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Optimal Reactive Power Dispatch at Selected Buses in Distribution Network with DGs for Loss Minimization

Niraj Kumar Sah [a], Menaka Karki [b], Shahabuddin Khan [c], Lalit Bikram Rana [d]

[a, b, c] Department of Electrical Engineering, Pashchimanchal Campus, Institute of Engineering, Tribhuwan University, Nepal
[d] Department of Electrical Engineering, Pokhara University
Corresponding Email: [a] esniraj@gmail.com

Abstract

Distribution systems hold a prominent position in the power system network as they are a key link between the power transmission and the end user consumer of electricity. Reactive power is critical to the operation of the distribution network on safety as well as economic aspects. The unreasonable distribution of reactive power would severely affect the power quality of the distribution network and increase the distribution loss. The reactive power dispatch optimization can reduce the system loss as well as improvement in voltage profile. The active and reactive power generation capabilities of the Distributed Generations has enabled more possibilities to achieve a flatter voltage profile along the distribution feeder line with reduction of line losses.

Reactive power dispatch problem is a nonlinear and has both equality constraints and inequality constraints. In this work, the particle swarm optimization algorithm is coded into MATLAB programming environment to get the results. The approach of reactive power dispatch in this work is to adjust the values of control variables on optimally placed distributed generation on radial distribution network to find the optimal reactive power injection into the distribution system under given load and line conditions to minimize the real power loss.

The proposed method in this work minimizes the real power loss in a distribution system and determines the optimal reactive power dispatch from distributed generations. IEEE 33 bus radial distribution system is used to evaluate the performance. The resistance to reactance ratio of the line is varied for the analysis of effectiveness of proposed algorithm. The results found to be effective for loss minimization with improvement in voltage profile. With the higher value of resistance to reactance ratio of the line, developed reactive power optimization algorithm found to be less effective. Distributed energy resources in context of Nepal, are operated in unity power factor due to economic benefits. Due to significant impact of reactive power injection into distribution system

Keywords

DG, Reactive Power, PS0

1. Introduction

Distribution systems hold a prominent position in the power system network as they are a key link between the power transmission and the end user consumer of electricity.In the past, the study was mainly focused on optimal switch configurations, conventional voltage regulation devices like shunt capacitors, tap-changers, and regulators to minimize the voltage deviation from nominal values. With energy and environmental challenges, distributed generations (DG, such as Wind, Solar, Fuel cell, Micro turbines, Gas turbines, and Small hydroelectric and other renewable energy technologies) have attracted a greater attention all over the world [1]. The active and reactive power generation capabilities of the Distributed Generations has enabled more possibilities to achieve a flatter voltage profile along the distribution feeder line with reduction of line losses. Also the capacity of the network improved by proper siting and sizing of the distributed generations [2].

Conventionally electric power in distribution feeders flow from substations to end of the feeder. However, the utilization of DGs might cause reverse power flow and different voltage profile than in base case. Also radial topology of distribution network is a weakly meshed structure with unbalanced operation and distribution of loads. There are large number of nodes and branches along the distribution network with wide range of resistance to reactance ratio of line [3]. The analysis of distribution network with penetration of distributed generations requires the modification in conventional load flow algorithm.

The integration of DGs into distribution system depends upon the characteristics of DGs, their operational behavior, point of connection and technology used. The energy sources of DGs can be categorized into stable energy sources such as fuel cell and micro-gas turbine, and unstable energy sources, such as wind and solar. Different energy sources combining with different energy converters will result in special output characteristics of DGs. If the induction generator is used to convert wind energy, it will act like a constant real power and variable reactive power generator. However, if the static electronic converter is used to convert wind energy, it will act like a generator with a constant power factor in normal operation condition. Therefore according to the output power characteristics, DGs can be specified as constant power factor model,constant voltage model or variable reactive power model.

Distributed generations are widely distributed in line. The proper placement and sizing of distributed generations into the distribution system plays important role in minimizing losses and improving voltage profile. The integration of DGs like solar and wind generators, active power generated by the DG is optimized by Maximum Power Point Tracking (MPPT) algorithm. In that condition a suitable method must be applied to meet the load demand considering DGs output and loss of the system. The reactive power generated by DGs can be optimized considering its maximum rating. But the operation of DGs at its maximum output results in more losses in DG itself. Hence the Reactive Power Optimization of distribution system with DG is fundamental to ensure the economic operation of the system without violating technical and operational limits and to provide consumer with sufficient power of high quality [4].

