Chapter 5

Optimal Reconfiguration of Radial Distribution Networks using PSO-CRO Algorithm for Loss Minimization and Voltage Stability Enhancement under Voltage Dependent Loads.

5.1 Introduction

In Chapters 2 to 4, the impact of optimal placement of DGs has been studied considering all loads in the system to be of constant power type. However, all loads are not of constant power type in a practical network. The loads may be voltage and frequency dependent as well as may be time-varying. Apart from DG placement, distribution system performance may also be enhanced through network reconfiguration by opening and closing certain branches that divert power flow from heavily loaded branches to lightly loaded branches. In this chapter, the impact of network reconfiguration in voltage stability enhancement, loss minimization, and voltage profile improvement has been studied in a radial distribution network consisting of voltage-dependent loads. The network has been reconfigured optimally by the PSO-CRO algorithm. Different voltage-dependent loads considered in this work are Constant Current (CI) load, Constant Impedance (CZ) load, Residential Load (RL), Summer Day Residential Load (SDRL), Winter Day Residential Load (WDRL), Winter Night Residential Load (WNRL), Industrial Load (IL), Commercial Load (CL), Summer Day Commercial Load (SDCL), Summer Night Commercial Load (SNCL), Winter Day Commercial Load (WDCL), Agricultural Load (AL), and Electric Vehicle (EV) loads. Apart from these, the above studies have also been carried out for Constant Power loads. Case studies have been performed on IEEE 33-bus radial distribution network. A comparative study of simulation results demonstrates the importance of considering the various types of voltage-dependent loads in the optimally reconfigured network.

5.2 Distribution Network Reconfiguration

5.2.1 System Model

The distribution network is made up of several buses connected to each other. Buses may also be connected to several electrical components like loads or distributed generators. This chapter focuses on a single-phase distribution network. Also, this assumption is not limiting in nature because multi-phase unbalanced networks can be modeled as single-phase circuit. So, the methods for single-phase networks can be applied to the equivalent models of multi-phase unbalanced networks [110].

The schematic diagram of 33-bus IEEE distribution network shown in Fig. 5.1 has a total of 37 switch-equipped branches. Initially, the switch-equipped branches with solid lines in Fig. 5.1 are in the Closed Switch Status (CSS), while the remaining ones (the branches with dashed lines) are in the Open Switch Status (OSS). Each branch status can change according to the desired topology through the opening and closing of switches, known as the reconfiguration of the network.

The distribution network reconfiguration process consists in sweeping all the possible network topology by changing the status of some/all switches while aiming at achieving a

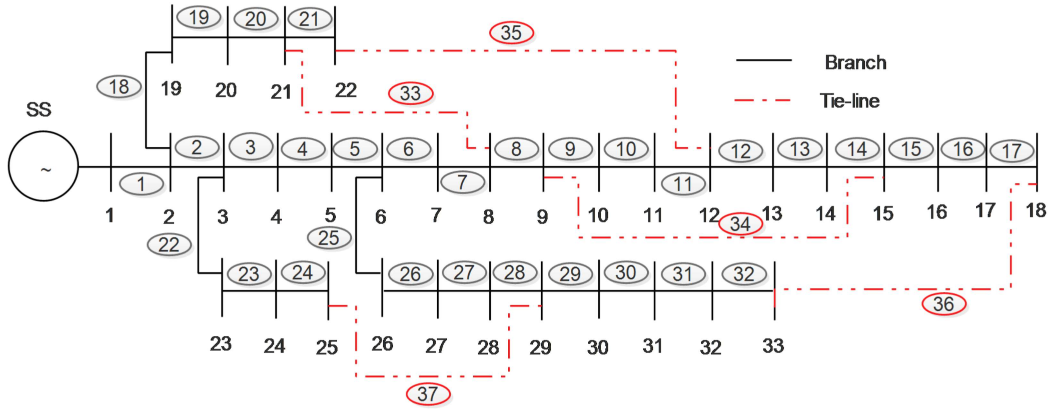

Fig. 5.1 33-Bus IEEE Network Topology in Base Case

specific objective. Note that a radial structure is usually preferred in distribution networks for reaching adequate operating conditions. In particular, the radial structure is maintained only if the network graph induced by the branches with closed switches is connected without any mesh formation.

Thus, for any possible configuration, the following equality has to be verified:

$$N_{br} - N_{OTS} = n - 1 \tag{5.1}$$

where, N_{br} is the total number of branches, N_{OTS} is the number of open tie-switches and n presents the total number of buses.

