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Multi-objective approach for distribution network reconfiguration with optimal DG power factor using NSPSO

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Abstract: In this study, a multi objective method for optimal network reconfiguration as well as reactive power dispatches of distributed generations (DGs) has been proposed to improve the network performances by using non-dominated sorting particle swarm optimisation. The various network performances in terms of multi objective function include minimisation of system power loss, voltage deviation and energy wastage from solar and wind generation system. The effectiveness of the proposed method has been tested on the IEEE 33-bus radial distribution system for different combinations of network reconfiguration and reactive power output of DGs or its varying power factor. The obtained results also compared and indicated that better network performances achieved with both network reconfiguration and power factor optimisation over other cases. In addition, this strategy also results in lesser energy wastage from distributed renewable generation over without network reconfiguration option; hence, this approach is also suitable for saving and utilising maximum capacity of available renewable sources.

Nomenclature

N_{bus}	total number of buses
V_{ref}	bus voltage reference value
N_s	total number of switches
S_j	switching state of *j*th switch at the current time interval
So_j	switching state of *j*th switch in the previous time interval
P_i	active power injection at *i*th bus
Q_i	reactive power injection at *i*th bus
V_i	voltage at *i*th bus
Y_{ij}	admittance between *i*th bus and *j*th bus
δ_i	power angle at *i*th bus
N_{br}	total number of connected branches
k_i	status of *i*th branch's switch
$Ploss_i$	power loss in *i*th branch
R_i	resistance of *i*th branch

1 Introduction

Distribution network reconfiguration (DNRC) is a network-altering process performed by power utilities of distribution networks for a number of purposes. It is achieved by modifying the connection status of distribution network branches by switching on/off normally closed/open switches in the system such that an optimal network topology achieved, which gives the best performance with respect to some specified objectives. Nowadays, DNCR has more significance when large numbers of distributed generations (DGs) are expected and being installed in distribution network to support environmental concerns as well as to improve the energy security. Each DGs have different operating characteristics and especially solar and wind based, which are available in abundance everywhere, have less/poor control over their reactive power output, which negatively impacts on maintaining the network voltage profile. Since, renewable based DGs are usually operated at unity power factor for economic reasons with no contribution of reactive power to the load, especially in low penetration of such type of renewable generations. However, due to exponential increase in load, the demand for reactive power in the future is likely to require DGs to operate at varying power factor for additional reactive power support to meet acceptable voltage profile and also line losses are to be maintained within limit in the network. Furthermore, at stressful loading conditions, especially during peak loading conditions, network reconfiguration alone may not be sufficient to support the network if the DGs are operated at unity power factor and, if the reactive power is supported by DGs then it will reduce net active power output, which can be considered as energy waste. In worst case, renewable based DGs (solar and wind) could be removed/shut down from their operation if reactive power deficit cannot be managed from other sources/options. Therefore, to support the reactive power a number of sources are available but apart from it there is another option to utilise DNCR, which help to alleviate reactive power deficit and reduces wastage of energy from DGs while simultaneously improving voltage profile as well in operating horizons.

DNRC is an optimisation problem which is considered a highly non-linear, mixed integer type and non-differentiable multi-objective problem which renders it impractical to solve with traditional optimisation approaches. This is due to the discrete nature of the switches and the characteristics of different constraints and objective functions of the network reconfiguration problem [1]. With the growing popularity of remote terminal units and supervisory control and data acquisition (SCADA) for distribution automation, real time DNRC has become more feasible option for power utilities for control and management of the electric grid. The optimisation process is further complicated when the variations in the load and the generation from renewables DGs, e.g. wind and solar are considered.

