

Chapter 3

Minimization of Operational Cost in Active Distribution System considering Network Reconfiguration and Soft Open Point

3.1 Introduction

Presently, electricity is a basic need for sustainable development of modern society. Therefore, energy demand has been increasing rapidly across the world. Conservation voltage reduction (CVR) is a promising technique utilized by distribution system operators (DSO) for peak demand reduction and energy savings in distribution system [60]. Traditionally, CVR operation has been conducted by OLTC transformer, switched capacitor banks (SCBs) and voltage regulator (VRs) for energy demand reduction. However, operation of these control devices is limited due to their physical constraints [138]. To cope up with increasing energy demand, existing network needs to be strengthened with the advanced operational tools in smart grid environment.

Distribution network reconfiguration (DNR) is an effective technique to improve the operation efficiency of distribution systems. Benefits of DNR operation in distribution system under different time zones has been conducted in [139]. On the other side, soft open points (SOP) are paying more attention due to flexibility of the power electronic devices in smart distribution system. SOP can provide active power flow control between the

adjacent feeders, the reactive power compensation and voltage regulation in distribution system [140].

In this regard, the proposed approach focuses on the optimally coordinated CVR operation considering traditional VVC devices (such as OLTC, SCBs and VR), DNR and SOP to minimize the operating cost as well as voltage deviations.

The main contributions of this chapter are summarized as follows

- A time series model of coordinated CVR scheme has been developed to minimize the energy demand including operating cost and eliminate voltage violations in active distribution network
- Combined impact of Volt-VAR control devices, soft open point (SOP) and distribution network reconfiguration (DNR) operation on energy demand has been studied
- Grey wolf optimization (GWO) has been modified and used for the optimal scheduling of mixed integer nonlinear programming (MINLP) problem without linearization or relaxation
- Inclusion of high penetration of DG in active distribution network considering forecast errors of PV generation and load demand
- Technical-economical-environmental benefits of proposed coordinated scheme operation has been presented
- Validation of proposed coordinated scheme on well-known 69 bus distribution system

3.2 Modelling of Soft Open Points (SOP)

Soft open points (SOP) is a flexible power electronic device, which can provide active power flow control between the adjacent feeders, the reactive power compensation and voltage regulation in distribution system. Generally, SOP devices are installed between the adjacent feeders in place of normally open points (NOP) in distribution system [45] as shown in Fig. 3.1. Due to the flexibility of power electronics devices, SOPs can be able to control the active power flow between the adjacent feeders, supply or absorb the reactive power and voltage regulation in distribution system. In this chapter, a back-to-back voltage source converter topology has been employed. Two voltage source converters

(VSC) are installed between the feeder endpoints and connected through a common dc link. These converters can provide fast control of active and reactive power at respective connected nodes. This makes the SOP device to afford flexible power control in the distribution network. The following constraints have been incorporated in the optimization process to represent the SOP in the steady state.

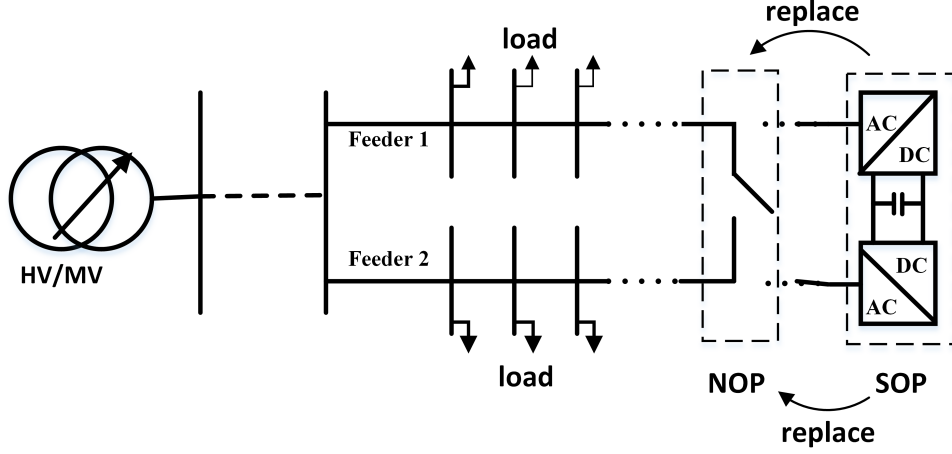


Figure 3.1: A typical SOP connected to adjacent feeder

SOP active power constraints

$$P_{i,sop}^t + P_{j,sop}^t + P_{i,sop}^{t,loss} + P_{j,sop}^{t,loss} = 0 \quad (3.1)$$

$$P_{i,sop}^{t,loss} = A_{i,sop} \sqrt{(P_{i,sop}^t)^2 + (Q_{i,sop}^t)^2} \quad (3.2)$$

$$P_{j,sop}^{t,loss} = A_{j,sop} \sqrt{(P_{j,sop}^t)^2 + (Q_{j,sop}^t)^2} \quad (3.3)$$

SOP reactive power constraints

$$Q_{i,sop}^{\min} \leq Q_{i,sop}^t \leq Q_{i,sop}^{\max} \quad (3.4)$$

$$Q_{j,sop}^{\min} \leq Q_{j,sop}^t \leq Q_{j,sop}^{\max} \quad (3.5)$$

SOP capacity constraints

$$\sqrt{(P_{i,sop}^t)^2 + (Q_{i,sop}^t)^2} \leq S_{i,sop} \quad (3.6)$$

$$\sqrt{(P_{j,sop}^t)^2 + (Q_{j,sop}^t)^2} \leq S_{j,sop} \quad (3.7)$$

The equations (3.1) – (3.3) represents the active power constraints of SOP, equations (3.4) & (3.5) represents the reactive power constraints of SOP, and equations (3.6) & (3.7) represents the capacity constraints of SOP.

3.3 Problem formulation

Utilities are more concerned towards the minimization of operating cost of distribution system, while maintaining the healthy operation. In order to achieve this, an advanced way of CVR operation has been incorporated into Volt/VAR optimization (VVO) models, where multiple devices such as OLTC, SCBs, DNR and SOPs are designed to work coordinately to minimize the total operating cost. Further, the total number of tap operation of OLTC, SCBs and RCS has been considered in optimization problem to avoid the deterioration of lifetime of these devices. The following control variables are considered in the optimization problem

- Tap position of OLTC transformer (tap^t)
- Step of Capacitor banks (st_i^t)
- Status of remote-controlled switches (RCS_m^t)
- Active ($P_{i,sop}^t$) and reactive ($Q_{i,sop}^t$) output power of soft open point (SOP) device

$$X = [tap^t, st_i^t, RCS_m^t, P_{i,sop}^t, Q_{i,sop}^t] \quad (3.8)$$

The input of the optimization model is the set of control variables as given in equation (3.8), output of the optimization model is the total operating cost of the distribution system.

3.3.1 Objective function

The objective function is formulated as minimization of total operating cost (TOC) in the distribution system as given in equation (3.9).

$$TOC = \sum_{t=1}^T \left[\begin{aligned} &\pi_{grid}^{p,t} P_{grid}^t + \pi^{tap} |tap^t - tap^{t-1}| + \sum_{i \in \Omega_{cap}} \pi^{cap} |st_i^t - st_i^{t-1}| \\ &+ \sum_{m \in \Omega_{rcs}} \pi^{rcs} |RCS_m^t - RCS_m^{t-1}| + \pi_{CO_2} P_{grid}^t + \sum_{i \in \Omega_{sop}} \pi_{grid}^{p,t} P_{i,sop}^{t,loss} \end{aligned} \right] \quad (3.9)$$

In the equation (3.9), first term ($\pi_{grid}^{p,t} P_{grid}^t$) represents the cost of energy consumption and loss, second, third and fourth terms represent the switching cost of OLTC, SCBs and RCSs respectively, the fifth term ($\pi_{CO_2} P_{grid}^t$) represents the emission cost, sixth term ($\pi_{grid}^{p,t} P_{i,sop}^{t,loss}$) represents the SOP loss cost.

3.3.2 System operational constraints

1. Active and reactive power flow constraints

$$P_{grid}^t - \sum_{i=1}^{nd} P_{i,loss}^t - \sum_{i=1}^{nd} P_{i,cons}^t + \sum_{i \in \Omega_{sop}} P_{i,sop}^t = 0 \quad (3.10)$$

$$Q_{grid}^t - \sum_{i=1}^{nd} Q_{i,loss}^t - \sum_{i=1}^{nd} Q_{i,cons}^t + \sum_{i \in \Omega_{cap}} Q_{i,cap}^t + \sum_{i \in \Omega_{sop}} Q_{i,sop}^t = 0 \quad (3.11)$$

here $P_{loss,i}^t = |I_i^t| \times R_i$; $Q_{loss,i}^t = |I_i^t| \times X_i$; where $|I_i^t| = \left(\frac{P_i^t + Q_i^t}{V_i^t} \right)^*$

2. Active ($P_{i,cons}^t$) and reactive ($Q_{i,cons}^t$) power consumption by voltage dependent loads

$$P_{i,cons}^t = P_{i,cons}^{n,t} \left(\frac{V_i^t}{V_i^{n,t}} \right)^{k_i^p} \quad (3.12)$$

$$Q_{i,cons}^t = Q_{i,cons}^{n,t} \left(\frac{V_i^t}{V_i^{n,t}} \right)^{k_i^q} \quad (3.13)$$