5.2.2 Problem Formulation

The distribution network optimal reconfiguration problem is basically finding the optimal combination of open/closed switches in order to minimize/maximize the selected objective function. In this chapter, the optimal reconfiguration problem is solved for 33-bus IEEE distribution network for minimizing the total system real power loss and voltage deviation at buses and maximizing the voltage stability of each bus. The formulation of power loss is presented in (2.1). Equations (2.6) and (2.8) present the mathematical formulation of voltage deviation and voltage stability index, respectively.

Constraints to be followed are presented in (2.11), (2.12), and (2.13). Apart from the cited constraints, constraint regarding the radial structure of the distribution network is presented below.

The number of open switches chosen among the distribution network branches has to be set equal to N_{OTS} (i.e., number of OSS); the number of closed switches has to be equal to the number of CSS. The sum of the switch status of all the branches is given by;

$$\sum_{j=1}^{N_{br}} \sigma_j = N_{br} - N_{OTS} \tag{5.2}$$

where, σ_j is the status of the switch at j^{th} branch. To ensure the radiality of the distribution network , an appropriate search space preparation is preliminarily executed before solving the optimization problem.

5.2.3 Mathematical Modelling of Voltage-Dependent Load

Traditionally, the power system networks are studied for constant power loads that are assumed to be unaffected by voltage variations. However, the power drawn by a load may change with voltage variations, in general. In this chapter, the impact of various types of voltage-dependent loads has been considered while deciding the optimal reconfiguration of the network. The loads have been expressed as an exponential model given by:

$$P_{Di} = P_{Di}^{0}(V_i/V_i^{0})^{\alpha} \tag{5.3}$$

$$Q_{Di} = Q_{Di}^{0}(V_i/V_i^{0})^{\beta} \tag{5.4}$$

where, P_{Di}^{0} and Q_{Di}^{0} are the real and reactive power load, respectively, at bus-i at nominal voltage; P_{Di}, and Q_{Di} are the real and reactive power load, respectively, at bus-i at actual voltage; V_i^{0} and V_i are the nominal and actual voltage at bus-i, respectively; α and β are the exponents. The exponents α and βvalues for different types of voltage-dependent loads are given in Table 5.1.

Table 5.1 Exponents α and β for Various Voltage Dependent Loads

Load	α	β	Load	α	β
CP [99]	0	0	EV [99]	2.59	4.06
CI [99]	1	1	SDRL [111]	0.72	2.96
CZ [99]	2	2	WDRL [111]	1.04	4.19
RL [99]	0.92	4.04	WNRL [111]	1.30	4.38
IL [99]	0.18	6	SDCL [111]	1.25	3.50
CL [99]	1.51	3.4	SNCL [111]	0.99	3.95
AL [99]	0.08	1.60	WDCL [111]	1.50	3.15

5.2.4 Optimal Reconfiguration of Distribution Network

A novel hybrid metaheuristic optimization technique the PSO-CRO was proposed in the previous chapter for loss minimization. In this chapter, PSO-CRO algorithm is proposed for optimal reconfiguration. It is apparent from the equation of power loss and voltage stability index that these depend on power flow through the branches. Branches of the test system may be opened/closed through switches/tie switches resulting in the diversion of power flows from heavily loaded to lightly loaded branches. This helps in minimizing system power loss and voltage deviation of the buses with respect to the reference value (taken as 1 pu in this work) and enhancing the voltage stability of each bus. In this work, the hybrid metaheuristic optimization technique PSO-CRO is used to get minimum system active power loss and voltage deviations, and maximum voltage stability index. The proposed approach provides information in the form of opening and closing combination of line switches. To minimize the objective function variables in the decision vector $[D_{var}]$ considered in the system are given below.

$$D_{var} = [[CSS] \qquad [OSS]] \tag{5.5}$$

where decision variable $[CSS]$ represents the set of branches having Closed Switch Status and $[OSS]$ represents the set of branches with Open Switch Status.

Both the group of decision variables ([CSS] and [OSS]) are initialized randomly and updated in each iteration. Closed and open tie switches are optimized by the hybrid optimization technique PSO-CRO. An optimal open and closed switching combination is selected for which the system active power loss and voltage deviation are minimum and the voltage stability index at each bus is maximum. By utilizing this approach the optimal switching combination is computed and presented in the result and discussion section for 33-bus IEEE network.