1.1 Constraints of Reactive Power Dispatch problem

Along with the development of economy, the scale of the power distribution network also keeps growing. In some areas construction and upgrading of network is not sufficient with the growing load demand. Power utility thus need to upgrade network or some of it, but it requires huge capital investment. The simplest and most economical way remains the reactive power dispatch.Reactive power plays a prominent role in minimizing the real power loss of the system. Power loss in the system is mainly due to active and reactive power losses.

There are numbers of methods to minimize the losses in the system as found on various literature survey. Capacitor placement in the optimized location, network reconfiguration method is used to reduce the losses. But with the development of distributed generation, new approaches for loss minimization in power network with penetration of DGs have evolved. Most of the literature survey contributed on minimizing real power losses considering DGs for reactive power optimization. The consideration of variable and high resistance to reactance ratio of line for analysis of reactive power optimization techniques has not been considered. In this work the impact of variable and high resistance to reactance ratio of the line along with the mode of operation of DGsare considered for reactive power dispatch of the distributed generation. Optimal reactive power dispatch proposed in this work is formulated for the PVbus connection mode of DGs using Particle Swarm Optimization (PSO) algorithm for active power loss minimization on IEEE 33 bus test system.

2. Distributed Generation Connection Modes

Modelling distributed generations in three phase distribution load flow by J.H. Tang [5], has described various mathematical models of distributed generation technology with their respective load flow algorithm.

2.1 Constant power factor model

The model can be used for the controllable DGs, such as synchronous generator based DGs and power electronic based DGs. For example, the output reactive power can be adjusted by controlling the exciting current and the trigger angles for synchronous generator based DGs and power electronic based DGs, respectively. For this model, the specified values are the real power output and power factor of this DG. The reactive power of the DGs can be calculated by equation

$$Q_{DG} = P_{DG} * tan^{-1}(cos^{-1}(pf)) \quad (1)$$

Where, QDG is reactive power output from DG, PDG is active power output from DG and pf is power factor of DG

2.2 Variable reactive power model

DGs employing induction generators as the power conversion devices will act mostly like variable reactive power generators. By using the induction generator based WT as an example, the real power output can be calculated by the WT power curve.Then, its reactive power output can be formulated as a function comprising the real power output, bus voltage, generator impedance and so on. However, the reactive power calculation like that is cumbersome and difficult to calculate efficiently.

2.3 Constant voltage model

The specified values of this DG model are the real power output and bus voltage magnitude. To calculate the equivalent current injection for the proposed load flow method, a two-loop algorithm is developed in this paper. The inner loop calculates the reactive power output of the DG which is necessary to keep the bus voltage magnitude on the specified value.After the required reactive power output has been obtained, the outer loop calculates the equivalent current injection. The distributed generation has the capability of regulating the reactive power within limits. Thus voltage of the bus at the point of connection can be controlled.

3. Load Flow Algorithm

Over the past decade, there have been much interest developed and is becoming a statutory requirement in electric power generation using renewable energy sources. During planning and operation, the effects of integrating Renewable energy sources in a power system network must be analyzed properly to avoid any adverse effects. One of the most popular analysis tools used in power systems is Load flow analysis. Various load flow methods have been developed in the past for both transmission and distribution studies. The fast decoupled load flow which is popular in transmission systems fails to solve distribution systems because of its high R/X ratio [6]. Due to higher value of resistance to reactance ratio, bidirectional power flow and voltage fluctuations due to DGs connection on distribution network, conventional load flow techniques are not applicable for distribution network with DGs. An algorithm for load flow analysis of distribution system with DGs is proposed. [1] [7].