3. Bus voltage magnitude (V_i^t) limits

$$V_{\min} \leq V_i^t \leq V_{\max} \quad (3.14)$$

4. OLTC Transformer tap (tap^t) limits

$$a^t = 1 + tap^t \frac{\Delta tap_{step}}{100} \quad (3.15)$$

here, $tap^t \in \{tap^{\min,t}, \dots, -1, 0, 1, \dots, tap^{\max,t}\}$

5. Switched capacitor banks ($Q_{i,cap}^t$) limits

$$Q_{i,cap}^t = st_i^t \Delta q_i^{cap}; i \in \Omega_{cap} \quad (3.16)$$

Where, $st_i^t \in \{0, 1, \dots, st_i^{\max}\}$

6. Maintenance of radial structure constraint for DNR

$$\sum_{m=1}^{nbr} csw_m = nd - 1 \quad (3.17)$$

3.4 Implementation of proposed modified binary GWO (MBGWO)

The MBGWO algorithm has been employed to solve the optimization problem expressed by equations (3.10)-(3.17). The solution vector is taken as given in equation (3.18)

$$\left. \begin{aligned}
 X &= [x_{oltc}, x_{Q_{i,cap}}, x_{RCS_m}, x_{P_{i,sop}}, x_{Q_{i,sop}}] \\
 x_{oltc} &= [x_{oltc}^1, x_{oltc}^2, \dots, x_{oltc}^{24}] \\
 x_{Q_{i,cap}} &= [x_{Q_{i,cap}}^1, x_{Q_{i,cap}}^2, \dots, x_{Q_{i,cap}}^{24}] ; i \in \Omega_{cap} \\
 x_{RCS_m} &= [x_{RCS_m}^1, x_{RCS_m}^2, \dots, x_{RCS_m}^{24}] ; m \in \Omega_{rcs} \\
 x_{P_{i,sop}} &= [x_{P_{i,sop}}^1, x_{P_{i,sop}}^2, \dots, x_{P_{i,sop}}^{24}] ; i \in \Omega_{sop} \\
 x_{Q_{i,sop}} &= [x_{Q_{i,sop}}^1, x_{Q_{i,sop}}^2, \dots, x_{Q_{i,sop}}^{24}] ; i \in \Omega_{sop}
 \end{aligned} \right\} \quad (3.18)$$

3.5 Simulation results and discussions

The 69 bus distribution system has been chosen for the case study. The detailed line data and load data has been taken from [141]. The original system does not have any OLTC and SCBs, and TVVD loads. Modifications in the original test system has been done to accommodate these devices explained as under.

3.5.1 Modified 69 bus system

In modified 69 bus system, it is assumed that OLTC transformer is connected between substation and node 1 and five SCBs are installed at buses 9, 18, 22, 57 and 62 respectively as shown in Fig. 3.2. The OLTC transformer can vary the substation secondary side voltage in the range of with 16 tap positions $\{-8,-7,-1,0,1,2,,7,8\}$, Change in each step would be 0.625%. Each SCBs can vary from 0 to 600 kVAR in four switching steps causing change in each switching step by 150 kVAR. Table 3.1 shows active (k_p) and reactive (k_q) power exponents of different types of customers such as industrial, residential and commercial respectively and their node locations on the distribution system. cost parameters are given in Table 3.2. Hourly load variations and price of energy from grid has been taken from [142] and plotted in Fig. 3.3. Simulations have been carried out under MATLAB environment.

Algorithm 4 Proposed MBGWO algorithm for minimization of total operating cost

- 1: **Input:** feed the distribution system data, set the MBGWO parameters such as population size (N_w) and maximum number of iterations ($iter^{max}$), k_1, k_2 coefficients, $w_{initial}$ & w_{final} as given Appendix A.1
 - 2: divide the agent dimension to accommodate the control variables (tap position of OLTC transformer, steps of SCBs, status of remote-controlled switches (RCS) and active and reactive power of SOPs) as given in equation (3.18)
 - 3: **repeat**
 - 4: initialise N_w agents randomly within allowable limit to construct a population
 - 5: check for radial topology of the distribution network using BBIM technique [126]. If YES goto 6, otherwise re-initialized population, then follow 5.
 - 6: conduct power flow analysis and evaluate the value of fitness function corresponding to each agent using (3.1) and find the W_α , W_β , and W_δ
 - 7: **while** $iter \leq iter^{max}$ **do**
 - 8: **for** each agent **do**
 - 9: update current agent position
 - 10: **end for**
 - 11: update the values of a , A , and C .
 - 12: evaluate the value of fitness function using (3.1)
 - 13: **if** system constraints (3.10) to (3.17) are satisfied **then**
 - 14: update the W_α , W_β , and W_δ
 - 15: **else**
 - 16: discard the result
 - 17: **end if**
 - 18: **end while**
 - 19: terminate iterative process and accept final wolf position as solution. Accept the settings of control devices
 - 20: **until** $t=T$
 - 21: **Output:** total operating cost of a distribution system over a specific time (T)
-

Table 3.1: value of k_p and k_q and their location

Load type	k_p	k_q	Node location on distribution system
Industrial	0.18	6.00	1-3,28-35
Residential	1.04	4.19	4-27,53-69
Commercial	1.5	3.15	36-52

Table 3.2: cost parameters

Parameters	Cost
Switching cost of OLTC tap	\$1.4/time [24]
Switching cost of SCB	\$0.24/time [24]
Switching cost of RCS	\$1/time [30]
Emission rate	0.4 tCO ₂ e/MWh [31]
Emission price	\$6.84/tCO ₂ e [31]

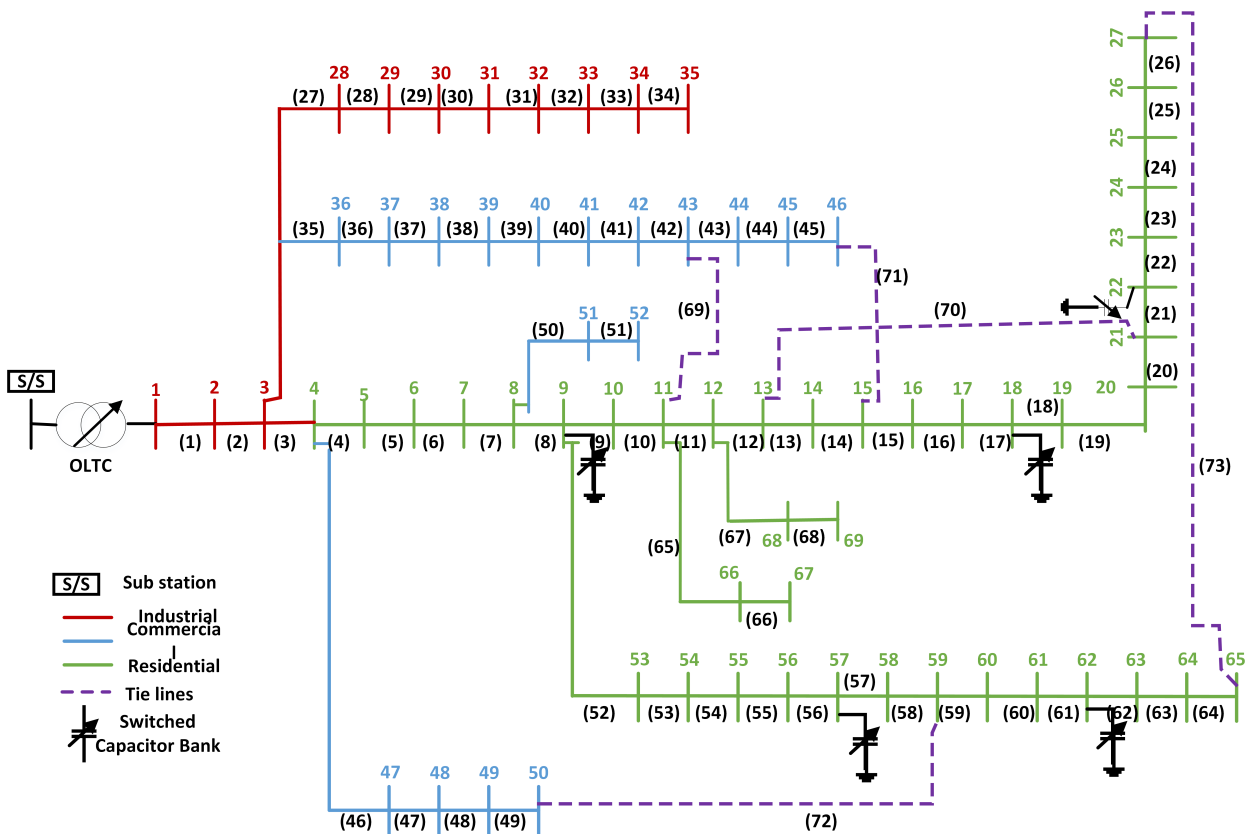


Figure 3.2: Modified 69 bus system

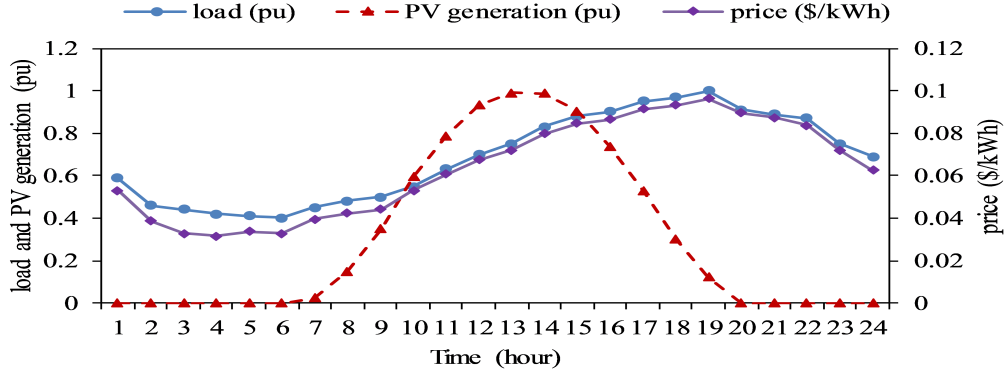


Figure 3.3: Typical Load, grid price and photovoltaic generation output

The parameters of GWO such as population size and number of iterations are taken as 50 and 100 respectively. In order to show the impact of combined operation of DNR and SOP operation on distribution system considering CVR operation, seven cases have been studied as under