The general flow chart and pseudo-code of the hybrid optimization technique PSO-CRO is shown in Fig. 4.8 (Chapter-4).

5.3 Results and Discussion

The proposed optimal reconfiguration approach is tested on 33-bus balanced system. The base case topology of the test system is shown in Fig. 5.1. The 33-bus radial distribution system consists of 32 branches (solid black lines) and 5 tie lines (dotted red lines). Case studies have been performed on the test system by considering various voltage-dependent load models presented in Table 5.1.

Optimal topology computed through PSO-CRO was achieved by closing tie-line switch numbers (lines) 33 (21-8), 34 (15-9), 35 (22-12), and 36 (33-18) and by opening switches (lines) 7 (8-7), 9 (10-9), 14 (15-14), 32 (33-32), and 37 (29-25).

The performance is measured in terms of real and reactive power loss, voltage deviation, and voltage stability index. The performance results for different types of loads are presented in Table 5.2 for basic topology and in Table 5.3 for optimal reconfigured topology.

In base topology for Constant Power (CP) load, total real and reactive power demands are 3.715 MW and 2.300 MVAr, respectively. The load flow resulted in total real and reactive power losses of 202.66 kW and 135.13 kVAr, respectively. The Voltage Deviation (ΔVD) calculated with respect to the reference voltage (i.e. 1 pu) as per (2.6) and minimum voltage stability index calculated as per (2.8) are 0.0515 pu and 0.6956, respectively. The most critical bus with the minimum voltage stability index of 0.6956 was found to be bus-18. Also, it is observed that the lowest voltage is found to be 0.9131 pu at the same bus-18. Real and reactive power demands and losses, voltage deviation from the reference voltage, minimum Voltage Stability Index (VSI_{min}) along with bus number where it occurs, and bus with minimum voltage magnitude for different types of voltage-dependent loads are also shown in Table 5.2 for base case topology. It is observed from Table 5.2 that all types of voltage dependent loads considered in this work have lower real and reactive power losses, lower voltage deviations with respect to the reference voltage of 1 pu and higher voltage stability index compared to Constant Power load. Thus, non-consideration of voltage dependency of loads yields a very conservative determination of power losses, bus voltage deviations, and voltage stability margin.

Table 5.2 Performance and voltage stability analysis under base case topology of IEEE 33-bus network

Load	$P_{load}(MW)$	$Q_{load}(MVAr)$	$P_{loss}(kW)$	$Q_{loss}(kVAr)$	ΔVD	$VSI_{min}(bus\ no.)$	$V_{min}(bus\ no.)$
CP	3.715	2.300	202.6573	135.1276	0.0515	0.6956 (18)	0.9131 (18)
CI	3.543	2.181	176.6231	117.5111	0.0480	0.7145 (18)	0.9194 (18)
CZ	3.400	2.082	156.8760	104.1780	0.0452	0.7304 (18)	0.9245 (18)
RL	3.564	1.885	159.3344	105.8517	0.0456	0.7269 (18)	0.9234 (18)
IL	3.684	1.717	161.6982	107.4856	0.0457	0.7252 (18)	0.9228 (18)
CL	3.475	1.948	154.9394	102.8760	0.0449	0.7310 (18)	0.9247 (18)
AL	3.700	2.108	186.7773	124.3857	0.0495	0.7056 (18)	0.9165 (18)
EV	3.334	1.906	140.3507	93.04247	0.0427	0.7440 (18)	0.9287 (18)
SDRL	3.593	1.977	167.6585	111.4649	0.0468	0.7203 (18)	0.9213 (18)
WDRL	3.546	1.874	157.0681	104.3222	0.0452	0.7289 (18)	0.9240 (18)
WNRL	3.508	1.862	152.9601	101.5496	0.0446	0.7324 (18)	0.9251 (18)
SDCL	3.513	1.936	157.6456	104.7042	0.0453	0.7286 (18)	0.9239 (18)
SNCL	3.553	1.893	158.8274	105.5079	0.0455	0.7274 (18)	0.9235 (18)
WDCL	3.475	1.970	156.3222	103.8076	0.0451	0.7299 (18)	0.9243 (18)