1.1 Literature surveys

Significant research work has been done on optimal distribution system reconfiguration, but now the trend is shifting from single objective consisting of loss minimisation or voltage drop minimisation to multiple objective problem formulation [2]. Many studies, both for single and multiple objectives have also been conducted for distribution network with DGs, switched capacitors or electric vehicle charging load [3–9]. Likewise, there have also been other works which merge DNRC with other techniques such as optimal sizing or placement of DGs, capacitors etc. in the network for a further improvement of network performance [10–13]. In [14], an adaptive multi-objective particle swarm optimisation (MOPSO) in conjunction with graph theory has been used for multi-objective optimisation of DNRC for distribution network. Similarly, authors in [15] have only shown the effect of DNRC on voltage profile, power and energy losses. Moreover, authors in [16] have used optimal DG placement strategy for network voltage improvement. In [17], the proposed algorithm considers the demand variation through the system load curves and determines the sequence of switching operations during the reconfiguration process to minimise the energy loss as a single objective. However, this method does not consider effect of variation in real and reactive power generations from existing DGs on optimal reconfigurations. Authors in [18] investigated feeder reconfiguration in balanced and unbalanced networks and present an efficient method to optimise practical distribution systems by means of simultaneous reconfiguration and distributed generation (DG) allocation. Authors in [19] presented a multi-objective reconfiguration and DG placement simultaneously considering critical system condition in distribution systems aiming to achieve the minimum active and reactive power losses etc. The study in [20] investigated multi-objective reactive power optimisation of distribution system penetrated with DG. Integrating the reactive power of DG as one type of decision variables, a multi-objective model for reactive power optimisation has been established to decrease the system active power loss, reduce voltage deviation and minimise the total capacity of reactive power compensation devices (or minimises investments on these devices). However, this reference paper has not considered impact of optimal network reconfiguration on performance. In [21], four objectives are considered for minimisation, active power loss, maximum node voltage deviation, number of switching operations and load balancing index. However, this article has main focus on developing of improved optimisation technique rather considering the effects of DGs with variable power factor on waste of renewable energy loss with reconfiguration. Authors in [22] propose a multi-period OPF approach for assessing the improvement of DG hosting capacity of distribution systems by applying static reconfiguration or dynamic reconfiguration, together with active network management schemes. However, this formulation only considered single objective approach with combining all in constraints and did not consider impact on renewable energy wastage. The optimal status of the switches in order to maximise the reliability and minimise the real power loss is found by a binary particle swarm optimisation-based search algorithm from method suggested in [23].

From aforementioned literatures, it could be observed that most of works formulated as a single objective combining others in constraints, which is less suitable approach to consider more than one conflicting objectives. Further, many works reported in literature focused only on improvement of voltage profile and reduce power/energy losses by optimal DG placement as well as network reconfiguration in planning horizon, however, it seems no one considered the combined effects of network reconfiguration as well as optimal reactive power dispatches from renewable DGs on voltage profile, power loss and renewable energy waste from DGs in operating horizon.

1.2 Contribution of the paper

Therefore, this paper proposes a multi-objective approach to assess the impacts of optimal network reconfiguration in combination with optimal reactive power dispatch of DGs on the various performances by using non-dominated sorting particle swarm optimisation (NSPSO) during different load demand periods in operating horizons. The considered network performances, i.e. minimisation of power loss, voltage deviation and energy waste from DGs for the proposed scheme, are examined considering frequent changes in load and DG output for a 24-hour period, and compared with that of the original network and also with cases with either network reconfiguration or reactive power dispatch from DGs alone. In addition, optimisation algorithm as well as proposed results have been compared and found to be better over

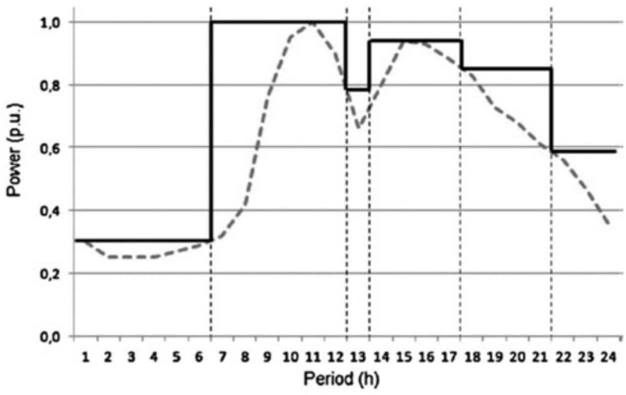

Fig. 1 *Typical demand curve [24]*

literature work in [14]. Further, it would be worthwhile to note that this work has not proposed any technique for optimal DGs placement, but its considered locations are assumed to be obtained for planning horizon based on some specific objectives. However, proposed method is not restricted to any particular locations of DGs.