- Case 1: Without enabling the operation of DNR, CVR and SOP
- Case 2: With enabling optimal operation of DNR alone (method in [14])
- Case 3: With enabling optimal operation of CVR alone (method in [53])
- Case 4: With enabling optimal operation of both DNR and CVR (method in [127])
- Case 5: With enabling optimal operation of SOP alone (method in [102])
- Case 6: With enabling optimal operation of both CVR and SOP (proposed method 1)
- Case 7: With enabling optimal operation of CVR, DNR and SOP (proposed method 2)

3.5.1.1 Case 1:

In this case, operation of DNR and SOP has not been considered. The tap position of OLTC is kept at 5, such that to maintain the minimum voltage of the system above the lower voltage limits (i.e. 0.95 pu). Status of SCBs in off state and set of opened RCS are 69, 70, 71, 72, 73. The energy demand taken from grid has been recorded as 64.753 MWh,

in which share of energy consumed and losses are about 62.524 MWh and 2.229 MWh respectively. The total operating cost of distribution has been calculated as \$4726.15. This can also find in second column of Table 3.3.

3.5.1.2 Case 2:

In this case, only optimal operation of DNR has been considered in order to show the impact of DNR operation in smart distribution system on total operating cost. Optimal DNR operation has been performed by MBGWO algorithm. During the hour 1:00 to 12:00, RCS 14, 58, 61 have been opened, corresponding RCS {71, 72, 73} have been closed in order to maintain radial network topology. Similarly, during 13:00 to 24:00, opened RCS are {57, 63}, corresponding closed RCS are 58, 61. Total number of switching operation of RCS is 10, which can be seen in Table 3.4 under case 2. The energy demand taken from grid has been reduced to 64.303 MWh (i.e. 0.694% reduction compared to case

Table 3.3: summary of results under different cases

Parameters		Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Energy demand (MWh)		64.753	64.303	62.146	61.197	64.61	61.597	60.239
Energy demand reduction (%)		—	0.694	4.02	5.49	0.22	4.87	6.97
Energy loss (MWh)		2.229	1.103	1.673	1.018	1.99	1.567	0.818
Energy loss reduction (%)		—	50.51	24.94	54.32	10.7	29.69	63.3
Energy consumed (MWh)		62.524	63.2	60.473	60.179	62.62	60.03	59.421
Energy consumed reduction (%)		—	-1.08	3.28	3.75	-0.153	3.99	4.96
CO2 emission (tCO2e)		25.9	25.72	24.85	24.47	25.844	24.63	24.09
Minimum Voltage (pu)		0.9505	0.978	0.95	0.95	0.957	0.95	0.95
Maximum voltage (pu)		1.031	1.031	1.013	1	1.031	1.004	0.982
SOP losses (MWh)		0	0	0	0	0.127	0.346	0.364
Energy consumed (\$)		4381	4432	4259	4235	4389	4225	4180
Energy loss (\$)		168	83	126	77	147.01	118.01	60.81
Co2 emission cost (\$)		177.15	175.92	169.97	167.37	176.77	168.46	164.77
switching operation cost	OLTC tap	0	0	18.2	12.6	0	14	15.4
	SCBs	0	0	15.6	9.12	0	14.88	9.6
	RCSs	0	10	0	14	0	0	14
SOP losses cost (\$)		0	0	0	0	8	21.8	22.93
Total operating cost (\$)		4726.15	4700.92	4588.77	4515.09	4720.78	4562.15	4467.51
Total cost savings (\$)		—	25.23	137.38	211.06	5.37	164	258.64

1), even though energy consumed has been increased to 63.2 MWh (i.e. 1.08% increment compared to case 1) and energy losses has been reduced to 1.103 MWh (i.e. 50.51% reduction compared to case 1). The total operating cost of system reduced to \$ 4700.92, which results in saving about \$ 25.23, although operating cost of RCS has been considered as seen in third column of Table 3.3.

Thus, optimal operation of DNR is helpful to reduce the energy demand and energy losses up to 0.694% and 50.51% respectively, which results in minimize the operating cost of the system by \$25.23, even though 1.08% increase in energy consumption than case 1. This happens because of increase in energy consumption has been overcome by energy losses reduction in the network.

3.5.1.3 Case 3:

In this case, with the help of MBGWO algorithm, optimal CVR operation has been conducted using traditional VVC devices (i.e. OLTC taps and SCBs). Obtained optimal setting of OLTC taps and SCBs have been depicted in Table 3.4. Total number of switching operation of OLTC taps and SCBs are 13 and 65 respectively, which can be seen in Table 3.4 under case 3. The energy demand taken from grid has been reduced to 62.146 MWh (i.e. 4.02% reduction compared to case 1), in which the energy consumed and losses are reduced to 60.473 MWh (i.e. 3.28% reduction compared to case 1) and 1.673 MWh (i.e. 24.94% reduction compared to case 1) respectively. The total operating cost has been reduced to \$ 4588.77, which results in saving about \$137.38, although operating cost of VVC devices has been considered as seen in fourth column of Table 3.3.

Thus, optimal operation of CVR is helpful to reduce the energy demand, energy consumption and energy losses up to 4.02%, 3.28% and 24.94 % respectively, which results in minimize the operating cost of the system by \$ 137.38.

Table 3.4: status of RCS, OLTC and SCBs under case 2 to case 4

Hour	Case 2		Case 3					Case 4						RCS				
	RCS		OLTC	CB #9	CB #18	CB #22	CB #57	CB #62	OLTC	CB #9	CB #18	CB #22	CB #57	CB #62	O	C		
	O	C													O	C		
1	14, 58, 61	71, 72, 73	-3	1	2	0	2	4	-3	2	0	0	0	0	13, 57, 62	71, 72, 73		
2			-4	0	1	1	1	4	-4	0	0	0	2	0				
3			-4	1	0	0	1	4	-4	0	0	0	0	0				
4			-4	1	0	0	1	4	-5	0	0	0	0	0				
5			-5	0	0	0	2	4	-5	0	0	0	0	0				
6			-5	0	1	0	1	4	-5	0	0	0	0	0				
7			-4	2	0	0	1	4	-4	0	0	0	2	0				
8			-4	0	2	0	1	4	4	0	0	0	2	0				
9			-3	0	1	1	1	4	-4	2	0	0	0	0				
10			-3	1	2	0	1	4	-4	2	0	0	2	0				
11			-2	1	2	0	2	4	-3	0	0	0	2	0				
12			-2	2	0	0	4	4	-2	2	0	0	0	0				
13	57, 63	58, 61	-1	1	2	0	4	4	-2	1	0	0	1	0	14, 58, 63	13, 57, 62		
14			0	2	2	0	4	4	-1	2	0	0	1	0				
15			0	4	0	1	4	4	-1	2	0	0	0	0				
16			1	4	2	0	4	4	-1	0	0	0	0	0				
17			1	4	2	0	4	4	0	0	0	0	0	0				
18			2	4	2	0	4	4	0	0	0	0	0	2				
19			2	4	2	0	4	4	0	0	0	0	0	0				
20			1	4	2	0	4	4	-1	0	0	0	0	0				
21			0	4	2	0	4	4	-1	0	0	0	0	0				
22			0	4	0	1	4	4	-1	2	0	0	0	0				
23			-1	0	2	0	4	4	-2	2	0	0	1	0			62	61
24			-2	2	0	1	4	4	-2	0	0	0	2	0				
TNS	10		13	20	24	9	8	4	9	18	0	0	16	4	14			
			65					38										

3.5.1.4 Case 4:

In this case, both CVR and DNR operation has been conducted. Optimal settings of OLTC taps, SCBs and RCSs obtained by MBGWO algorithm and depicted under case 4 in Table 3.4. Total number of switching operation of OLTC taps, SCBs and RCSs are 9, 38 and 14 respectively. The energy demand taken from grid has been reduced to 61.197 MWh (i.e. 5.49% reduction compared to case 1), in which the energy consumed and losses are reduced to 60.179 MWh (i.e. 3.75% reduction compared to case 1) and 1.018 MWh (i.e. 54.32% reduction compared to case 1) respectively. The total operating cost saving has been reduced to \$ 4515.09, which results in saving about \$211.06, although operating cost of VVC devices and DNR have been considered as seen in fifth column of Table 3.3. Thus, optimal operation of both CVR and DNR is helpful to reduce the energy demand, energy consumption and energy losses up to 5.49%, 3.75% and 54.32 % respectively, which results in minimize the operating cost of the system by \$211.06.

3.5.2 Impact of soft open point

In 69 bus system, the normal open point (NOP) between node 27 and 65, has been replaced by SOP as seen in Fig. 3.4, in order to demonstrate the impact of SOP operation in distribution system. The capacity of SOP has been taken as 500 kVA. The lower and upper limit of reactive power has been considered as -300 kVAR and 300 kVAR. The loss coefficient of each VSC in SOP is taken as 0.02 [24]. The coefficient of operation and maintenance cost is taken as 0.01 [24].