Different methods developed for power flow analysis by exploiting these features of distribution systems are available. The backward forward sweep method is quite popular among the distribution load flow algorithms. In general all the methods used for a radial system works as backward-forward fashion. It starts with some assumed voltages at each bus, except the source node. In the backward propagation, adds all the load currents and downstream branch currents (computed at the assumed voltages) to compute current in the upstream branch. Starting from the source node, in the forward propagation, updates the bus voltages utilizing the branch currents computed in the backward propagation. Backward-forward propagation continues till voltages at all the buses converge within pre-specified tolerance. The load flow algorithm for distribution system in backward-forward sweep begins with the development of BIBC and BCBV matrices. These matrices provide relation between bus voltage, branch current and bus current [5]. The constant BIBC matrix is an upper triangular matrix and has non zero entry of +1 only. The dimension of BIBC matrix is m x (n-1) for distribution system with m branches and n buses. If a line section l is located between bus i and bus j, copy the column of the ith bus of BIBC matrix to the column of the jth bus and fill a +1 to the position of the lth line row and the jth bus column. The relation between bus injection current and branch flow current can be written as:

$$[B] = [BIBC][I] \tag{2}$$

Where [B] and [I] are vector of branch current and bus injection current respectively. The constant BCBV matrix has non zero entries consisted by line impedance values. The dimension of BCBV matrix is for distribution line with m branch and n buses is (n-1) x m. If a line section l is located between bus i and bus j , copy the row of the ith bus of BCBV matrix to the row of the jth bus and fill the line impedance (Zij) to the position of the jth bus row and the lth line column. The relation between branch current and bus voltages can be written as:

$$[\Delta V] = [BCBV][B] \tag{3}$$

Combining above equations the relation between bus current injection and bus voltage can be rewritten as:

$$[\Delta V] = [BCBV][BIBC][I] = [DLF][I] \tag{4}$$

And solution of distribution load flow can be obtained by solving equations iteratively

4. Methodology

The losses in the distribution system mainly consists of active power losses, reactive power losses and losses associated with DG power output. The loss of the distribution network depends on the flow of active and reactive current through the branches. To minimize the losses in the system with distributed generation availability, the branch flows can be reduced by properly dispatching active and reactive power from the DGs. Mainly the PV and wind based DGs have optimal active power output for given solar irradiance or wind speed by Maximum Power Point Tracking (MPPT) algorithm. Depending upon the characteristics and mode of connection of DGs the output reactive power can be varied with respect to its maximum capacity. When DGs are operated in maximum power output the efficiency of the DG reduces while operating it in low penetration, its impact in distribution system loss reduction may not be sufficient as well as its economy of operation influenced. Hence the optimum reactive power dispatch may lead to the loss minimization and economy of operation of distribution network.

4.1 Reactive Power Dispatch Problem Formulation

4.1.1 Objective Function

Reactive power dispatch problem in power network may have different goals. But in our case we only choose minimizing real power loss.

$$Minf_{Loss} = \sum_{k=1}^{bra} \frac{P_{bra}^2}{V^2} * R_k \quad (5)$$

4.1.2 Equality Constraints

The equality constraints are power balance equations which can be described by the equation below.

$$P_{Gi} + P_{Dgi} - P_{Li} = V_i \sum_{j=1}^{Nbus} V_j (G_k cos\theta_{ij} + B_k sin\theta_{ij}) \quad (6)$$

Where, PGi is active power from generator (zero value except for bus 1), PDgi active power from DG at bus i, PLiis active load at bus i, Vi is Voltage magnitude at bus i,

$$\theta_{ij} = \theta_i - \theta_j \quad (7)$$

Gk is conductance of branch k,
Bk is susceptance of branch k

$$Q_{Gi} + Q_{Dgi} - Q_{Li} = V_i \sum_{j=1}^{Nbus} V_j (G_k sin\theta_{ij} + B_k cos\theta_{ij}) \quad (8)$$

Where, QGi is reactive power from generator(zero value except for bus 1), QDgi reactive power from DG at bus i,
QLi is reactive load at bus i

4.1.3 inequality Constraints

The inequality constraints are the ranges of the voltage magnitudes reactive power injection, line branch capacity, bus voltage magnitude, active and reactive power generation etc. Some of the parameters are continuous such as voltage magnitudes. While some are discrete reactive power injection.