2 Description of generation, load and tie switches

For demonstrating the impact of reconfiguration, the load demand periods/intervals are constructed from the average of historical data (typical daily demand curve), and the curve is divided into six periods with fixed load demand in each interval. The representative load/demand as well as DG's profile for one entire period is the maximum value observed/assumed in it. In this way, constraints are always tested for the worst case expected for the whole period, and there is a lower risk that the configuration at a particular load demand and DG profile presents a constraint in another demand period. Though forecasted data for day ahead is not much accurate, here it has been assumed that it is available with uncertainty limited to six intervals only. Based on a day ahead forecasted data, a switching schedule is planned ahead for various time segments in the day in order to have the optimal performance for the entire time period considered. The best network configuration for each time frame is evaluated from the optimisation algorithm based on the loading and the DG generation at that time frame. This is done to avoid too many switching operations of the switches in the network [24]. Likewise, cases of overloading in the system are also considered to depict the impact of increase in load demand in the future.

2.1 Demand evaluation

In this work, IEEE 33-bus system is considered to be the test system for this study and so total load of it is approximated along demand curve as shown in Fig. 1. The load at each of the six time frames is considered to be fixed, and equal to the maximum load at that time frame to be considered the worst case condition. In other words, load curve is fixed at maximum demand value during particular period of the day (here assumed total six periods per day). At the beginning of each period, the optimal configuration for the next period is determined.

2.2 DG profile

In this paper, it has been assumed that all DGs are of small scale range connected to the system at medium voltage. Like in the case of load profile, the DG profile is considered for a 24 h duration, which is divided into the same six time frames. The DG generation output for each time frame is considered to be the average output for that time frame. In addition, these days renewable penetration is not high in most of networks, and so they are always encouraged to operate at unity power factor for maximum renewable energy generation/utilisation. However, this scenario may not exist in future

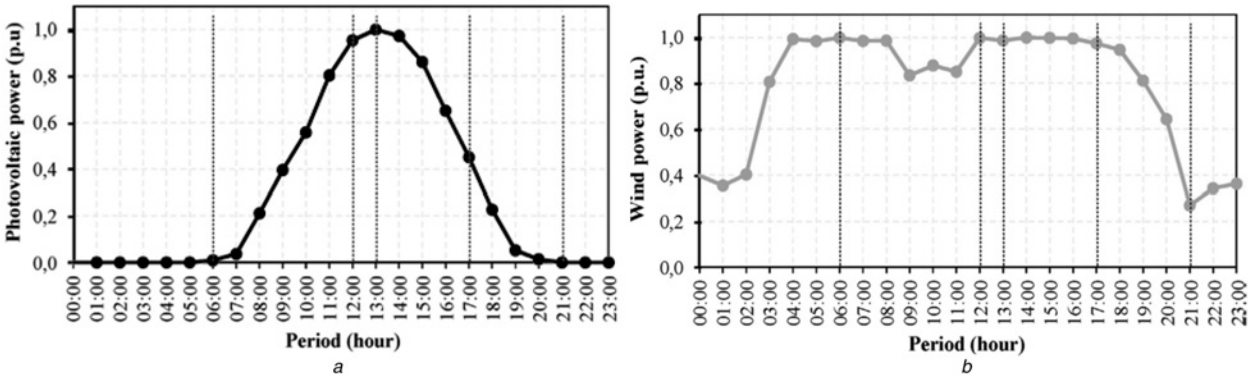

Fig. 2 *Normalised DG generation curve [1]*
a For solar PV-type DG
b For Wind-type DG

because of high penetration of renewable based DGs, where voltage supports is no longer avoidable from it due to technical reasons. Therefore, in this work, it is assumed that DGs are able to operate from 0.8 lagging to unity power factor to take voltage support from them during requirement as case may be. Further, optimal reconfiguration is suggested to minimise the dependency of voltage support on DG sources only and, hence, allowed to generate/utilise maximum possible renewable energy from available sources.

(i) Solar generation: For this work, a typical daily solar photovoltaic(PV) generation curve for a clear sky condition is considered for estimation of PV output for a given day as shown in Fig. 2*a*. It is assumed that the PV-based DG capacity of 1.5 MW is installed at bus-16 in the IEEE 33-bus radial system. In other words, solar PV uncertainty is considered conservatively up to six intervals per day only, rather taking it as fixed values for whole day.

(ii) Wind generation: Further, a typical daily wind power generation curve is considered as shown in Fig. 2*b*. For practical purpose, such curve may be derived from statistical analysis of the historical data for average wind speed. In other words, wind uncertainty is considered conservatively up to six intervals per day only, rather taking it as fixed values for whole day. Therefore, it is assumed that a 0.8 MW wind powered DG is installed at bus-30 in same IEEE 33-bus system.