Here, case 5 to case 7 demonstrates the performance of SOP alone and combined with DNR and CVR operation.

3.5.2.1 Case 5:

In this case, only SOP operation has been conducted. Optimal active and reactive power scheduling of SOP obtained by MBGWO algorithm and depicted in Fig. 3.5. The energy demand taken from grid has been reduced to 64.61 MWh (i.e. 0.22% reduction compared to case 1), in which the energy consumed has been increased to 62.62 MWh (i.e. 0.153% increment compared to case 1) and energy losses has been reduced to 1.99 MWh (i.e. 10.7% reduction compared to case 1). The total operating cost saving has been reduced

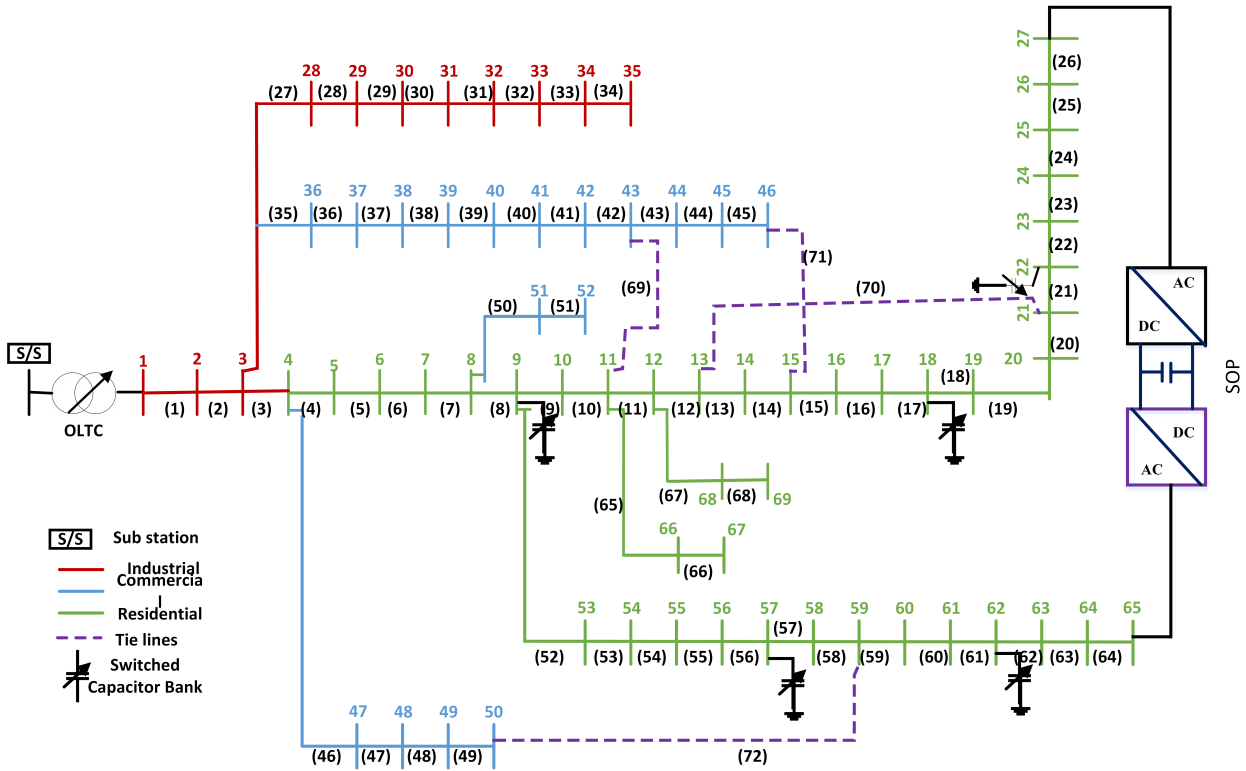


Figure 3.4: Modified 69 bus system with SOP

to \$4720.78, which results in saving about \$5.37 as found in sixth column of Table 3.3.

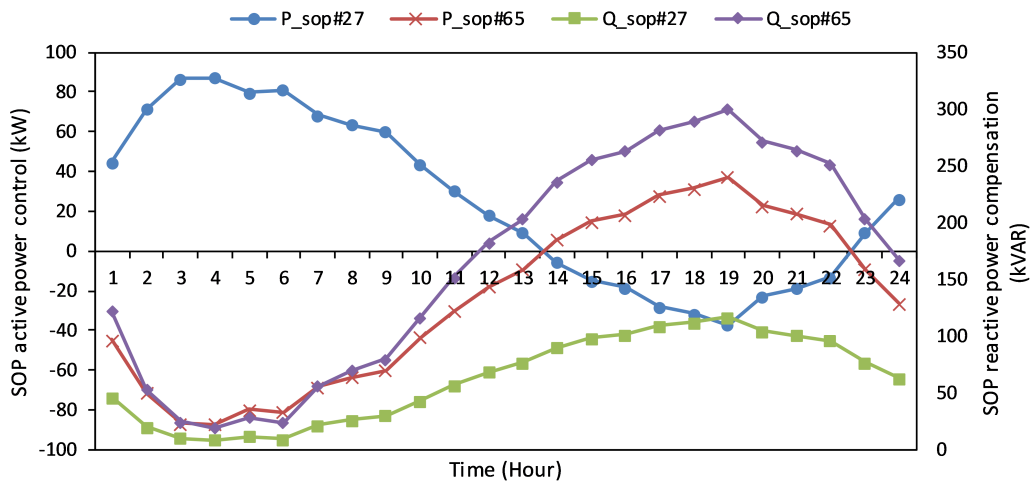


Figure 3.5: Active and reactive power scheduling of SOP-27 and SOP-65 under case 5

Thus, optimal operation of SOP is helpful to reduce the energy demand and energy losses up to 0.22% and 10.7% respectively, which results in minimize the operating cost of the system by \$5.37, even though 0.153% increase in energy consumption than case 1. This happens because of increase in energy consumption has been overcome by energy

losses reduction in the network.

3.5.2.2 Case 6:

In this case, both CVR and SOP operation has been conducted. Optimal active and reactive power scheduling of SOP obtained by MBGWO algorithm and depicted in Fig. 3.6. Optimal setting of OLTC taps and SCBs have been depicted in Table 3.5. Total number of switching operation of OLTC taps, and SCBs are 10 and 62 respectively. The energy demand taken from grid has been reduced to 61.597 MWh (i.e. 4.87% reduction compared to case 1), in which the energy consumed and losses are reduced to 60.03 MWh (i.e. 3.99% reduction compared to case 1) and 1.567 MWh (i.e. 29.69% reduction compared to case 1) respectively. The total operating cost saving has been reduced to \$ 4562.15, which results in saving about \$ 164, although CVR operation has been considered as seen in seventh column of Table 3.3.

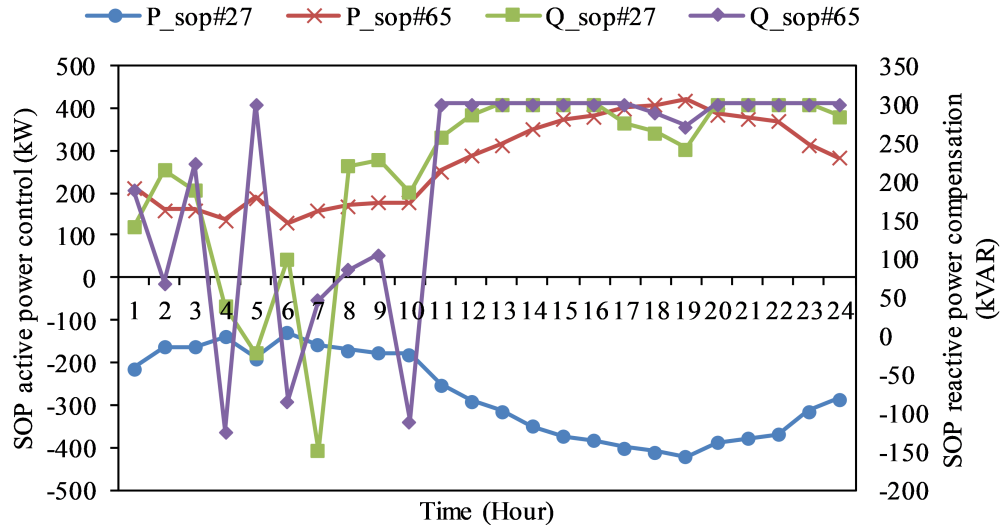


Figure 3.6: Active and reactive power scheduling of SOP-27 and SOP-65 under case 6

Thus, optimal operation of both CVR and SOP is helpful to reduce the energy demand, energy consumption and energy losses up to 4.87%, 3.99% and 29.69 % respectively, which results in minimize the operating cost of the system by \$164.

3.5.2.3 Case 7:

In this case, CVR, DNR and SOP operation has been conducted. Optimal active and reactive power scheduling of SOP obtained by MBGWO algorithm and depicted in Fig. 3.7. Optimal setting of OLTC taps, SCBs and RCSs have been depicted in Table 3.5. Total number of switching operation of OLTC taps, SCBs and RCSs are 11, 40 and 14 respectively. The energy demand taken from grid has been reduced to 60.239 MWh (i.e. 6.97% reduction compared to case 1), in which the energy consumed and losses are reduced to 59.421 MWh (i.e. 4.96% reduction compared to case 1) and 0.818 MWh (i.e. 63.3% reduction compared to case 1) respectively. The total operating cost saving has been reduced to \$4467.51, which results in saving about \$258.64, although CVR and DNR operation have been considered as seen in eighth column of Table 3.3.