$$V_{imin} \leq V_i \leq V_{imax} \quad (9)$$

Where,Vimin is minimum voltage at bus i,
Vimaxis maximum voltage at bus i

$$Q_{DGimin} \leq Q_{GDii} \leq Q_{DGimax} \quad (10)$$

QDGimin is minimum reactive power from generator at bus i (i=1)
QDGimaxis maximum reactive power from distributed generator at bus i

4.1.4 Exterior Penalty Function

Reactive power dispatch problem is a constrained problem. In optimization, the constrained problems are usually converted into unconstrained problem for convenience. One of the commonly used method is by adding exterior penalty function terms to the objective function. If all the control variables are within limits, the penalty function would be zero. Else penalty function terms would be added to the objective function to penalize the violation. Penalty multipliers are always assigned a big number. When the penalty multipliers keep increasing until approaching the infinity, the constrained problem will transform to the unconstrained problem. In reactive power dispatch problem if control variables exceed the voltage limit, tap positions and reactive power injection have to be carefully examined.

$$MinimizeF : f + P(X, r_h, r_g) \quad (11)$$

Where,P(X,rh,rg) is penalty function, rh is penalty multiplier for equality function, rg is penalty multiplier for inequality function, F is called augmented function

4.2 Particle Swarm Optimization Applied for Reactive Power Dispatch

The particle swarm optimization tool is a simple, powerful, intelligent and meta-heuristic optimization tool, applicable in various fields. In this work, particle swarm optimization tool is used to minimize the real power loss of the distribution network by utilizing the optimization function, equality and non-equality constraints. During execution of particle swarm optimization based algorithm for reactive power dispatch, we need to define some variables. The swarms in this algorithm consists of desired value of voltage magnitude at the DG connected bus. Representation of position of each particle in six dimensional space,

$$V_3 \quad V_6 \quad V_9 \quad V_{12} \quad V_{15} \quad V_{18}$$

V represents the voltage magnitudes at the PV bus. When the optimization process starts the position of each particle will be continuously updated until reaching the stopping criteria. Corresponding to voltage magnitude at DG connected bus, total required reactive power generation by DG is calculated by above equation and corresponding voltage angle by equation.

During application of PSO algorithm for reactive power dispatch,stopping criteria, number of particles, position, velocity, acceleration factor, inertia factor, personnel best and global best need to be initialized.

Once the initialization is complete the bus and branch data for test system is loaded into algorithm. Base loss of the system is evaluated. Corresponding to each particle values, reactive power generation at DG connected bus and voltage angle is calculated.By updating the reactive power generation, voltage magnitude and voltage angle at DG connected bus the load flow is carried out to determine the losses.

For each particle if the calculated loss value is less than previous loss value the personnel best value is updated to currently evaluated loss value. When such update on each particle is complete the global best value is compared with the minimum value of personnel best value of each particle. If minimum of personnel best value is less than previous global best value then global best value is updated.

Based upon the inertia value, acceleration factors, just updated personnel and global best values the new velocity of each particle is evaluated. The new position of each particle is then updated with new velocity value and previous position of particles.

Once the stopping criteria is met the least loss, voltage magnitude at each bus, reactive power injection by DG at their connected bus is recorded and analyzed.. To conclude, the main optimization steps of the PSO based reactive power dispatch flow chart has been drawn as shown in Figure

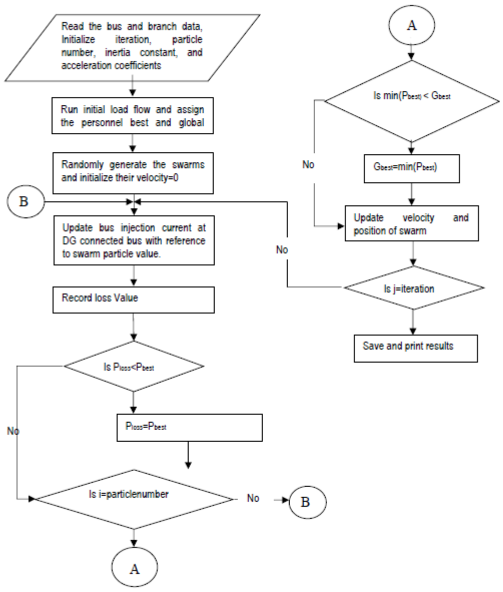

Figure 1: Flow chart

5. Result and discussion

Main objective of this work is to reduce the active power loss in distribution system with distributed generation by optimal reactive power dispatch from DGs. The performance of proposed method is verified on IEEE 33 bus system. The structure of the 33 bus network is shown below There are 33 nodes and 32