2.3 Tie switches

In this study, the effect of switching transient (which could be matter of dynamic analysis) has been omitted because focus is on enhancement of steady state performance. However, due to recent development in power electronics, more sophisticated switching devices have been designed and so, it is assumed that no issue here. For example, flexible tie switch (FTS) [25] is a new kind of tie switch based on power electronics technology, which is better than traditional disconnectors and circuit breakers; it can accurately control the active power and reactive power flow between the two connected feeders. Moreover, FTS also has the advantage of fast response speed, ability of frequent action and continuous control. Similarly, solid-state circuit breakers (SCBs) [26], based on modern high-power semiconductors, offer considerable advantages when compared with mechanical circuit breakers with respect to speed and life. To enhance performance further, an SCB based on thyristors, which is able to actively turn-off short circuit currents, is also developed in literature.

3 Problem formulation

3.1 Main objective functions

Four different objectives have been considered in this paper for performance improvement of the distribution system and formulated as follow.

$$\text{Minimise} f(\boldsymbol{x},\boldsymbol{pf}) = [f_1(x,\boldsymbol{pf}), f_2(x,\boldsymbol{pf}), f_3(\boldsymbol{pf}), f_4(\boldsymbol{pf})] \quad (1)$$

where, $f_1(\boldsymbol{x},\boldsymbol{pf})$ = Line loss; $f_2(\boldsymbol{x},\boldsymbol{pf})$ = Voltage deviation; $f_3(\boldsymbol{pf})$ = Energy wastage from solar PV-based DG due to varying power factor operation; $f_4(\boldsymbol{pf})$ = Energy wastage from wind-based DG due to varying power factor operation; $\boldsymbol{x} = [x_1, x_2, x_3, \ldots, x_n]$ = minimised the set of switches selected to be opened for reconfigurations; $\boldsymbol{pf} = [pf_{PV}\ pf_{Wind}]$ = set of DGs power factors; pf_{PV} = power factor of solar PV-based DG; pf_{Wind} = power factor of wind-based DG.

(i) Minimisation of power loss: The first objective is to minimise the total line real power loss in the network as formulated as

$$\text{Minimise} f_1(\boldsymbol{x},\boldsymbol{pf}) = \sum_{i=1}^{N_{br}} Ploss_i = \sum_{i=1}^{N_{br}} k_i R_i |I_i^2| \quad (2)$$

where, $i = 1, 2, \ldots, N_{br}$; $k_i = 0$, (if ith branch is open) and; $k_i = 1$, (if ith branch is closed).

(ii) Minimisation of voltage deviation: The second objective is to minimise the maximum voltage deviation in any of the given bus after reconfiguration as formulated as

$$\text{Minimise} f_2(\boldsymbol{x},\boldsymbol{pf}) = \max\left[\left|V_{ref} - \min_{i=1,2,\ldots,N_{bus}}\{V_i\}\right|, \left|V_{ref} - \max_{i=1,2,\ldots,N_{bus}}\{V_i\}\right|\right] \quad (3)$$

(iii) Minimisation of reduction of active power generation from DG: The third and fourth objectives are to minimise the reduction of active power generation from solar PV and wind based DGs each due to operation at lagging power factor as formulated in (4). For this study, both solar PV and wind based DGs are assumed to have a simplified capability curve within the power factor limit of 0.8 lagging to unity. This capability is now necessary to include grid code compliance in DGs so that they can be employed for voltage support during need, especially heavy loading and/or high penetration of DGs.

$$\text{Minimise} f_3(\boldsymbol{pf}) = \text{PV\_Gen} \times (1 - pf_{PV}) \quad (4)$$

$$\text{Minimise} f_4(\boldsymbol{pf}) = \text{Wind\_Gen} \times (1 - pf_{Wind}) \quad (5)$$

where, PV_Gen = Maximum generation capacity of PV-based DG at a given time frame;
Wind_Gen = Maximum generation capacity of Wind-based DG at a given time frame.