Thus, optimal operation of CVR, DNR and SOP is helpful to reduce the energy demand, energy consumption and energy losses up to 6.97%, 4.96% and 63.3% respectively, which results in minimize the operating cost of the system by \$258.64.

Table 3.5: status of RCS, OLTC and SCBs under case 6 and case 7

Hour	Case 6						Case 7						RCS		
	OLTC	CB #9	CB #18	CB #22	CB #57	CB #62	OLTC	CB #9	CB #18	CB #22	CB #57	CB #62	O	C	
	1	-4	0	0	1	0	4	-7	0	0	0	0	4	14, 56, 61	71, 72, 73
2	-5	0	0	0	0	4	-7	0	0	0	0	4			
3	-5	0	0	0	4	0	-7	0	2	0	0	4			
4	-5	3	0	0	0	4	-7	0	1	0	0	4			
5	-5	0	0	2	0	0	-6	0	0	0	0	4			
6	-5	0	0	0	4	2	-5	0	0	2	0	4			
7	-5	0	0	3	0	4	-4	0	0	0	0	4			
8	-5	0	0	2	0	4	-7	0	0	0	0	4			
9	-4	0	0	1	0	4	-7	0	0	0	0	4			
10	-4	0	0	0	4	4	-7	0	1	0	0	4			
11	-3	0	0	0	4	0	-6	1	1	0	2	4			
12	-2	0	0	0	4	0	-6	0	0	1	0	4			
13	-2	0	0	0	4	0	-5	0	1	0	0	4	13, 58, 63	14, 56, 61	
14	-1	0	0	0	4	0	-5	0	0	0	0	4			
15	-1	0	0	0	4	0	-4	0	0	3	0	4			
16	-1	0	0	0	4	0	-4	0	0	0	0	4			
17	0	0	0	0	4	0	-3	0	0	0	0	4			
18	0	0	0	0	4	0	-3	0	0	0	0	4			
19	1	0	0	0	4	0	-3	0	0	0	0	4			
20	0	0	0	0	4	0	-4	0	0	0	0	4			
21	-1	0	0	0	4	0	-4	0	0	0	0	4			
22	-1	0	0	0	4	0	-4	0	0	3	0	4			
23	-2	0	0	0	4	0	-5	0	1	0	0	4	61	63	
24	-2	0	0	0	4	0	-6	0	0	2	0	4			
TNS	10	6	0	12	20	24	11	2	10	20	4	4	14		
		62						40							

3.5.3 Comparative analysis of different cases:

In this section, comparison of different cases with respect of various parameters such as voltage profile, active power losses, energy demand, energy consumption, energy losses, carbon emissions and totals operating cost and savings has been described.

3.5.3.1 Effect of voltage profile of the system

The voltage behaviors of the system under different cases at 19th hour (peak hour which can be seen from Fig. 3.3) have been drawn in Fig. 3.8. It can be observed that voltage profile of the system has been brought to lower range of the permissible limits; thereby energy consumption has been reduced due to dependency of loads on voltage. Among all cases, case 7 maintains lower range voltages due to CVR with support of both SOP and DNR operation and gains maximum reduction of energy consumption i.e. 4.96% (which can be seen in eighth column of Table 3.3).

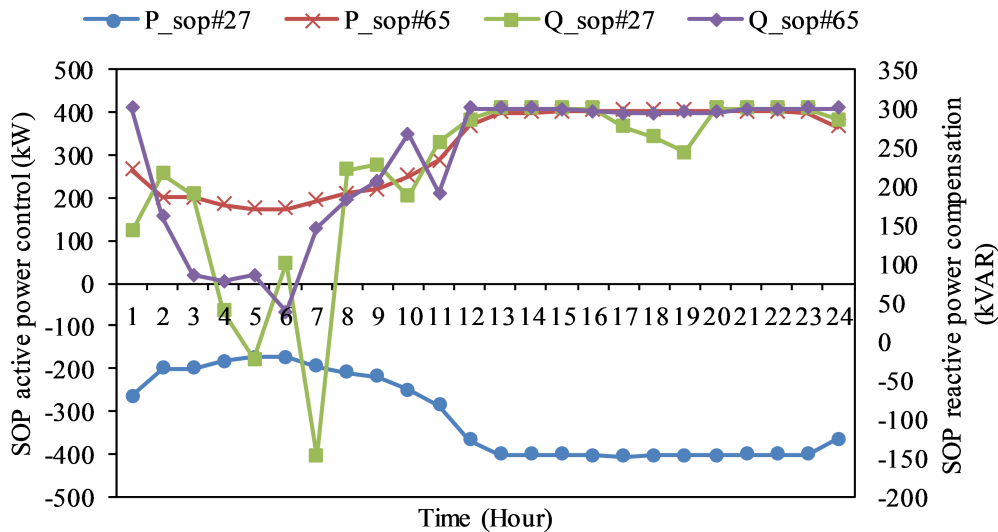


Figure 3.7: Active and reactive power scheduling of SOP-27 and SOP-65 under case 7

3.5.3.2 Effect of active power losses

Fig. 3.9 shows power loss of the network over 24 hours under different cases. It can be observed that cases performing DNR operation alone (or) combined, achieves minimum active power losses, which can be seen case 2, case 4 and case 7. It can also noticed that active power losses has been increased due to the CVR operation as seen in case 3 and

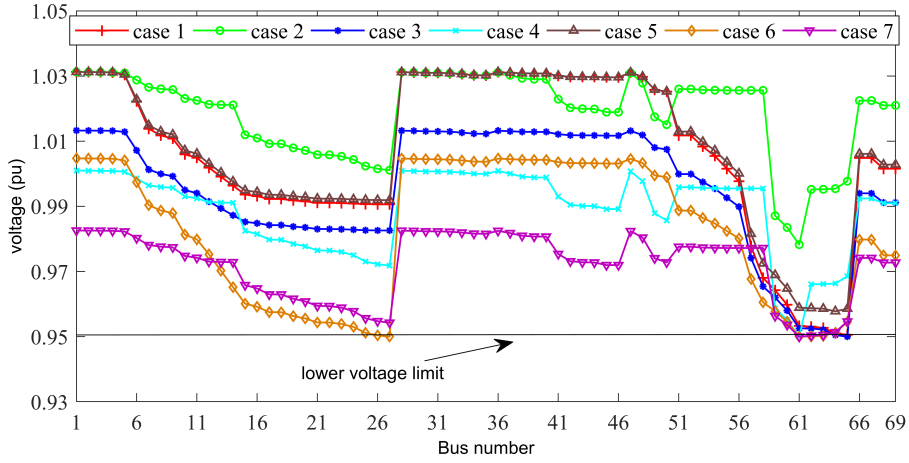


Figure 3.8: voltage profile of 69 bus system under different cases

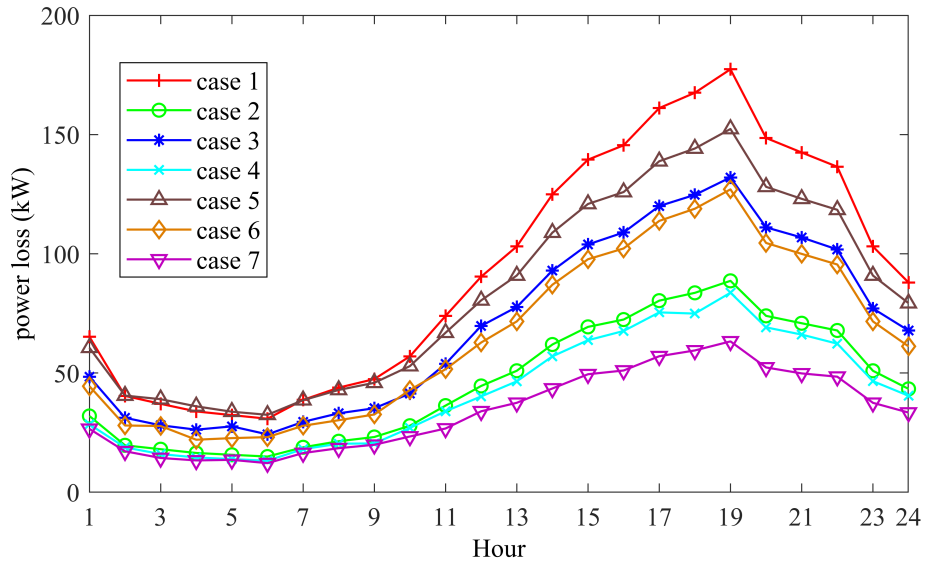


Figure 3.9: active power losses over a typical day under different cases

case 6. However, which is less than case 1. Among all cases, case 7 achieve maximum power loss reduction over 24 hour period.

3.5.3.3 Effect of energy demand, energy consumption and energy losses

Fig. 3.10 shows total energy demand of the system, in which share of energy consumption and losses has been differentiated under different cases. Among all cases, case 7 achieves minimum energy demand about 60.239 MWh, in which the amount of energy consumed and losses are about 59.421 MWh and 0.818 MWh respectively. The percentage reduction of energy demand with respect to case 1 has been plotted in Fig. 3.10, The percentage

reduction of energy consumption and energy losses have been plotted in Fig. 3.11. Among all cases, case 7 yields maximum percentage reduction of energy demand, energy consumption and losses i.e. 6.97%, 4.96% and 63.3% respectively. As seen Fig. 3.11, the energy consumption in case 2 and case 5 has been increased by 1.08% and 0.153% respectively with respect to case 1. This happens because of increase in voltage causing increase in energy consumption due to dependency of loads on voltage. Further, no CVR operation has been performed in these cases (i.e. case 2 and case 5). However, the energy demand has been reduced by 0.694% and 0.22% in case 2 and case 5 respectively as seen in Fig. 3.10. This happens because of reduction of energy losses by 50.51% and 10.7% in case 2 and case 5 (as seen in Fig. 3.11) respectively overcome the increase in energy consumption in the network.