The load flow study is repeated for optimal reconfigured topology for all types of loads. The simulation results are shown in Table 5.3. It is observed from Table 5.3 that the real power loss gets reduced to 139.53 kW from 202.66 kW while the reactive power loss gets reduced to 102.29 kVAr from 135.13 kVAr, for Constant Power (CP) load. The Voltage Deviation (ΔVD) is decreased to 0.0348 pu from 0.0515pu, VSI_{min} is improved to 0.7736 from 0.6956, and the lowest voltage 0.9131 pu at bus-18 gets enhanced to 0.9378 pu (occurring at bus-32) for Constant Power (CP) load. It is also observed from Table 5.2 and Table 5.3 that a significant reduction in real and reactive power losses and improvement in voltage stability and voltage profile have been obtained for different types of voltage-dependent loads considered in this work if the distribution network is reconfigured optimally by PSO-CRO algorithm. Results presented in Table 5.3 also demonstrate the conservative estimation of power losses, bus voltage deviation from the reference value, and voltage stability index in case the voltage dependency of loads are ignored.

Table 5.3 Performance and voltage stability analysis under optimal reconfigured topology of IEEE 33-bus network

Load	$P_{load}(MW)$	$Q_{load}(MVAr)$	$P_{loss}(kW)$	$Q_{loss}(kVAr)$	ΔVD	$VSI_{min}(bus\ no.)$	$V_{min}(bus\ no.)$
CP	3.715	2.300	139.5309	102.2902	0.0348	0.7736 (32)	0.9378 (32)
CI	3.589	2.212	127.4815	93.3964	0.0332	0.7843 (32)	0.9411 (32)
CZ	3.479	2.135	117.4645	85.9989	0.0319	0.7936 (32)	0.9438 (32)
RL	3.604	1.982	117.6147	86.4275	0.0320	0.7949 (32)	0.9442 (32)
IL	3.693	1.849	117.4229	86.5347	0.0319	0.7968 (32)	0.9448 (32)
CL	3.536	2.031	115.8528	84.9985	0.0318	0.7959 (32)	0.9445 (32)
AL	3.704	2.159	131.6597	96.6769	0.0338	0.7812 (32)	0.9401 (32)
EV	3.424	1.993	108.1092	79.2187	0.0307	0.8031 (32)	0.9467 (32)
SDRL	3.626	2.057	122.1745	89.7253	0.0326	0.7902 (32)	0.9428 (32)
WDRL	3.590	1.973	116.4470	85.5620	0.0318	0.7960 (32)	0.9445 (32)
WNRL	3.561	1.963	114.3560	84.0003	0.0315	0.7979 (32)	0.9451 (32)
SDCL	3.565	2.022	117.1203	85.9746	0.0319	0.7949 (32)	0.9442 (32)
SNCL	3.595	1.989	117.4281	86.2731	0.0320	0.7950 (32)	0.9442 (32)
WDCL	3.536	2.048	116.6619	85.5747	0.0319	0.7950 (32)	0.9443 (32)

In comparison to basic topology, the real power loss decrement under optimal reconfiguration by the proposed approach is presented in Fig. 5.2 for different types of voltage-dependent loads considered in this work. It is observed from Fig. 5.2 that optimal reconfiguration of the network by the proposed approach results in the significant reduction in real power loss under all types of voltage-dependent loads considered in this work.

In comparison to basic topology, the reactive power loss decrement under optimal reconfiguration by the proposed approach is presented in Fig. 5.3 for different types of voltage-dependent loads considered in this work. It is observed from Fig. 5.3 that optimal reconfiguration of the network by the proposed approach results in a considerable decrease in reactive power loss under all types of voltage-dependent loads considered in this work.

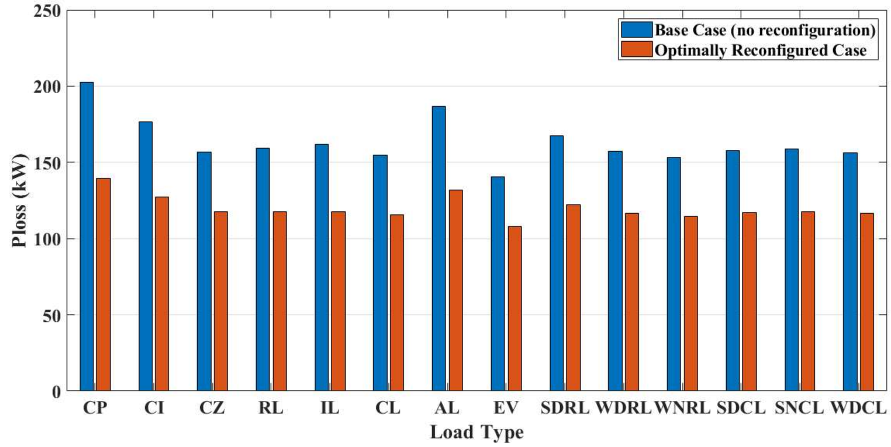

Fig. 5.2 P_{loss} decrement corresponding to various load types for base case and optimal reconfigured topology of 33-Bus IEEE Network