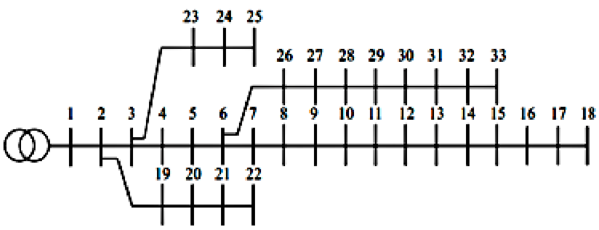

Figure 2: IEEE 33 bus test system

branches with one generator or substation at bus one. Total load on the distribution system is 3715 kW and 2300 kVAr. The distributed generation connection bus, installed capacity and connection bus type are presented in table below

Table 1: DG connection bus and mode of connection

Bus No	Installed Capacity(kVA)	Connection Bus Type
3	50	PV
6	150	PV
9	150	PV
12	150	PV
15	150	PV
18	50	PV

5.1 Reactive power dispatch with DG and R/X ratio of line is 0.5

Bus and branch parameters of IEEE 33 bus system are listed as below in Appendix. The resistance to reactance ratio of line for this case is 0.5. When the optimization process starts, the position of each particle will be continuously updated until reaching the stopping criteria.

The optimization process of reactive power dispatch. Real power loss at zero DG penetration is noted and then fixed amount of active power from DG are injected into the distribution system. For reactive power dispatch proposed algorithm applied. the position of particles are randomly selected. The real power loss is about 50 kW at the beginning. As the particles continually update their position towards the best solution, the real power loss keeps decreasing. After 120iterations, no improvement can be observed and active power loss converges to 39 kW.

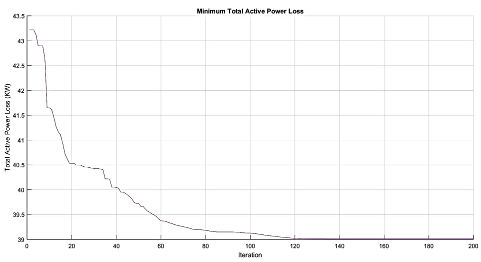

Figure 3: Loss reduction process

In base case lowest voltage can be observed at bus no 18. After injecting fixed amount of active power into the network voltage profile slightly improves. The proposed algorithm with fixed active power dispatch and optimized reactive power dispatch is applied to find the minimum real power loss. From Figure 4, the voltage improvement is better at the optimum solution of the algorithm. The impact of active power injection only is less effective than reactive power injection

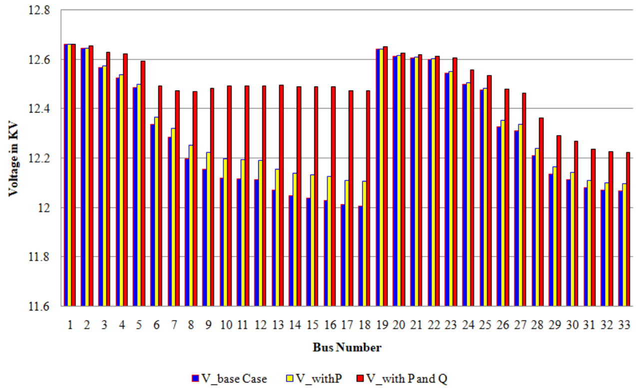

Figure 4: Bus Voltage profile of line when R/X=0.5

5.2 Reactive power dispatch with R/X ratio of 1

Second case study is about application of proposed algorithm into 33 bus system with resistance to reactance ratio of one . The initial active power loss in the system is 104 kW (active power injection only), and after optimization process active power loss was reduced to 82 kW. This shows significant reduction of active power loss in most of the branches. Significant improvement on voltage profile can be observed after optimization.