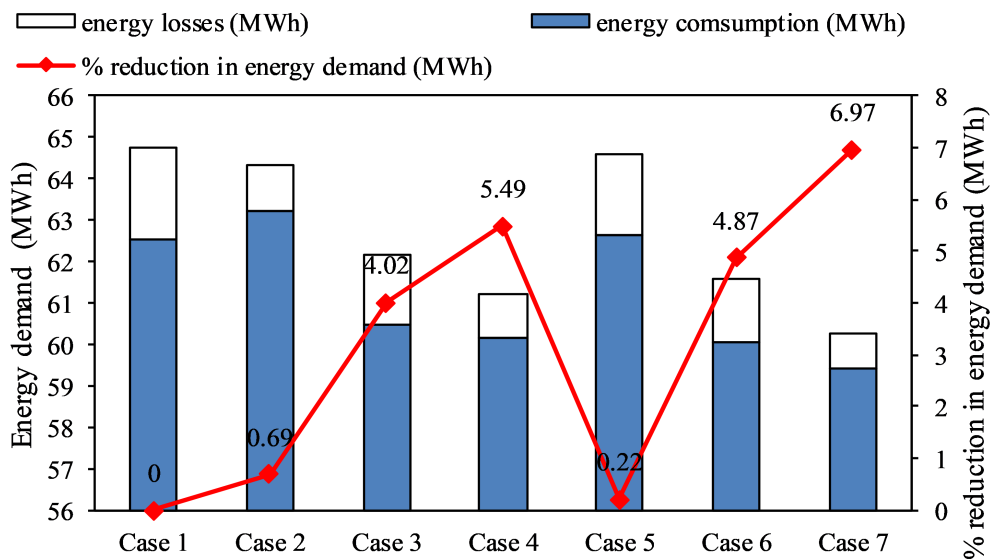


Figure 3.10: energy demand of 69 bus system under different cases

3.5.3.4 Effect of Carbon emissions

Fig. 3.12 shows carbon emissions of the system under different cases. It can be observed that least carbon emissions (i.e. 24.09 tCO₂e) are found in case 7. This is due to the maximum reduction of energy demand in case 7.

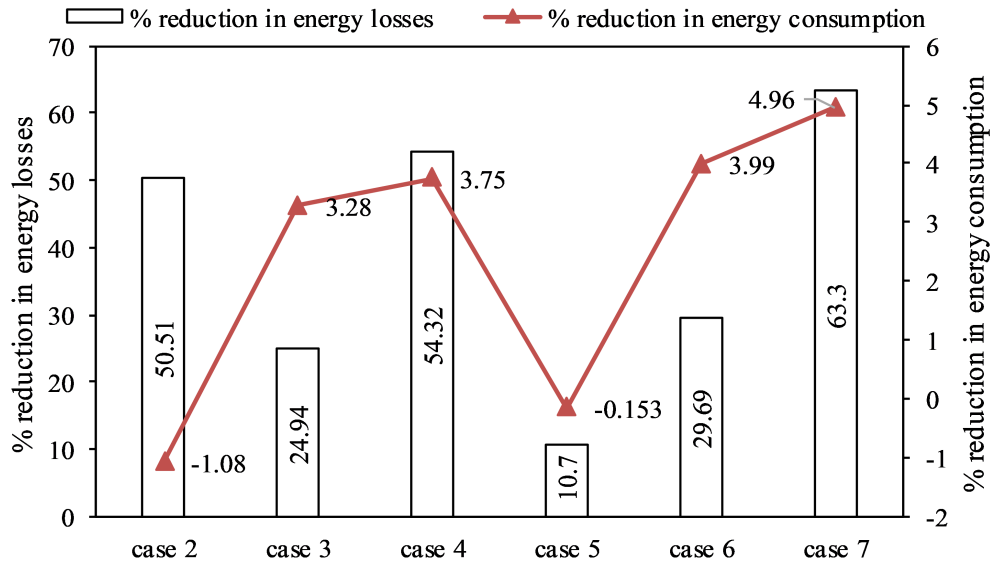


Figure 3.11: Percentage reduction in energy consumption and losses under different cases w.r.t case 1

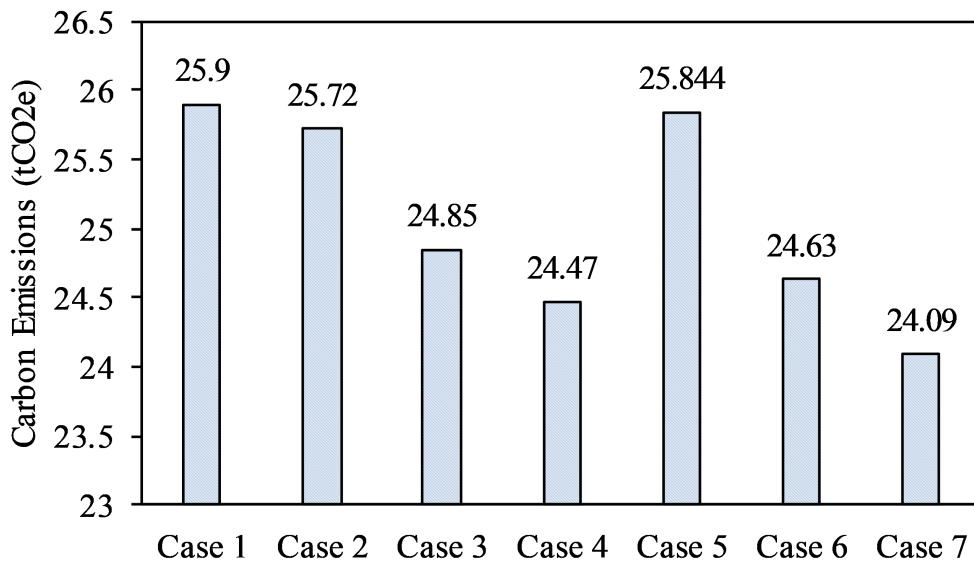


Figure 3.12: carbon emissions of the system under different cases

3.5.3.5 Effect of total operating cost and savings

The total operating costs of different cases have been plotted in Fig. 3.13. It can be observed that, case 1 has been operating at maximum cost i.e. \$4726.15, whereas case 7 has minimum operating cost i.e. \$4467.51. Further, savings in operating cost with respect to case 1 has been plotted in Fig. 3.13. It can be observed that case 7 achieves maximum cost savings about \$258.64.

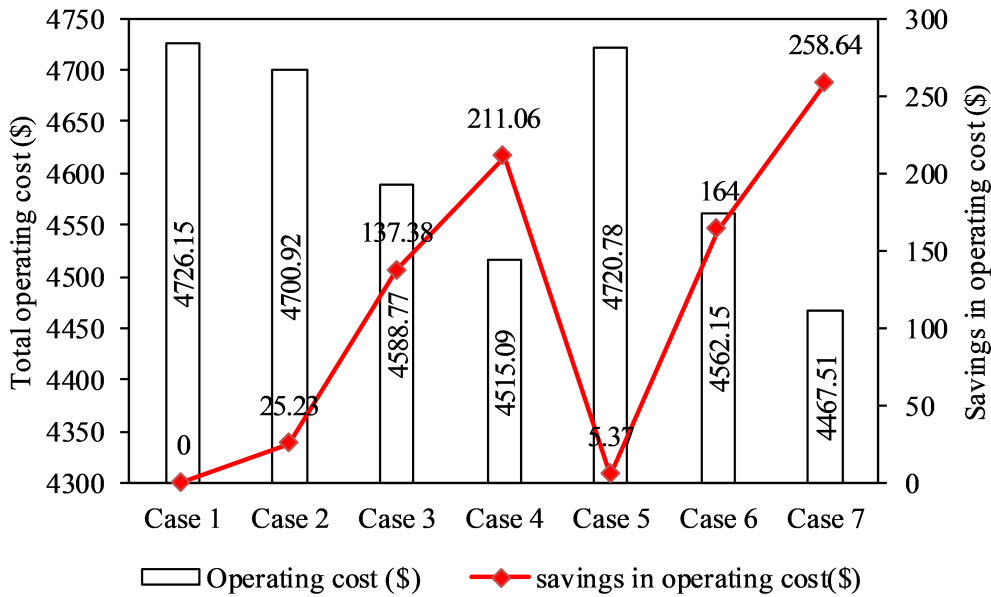


Figure 3.13: Total operating cost of 69 bus system under different cases

3.5.4 Performance of modified grey wolf optimization (MBGWO)

The performance of proposed MBGWO has been tested on different cases. The population size and maximum iterations of this system has been taken as 50 and 100 respectively. The number of runs of algorithm is 10. The convergence pattern of MBGWO for different cases has been plotted in Fig. 3.14. It can be observed that MBGWO convergence to minimum i.e. \$4700.92, \$4588.77, \$4515.09, \$4720.78, \$4562.15 and \$4467.51 for case 2 to case 7 respectively. Among all cases, case 7 achieved minimum operating cost i.e. \$4467.51, which is due to flexibility of distribution network considering CVR, DNR and SOP operation.

