmental performance of the distribution system simultaneously. Thus, it can be recommended for the DER planning scheme in an active distribution system.