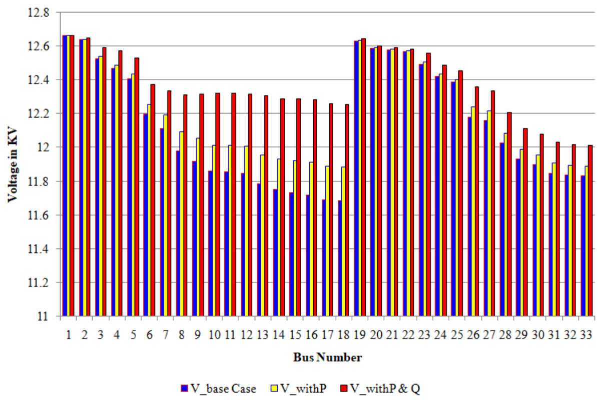

Figure 5: Bus Voltage profile of line when R/X ratio is one

5.3 Reactive power dispatch with R/X ratio of 1.5 and 2

Similar case study is made on proposed algorithm into 33 bus system with resistance to reactance ratio of 1.5 and 2, When R/X ratio of line is 1.5, the initial active power loss in the system is 162 kW and reduced to 128 kW after reactive power dispatch optimization. The voltage profile before and after optimization are shown below . The active power loss of the 33 bus system is reduced to 185 kW from 222 kW by the application of proposed algorithm when R/X ratio of line is two. The voltage profile of this case is presented in Figure below . The worst voltage profile is observed among all case when R/X ratio of line is two. The active power loss reduction percentage is lowest for this case. The branch losses found to be decreasing significantly with the exception at some buses, but the overall loss of the system is reduced. The impact of active power injection on voltage profile is found more effective than reactive power injection in both the cases

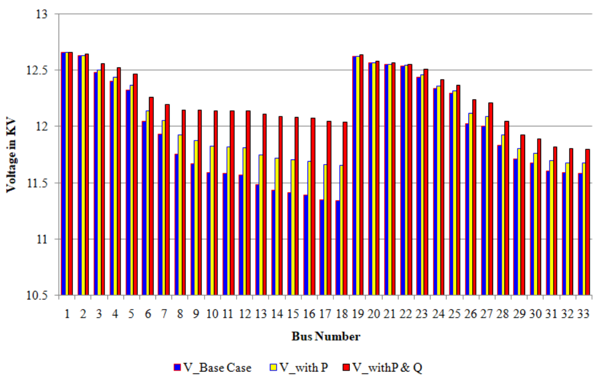

Figure 6: Bus Voltage Profile when R/X ratio is 1.5

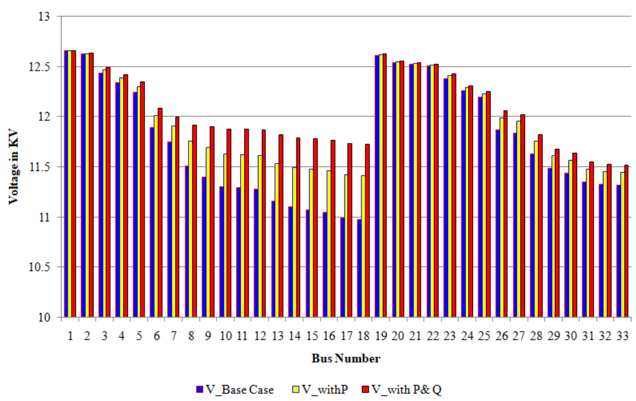

Figure 7: Bus voltage Profile of line when R/X ratio is two

The voltage profile comparison of these two cases as in Figure 6 and Figure 7 indicates that, the impact of reactive power injection has least effect on voltage profile improvement when R/X ratio of line is 2.Comparison of voltage profile of all cases are presented in Figure 8.Node voltage at different bus are found to be improved for lower value of R/X while for higher value the Q injection into the system has less impact on voltage profile improvement on bus voltage. When R/X ratio is 0.5, the bus voltage profile is almost smooth.