The performance of conventional GWO (CGWO) and MBGWO has been tested on case 7 only, due to its complexity. The convergence pattern of CGWO and MBGWO has

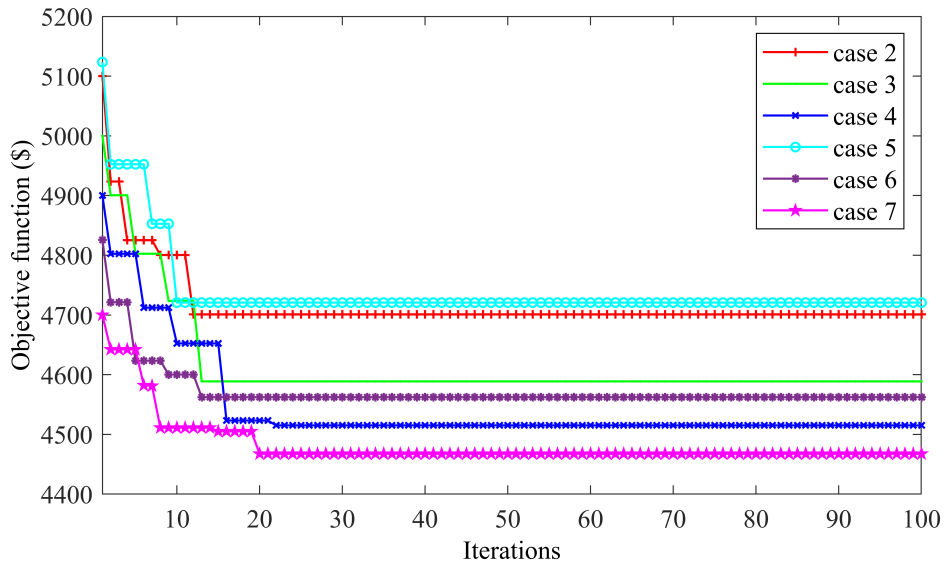


Figure 3.14: Convergence pattern of MBGWO under different cases

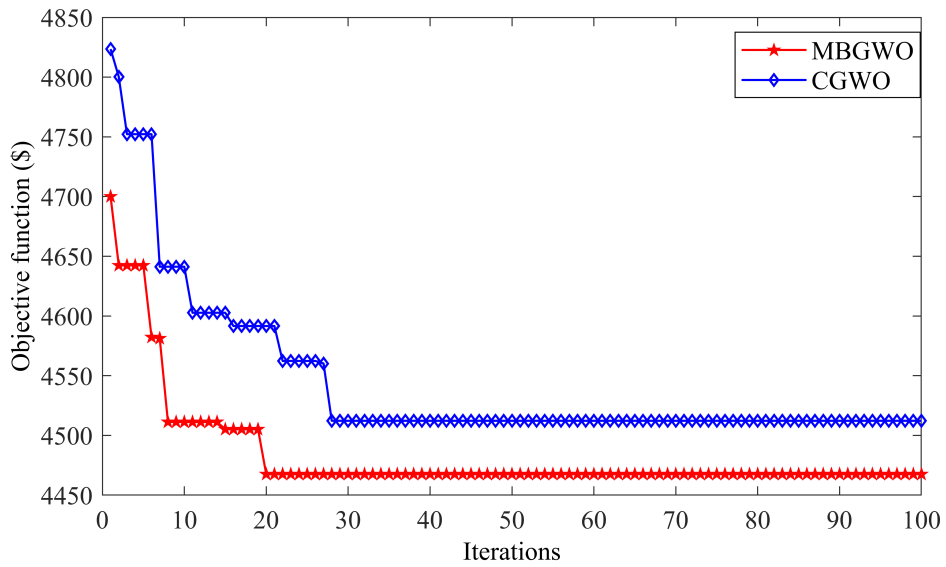


Figure 3.15: Convergence pattern of CGWO and MBGWO under case 7

Table 3.6: Results of CGWO and proposed MBGWO

Algorithm	Objective function (\$)				Convergence Time (s)
	best (\$)	mean (\$)	worst(\$)	standard deviation (\$)	
CGWO	4512.23	4545.25	4823.52	68.26	325
MBGWO	4467.51	4484.05	4700.02	44.43	296

been plotted in Fig. 3.15. It can be observed that MBGWO convergence to minimum value i.e. \$4467.51, whereas CGWO is \$4512.23. Table 3.6 shows the best, mean and the worst values of CGWO and proposed MBGWO. It can be observed that MBGWO dominates the CGWO in all aspects. It can say that, modifications in diversification-intensification balance and binary updating mechanism helpful for MBGWO algorithm to reach near optimum results than CGWO algorithm.

3.5.5 Cost benefit analysis of SOP

In this section, the cost-benefit analysis of SOP has been studied. The investment and maintenance cost of SOP [24] have been given in equation (27) and (28) respectively.

$$C_{sop}^{inv} = \sum_{i \in \Omega_{sop}} c_{sop} S_{i,sop} \quad (3.19)$$

$$C_{sop}^{main} = \eta \sum_{i \in \Omega_{sop}} c_{sop} S_{i,sop} \quad (3.20)$$

Where c_{sop} is the investment cost of SOP, $S_{i,sop}$ denotes the capacity of SOP at i th node and is the coefficient of annual maintenance cost. The annual total operating cost (ATOC) of the distribution system can be calculated by using equation (29)

$$ATOC = 365 \times \sum_{t=1}^T \left[\begin{aligned} & \pi_{grid}^{p,t} P_{grid}^t + \pi^{tap} |tap^t - tap^{t-1}| + \sum_{i \in \Omega_{cap}} \pi^{cap} |st_i^t - st_i^{t-1}| + \\ & \sum_{m \in \Omega_{rcs}} \pi^{rcs} |RCS_m^t - RCS_m^{t-1}| + \pi_{CO_2} P_{grid}^t + \sum_{i \in \Omega_{sop}} \pi_{grid}^{p,t} P_{i,sop}^{t,loss} \end{aligned} \right] \quad (3.21)$$

The following two scenarios have been studied to show the benefits of SOP installation in modified 69 bus active distribution network (ADN) as given in Fig. 3.4.

- Scenario 1: ADN without SOP installation
- Scenario 2: ADN with SOP installation

Table 3.7 shows that the scenario 2 has better economic benefits than the scenario 1. Even though after inclusion of switching operating cost and SOP maintenance cost, the annual total cost of system operation has been reduced to \$ 1623810, which results in savings of about \$ 24210 as seen in Table 3.7. The investment cost of installed SOP device between node 27 and 65 is about \$ 154400. In order to cover the SOP investment cost, scenario 2 takes 6.377 years. This time period could be reduced in future due to the rapid decreasing in the price of power electronics devices.

Table 3.7: Results of cost benefit analysis of SOP

Parameters	Scenario 1	Scenario 2	Cost reduction
Annual cost of energy consumption (\$)	1545780	1525700	20080
Annual cost of power losses (\$)	28110	22190	5920
Annual cost of switching operation (\$)	13040	14240	-1200
Annual cost of Co2 emission (\$)	61090	60140	950
Annual SOP maintenance cost (\$)	0.00	1540	-1540
Annual total cost of system operation (\$)	1648020	1623810	24210

3.5.6 Impact of high penetrated photovoltaic (PV)-based distributed generation

In order to show the performance of proposed coordinated scheme in presence of high penetrated of distributed generation (DG). It is assumed that photovoltaic (PV)-based DG has installed at buses 15, 27 and 65 with the capacity of 0.8, 1.0 and 0.4 MVA respectively in modified 69 bus distribution system (i.e. 60 % penetration of DG). The following constraints have been incorporated in optimization model to represent the penetration of the DG

1. The active and reactive power flow constraints equation (11) and (12) have been modified as equation (30) and (31) respectively in order to incorporate the DG penetration

$$P_{grid}^t + \sum_{i \in \Omega_{DG}} P_{i,DG}^t - \sum_{i=1}^{nd} P_{i,loss}^t - \sum_{i=1}^{nd} P_{i,cons}^t + \sum_{i \in \Omega_{sop}} P_{i,sop}^t = 0 \quad (3.22)$$

$$Q_{grid}^t + \sum_{i \in \Omega_{DG}} Q_{i,DG}^t - \sum_{i=1}^{nd} Q_{i,loss}^t - \sum_{i=1}^{nd} Q_{i,cons}^t + \sum_{i \in \Omega_{cap}} Q_{i,cap}^t + \sum_{i \in \Omega_{sop}} Q_{i,sop}^t = 0 \quad (3.23)$$

2. DG operation constraints: The equation (32) shows the active power ($P_{i,DG}^t$) generated by DGs is equal to the forecasted value ($P_{i,DG}^{t,f}$). Equation (33) represents the reactive power ($Q_{i,DG}^t$) generated using power factor angle ($\phi_{i,DG}$) of DGs. Equation (34) represents the DGs capacity ($S_{i,DG}$) constraint.

$$P_{i,DG}^t = P_{i,DG}^{t,f} \quad (3.24)$$

$$Q_{i,DG}^t = P_{i,DG}^t \tan \phi_{i,DG} \quad (3.25)$$

$$\sqrt{(P_{i,DG}^t)^2 + (Q_{i,DG}^t)^2} \leq S_{i,DG} \quad (3.26)$$

The following two scenarios have been studied to show the impact of high penetrated PV-based DG in active distribution network (ADN) on proposed coordinated scheme.