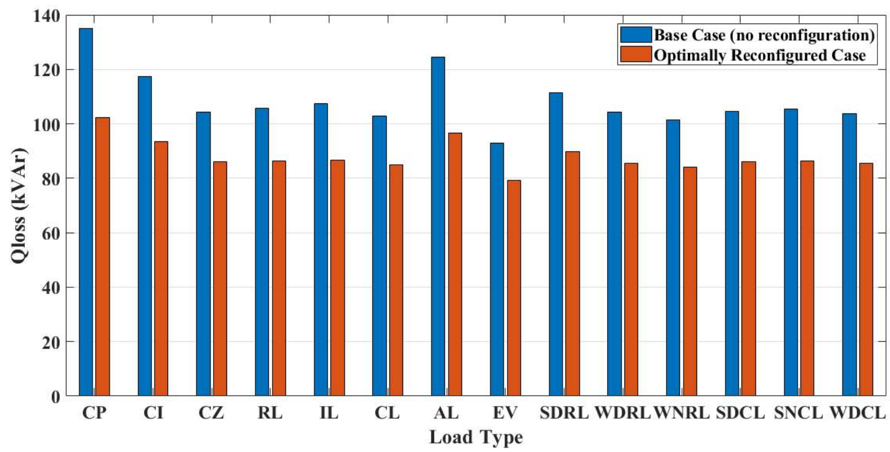

Fig. 5.3 Q_{loss} decrement corresponding to various load types for base case and optimal reconfigured topology of 33-Bus IEEE Network

Fig. 5.4 presents the minimum Voltage Stability Index (VSI_{min}) of the optimally reconfigured network as compared to the base case corresponding to all types of voltage-dependent loads. It is observed from Fig. 5.4 that network reconfiguration by the proposed approach results in considerable enhancement in voltage stability margin for all types of voltage-dependent loads considered in this work.

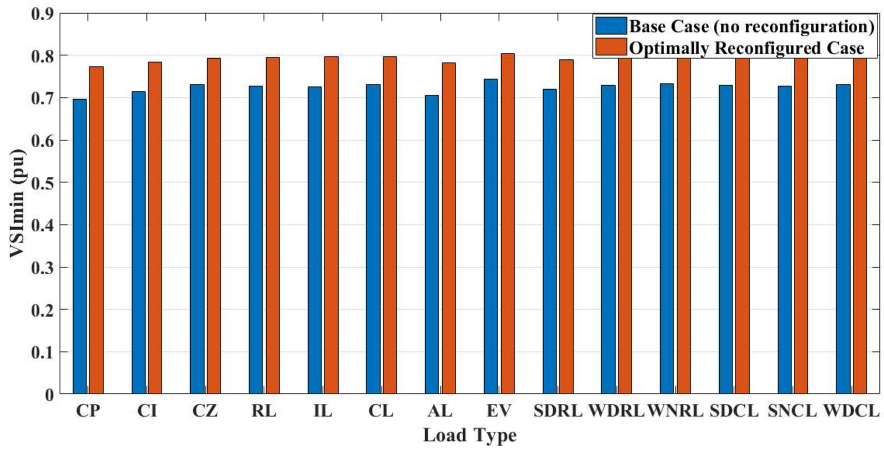

Fig. 5.4 VSI_{min} corresponding to various load types for base case and optimal reconfigured topology of IEEE 33-bus network

5.4 Summary

In this chapter impact of various types of voltage-dependent loads on real and reactive power loss, voltage profile, and voltage stability of radial distribution network were studied. Network reconfiguration through the PSO-CRO approach was proposed to minimize power loss and bus voltage deviations from the reference value and enhance voltage stability margin under different types of voltage-dependent loads. Case studies performed on 33-bus radial distribution network demonstrate the effectiveness of the proposed approach of network reconfiguration. Proposed approach of network reconfiguration through PSO-CRO algorithm is able to cause significant reduction in real and reactive power loss and considerable improvement in voltage profile as well as voltage stability margin of the system under all types of voltage-dependent loads considered in this work.

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