The capacity, bus number and connection mode of

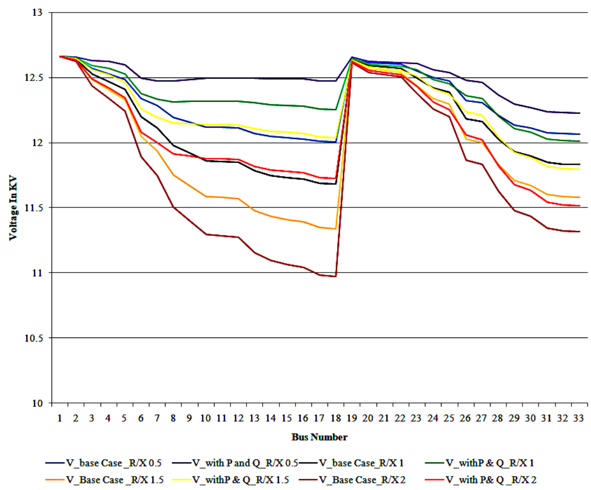

Figure 8: Bus voltage comparison of line for different cases

distributed generation connected in this test case is shown in Table 1. As discussed , developed algorithm for reactive power dispatch is applied into IEEE 33 bus test system with varying R/X ratio of line. The summary losses at different cases are as follows. The reactive power injection into DG connected buses are presented in Table 3 while reference voltage are presented in Table 2 From Table 3 it is observed that reactive power injection in distribution system with higher R/X ratio is more than in lower R/X ratio of line.

Table 2: Reference Voltage at DG connection buses at different R/X ratio

Bus No	R/X=0.5	R/X=1	R/X=1.5	R/X=2
3	1.0361	1.0314	1.0297	1.0297
6	1.0320	1.0040	1.0000	1.0010
9	1.0500	1.0500	1.0500	1.0500
12	1.0470	1.0420	1.0161	1.0161
15	1.0489	1.0188	1.0104	1.0104
18	1.0012	1.0009	1.002	1.0002

From Table 3, as R/X ratio of line increases from lower to higher value the loss of the system increases. During this work the R/X ratio of line was varied from 0.5, 1, 1.5 2 and results was analyzed. The reduction of loss in active and reactive power loss was observed for all cases after applying developed algorithm. The key point in loss reduction with varying resistance to reactance ratio, loss reduction of line with lower R/X ratio found to be better than higher R/X ratio.

Table 3: Loss comparison for different cases

Loss / Cases	R/X=0.5	R/X=1	R/X=1.5	R/X=2
Active power losses (kW) before optimization	50.92	104.71	161.76	222.54
Active power losses (kW) after optimization	39.02	81.42	127.98	185.43
Percentage reduction in loss (active)	22.36	22.24	20.88	16.67
Reactive power losses (kVAr) before optimization	101.85	104.71	107.84	111.27
Reactive power losses (kVAr) after optimization	78.02	81.42	85.32	92.71

5.4 Discussions

By analyzing the results of the four cases, the following conclusions can be obtained:

- Reactive power optimization can significantly reduce the real power loss of the IEEE 33 bus test system.
- Reduction of active power loss can be observed after active power injection only, but the impact of active power on loss reduction is more effective in line with higher resistance to reactance ratio than lower value.
- Injection of fixed active power and optimized value of reactive power into the DG connected bus of test system, active power loss are further reduced. The loss reduction impact of reactive power injection is more effective in line with lower value of resistance to reactance ratio of line.

6. Conclusions

In this paper, the approach of reactive power dispatch is to adjust the values of control variables on optimally placed distributed generation on radial distribution network to find the optimal reactive power injection into the distribution system under given load and line conditions to minimize the loss. During application of developed algorithm, IEEE 33 bus radial distribution system with 6 Distributed Generations connected at bus 3,6,9,12,15 and 18 .Particle swarm optimization based algorithm is used to minimize the real power losses of the system by finding optimum reactive power dispatch from DGs. Distributed generations were connected in bus with PV mode. Reactive power injection into the bus by Distributed generations are noted for varying R/X ratio of the line. When R/X ratio of the line is increased from low value to high value (0.5, 1, 1.5, and 2are used in this paper) the loss of the distribution system network found to be increasing. Voltage at different nodes are in declining order as we increase R/X values of line. By dispatching reactive power into the distribution network the loss of the system can be minimized by using the developed algorithm. For higher value of the R/X ratio of line, effect of reactive power injection was found to be less effective than lower values of R/X for improvement of the node voltages and loss minimization.

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