- Scenario 1: ADN in presence of high penetrated PV based DG without operation of proposed coordinated scheme
- Scenario 2: ADN in presence of high penetrated PV based DG with operation of proposed coordinated scheme

Fig. 3.16 shows the minimum and maximum voltage of the system at each hour under two scenarios. It can be observed that in scenario 1, over voltage occurred between hour 11:00 and hour 14:00, due to high penetration of PV based DG. Further, low voltage has also occurred between hour 16:00 and hour 24:00, which is due to the high loading condition. With proposed coordinated operation of multiple voltage regulated devices and SOP, the voltage violations occurred between above mentioned hours has mitigated and further voltage profile has flattened just above lower permissible limit (i.e. 0.95 pu), which results in reduction of energy consumption as seen in scenario 2.

3.5.6.1 Cost analysis

Table 3.8 shows that the scenario 2 has better economic benefits than the scenario 1. Even though after inclusion of switching operation cost and SOP maintenance cost, the annual total cost of system operation has been reduced to \$ 1609055.9, which results in savings about \$ 64092.3 as seen in Table 3.8.

Based on the above analysis, it can be concluded that the proposed coordinated scheme can eliminates the voltage violations and also reduce the annual total cost of system operation simultaneously.

3.5.6.2 Impact of forecast error

In reality, the PV generation output and load of the any particular day have some forecasting error. A stochastic analysis to be applied in order to consider the impact of forecast error on results of the optimization problem. Here, the standard deviation of

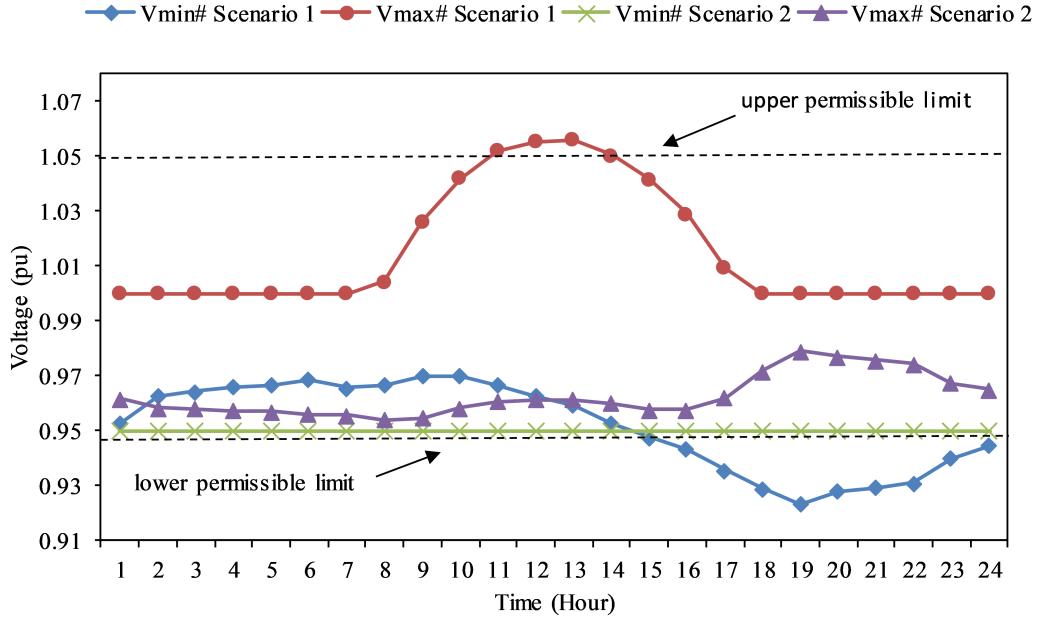


Figure 3.16: minimum and maximum voltage of the system at each hour under two scenarios

Table 3.8: Cost benefit analysis in presence of high penetration of DG

Parameters	Scenario 1	Scenario 2	Cost reduction
Annual cost of energy consumption (\$)	1554856	1519977	34879
Annual cost of power losses (\$)	55567.6	13664.1	41903.5
Annual cost of switching operation (\$)	0	14235	-14235
Annual cost of Co2 emission (\$)	62724.6	59639.8	3084.8
Annual SOP maintenance cost (\$)	0	1540	-1540
Annual total cost of system operation (\$)	1673148.2	1609055.9	64092.3

the forecasted PV output and load are taken as $\pm 15\%$ and $\pm 10\%$ of their mean value respectively for each hour. A Gaussian distribution [44] have been employed to simulate the PV output and the load demand, respectively. Further, Monte Carlo simulation has been performed with 500 scenarios. In order to reduce the computational burden, scenarios have been reducing to 15 scenarios by using k-means clustering [137]. The total operating cost of system at each hour with/without optimal scheduling of control devices and with/without consideration of forecasted errors have been plotted in the Fig. 3.17.

The star symbols (*) in Fig. 3.17 indicates the total operating cost value at each

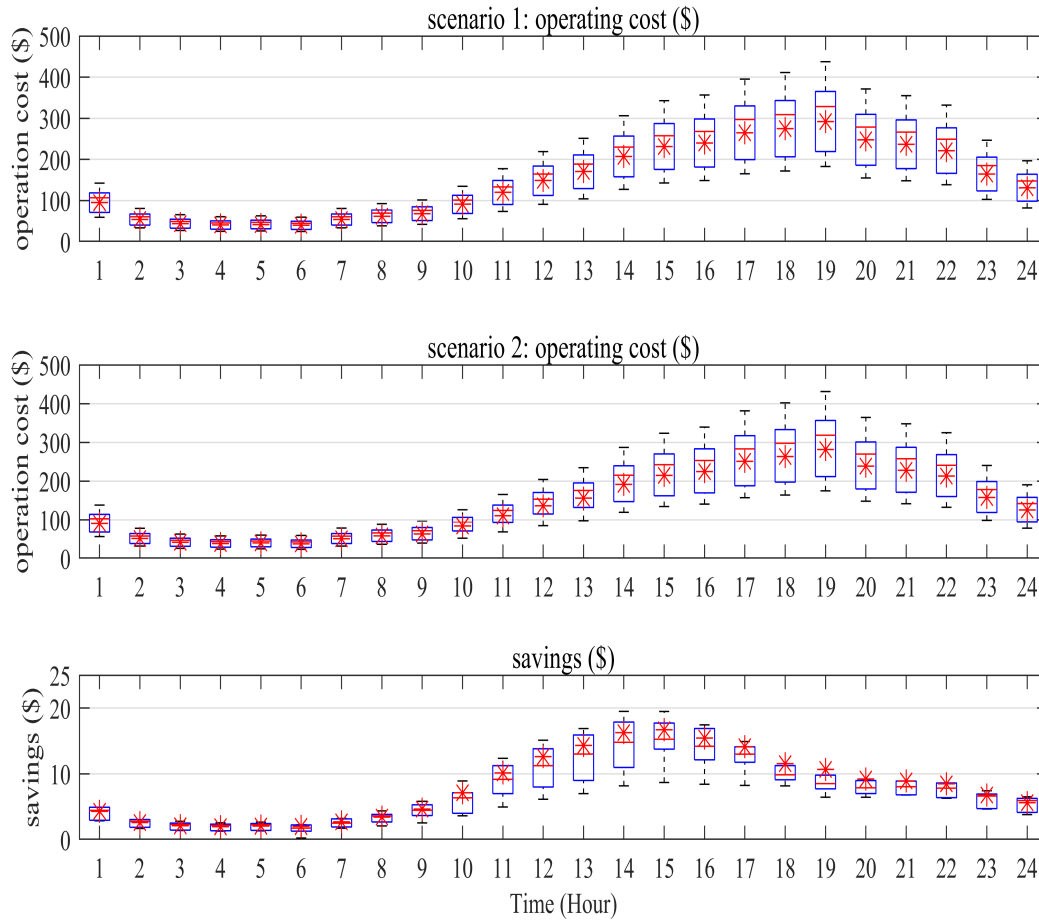


Figure 3.17: Stochastic analysis comparison of total operating cost with/without optimal control & with/without forecasted errors

hour obtained without consideration of forecasted error (i.e. exactly same as the forecasted values given in Fig. 3.3). Further, in this figure, box-plot represents the objective function value with considering forecasted errors at each hour. It can be observed that significant reduction in total operating cost has been achieved by optimal control setting obtained by scenario 2 (i.e. proposed scheme) compare to scenario 1 (i.e. no control) even in consideration of forecast errors. Thus, it can be concluded that the control setting obtained by proposed scheme is effective even in the occurrence of forecast errors.

3.6 Conclusion

This chapter presented a time-series optimization model of coordinated CVR scheme, in which the OLTC, SCBs, RCS and SOP are all formulated as controllable devices. The formulated MINLP problem has been solved by a modified binary GWO algorithm. The reported test results on well-known 69 bus distribution system have been corroborative evidence of the proposed coordinated scheme, which reveals that

- Optimally coordinated operation of OLTC, SCBs and DNR for CVR yield upto 5.49% energy demand reduction.
- Additional 1.48% energy demand reduction has been achieved with the incorporation of an SOP operation in the existing distribution system.
- Total number of switching operations of traditional VVC devices and RCSs have been reduced by using a coordinated scheme that enhances their life span time.
- The proposed coordinated scheme can eliminate the voltage violations and also reduce the annual total cost of system operation simultaneously even in the presence of high penetration of DG.
- Proposed coordinated scheme does not require the participation of consumers to achieve energy saving.
- Proposed scheme is capable of coping up with uncertainty in load/generation and intermittent nature of PV output generation.
- Deployment of CVR operation along with DNR and SOP can make the voltage profile more flattened compared to the deployment of CVR or DNR or SOP only.
- Benefits of techno-economic analysis and value addition in environmental concern (i.e. carbon emission reduction) show the proposed scheme's effectiveness.