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3.2 Network technical constraints

(i) Power balance

$$P_i - V_i \sum_{j=1}^{N_{\text{bus}}} V_j Y_{ij} \cos(\delta_i - \delta_j - \theta_{ij}) = 0 \quad (6)$$

$$Q_i - V_i \sum_{j=1}^{N_{\text{bus}}} V_j Y_{ij} \sin(\delta_i - \delta_j - \theta_{ij}) = 0 \quad (7)$$

where, $i = 1, 2, \ldots, N_{\text{bus}}$.
(ii) Bus voltage operating limit: All bus voltages should be within the specified operational limit after reconfiguration in order to ensure stability and power quality, as

$$V^{\min} \le V_i \le V^{\max} i = 1, 2, \ldots, N_{\text{bus}} \quad (8)$$

(iii) Line current limit: All connected lines should be operated with current passing through them maintained within their specified limit in order to ensure system security, as formulated below

$$k_i |I_i| \le I_i^{\max} \quad i = 1, 2, \ldots, N_s \quad (9)$$

Satisfying (8) for all lines in the distribution network also ensures that the distribution feeders operate within their specified limit as well.
(iv) Radiality of distribution network: It is desired that even after reconfiguration, the network still remains a radial one. In order to do so, the following relationship has to be followed for the number of branches connected in the system.

$$N_{\text{br}} = N_{\text{bus}}\text{-}1 \quad (10)$$

3.3 Backward/forward sweep load flow algorithm

Electric distribution network differ from transmission network in various aspects, as follows:

- They usually have a radial network structure, whereas a transmission network is usually a mesh network.
- The load they serve is usually non-uniformly distributed which may result in unbalanced operation.
- Distribution networks usually have an extremely large number of branches/nodes, with lesser number of connections for each bus/node.
- They may have a wide variation in resistance and reactance values for all branches, with usually higher value of resistance to reactance ratio(R/X) than for transmission lines.

Due to these differences, the conventional load flow methods, like Newton–Raphson method or Gauss–Siedel method, which are used in transmission networks, may not be applicable or accurate for load flow in distribution network. Hence, an alternative load flow method suited for distribution networks called backward/forward sweep load flow algorithm is used in this work assuming that the network has a balanced three-phase system. The general algorithm consists of two basic steps, backward sweep and forward sweep, which are repeated until convergence is achieved. The backward sweep is primarily a current or power flow summation with possible voltage updates. The forward sweep is primarily a voltage drop calculation with possible current or power flow updates.

4 Implementation of NSPSO approach for optimum network reconfiguration

This paper incorporates NSPSO, which is a multi-objective optimisation technique based on evolutionary theory and is a modification of the conventional PSO technique that is designed to solve multi-objective optimisation problems [27]. NSPSO is an optimisation technique based on evolutionary theory and is a modification of the conventional PSO technique that solves multi objective problems. Instead of a single comparison between a particle's personal best and its offspring as in the conventional single objective PSO, NSPSO compares all particles' personal bests and their offspring in the entire population. This measure provides a better means to filter out the best solution out of the entire population in order to drive the solution closer to the true Pareto optimal front. Therefore, the overall methodology implementation of NSPSO for network reconfiguration as well as optimal reactive power dispatch from DGs is demonstrated in following steps.

(i) Input time frame of day(t).
(ii) Change in time frame from the previous count?
  a) No, go to step-(ix).
  b) Yes, go to next step.
(iii) Based upon day-ahead forecasted data, estimate the average DG generation and maximum load profile for ith time frame of day.
(iv) Consider the overloading percentage of load data, if require.
(v) Perform optimisation of network reconfiguration and/or DG power factor using NSPSO and back–forward sweep load flow method.
(vi) Select the best compromise solution from the Pareto-front set.
(vii) Reconfigure the network as per the obtained optimal configuration and also adjust the power factor of DGs to the optimal value.
(viii) Is all time frame of day is completed?
  a) No, go to step-(i).
  b) Yes, go to next step.
(ix) End and print the results.

However, the basic steps for implementation of NSPSO for network reconfiguration are demonstrated by the flowchart in Fig. 3. This algorithm is implemented just before each time frame in the 24 h period considered after real time measurements give an approximation of the load forecasted for the upcoming time frame. The best compromise solution is selected for each time frame and the corresponding configuration is maintained throughout the time period to reduce too many switching operations. Likewise, back–forward sweep load flow method is adopted for this work as it is more suited for distribution network [28].

For implementation of NSPSO in this work, it takes a combination of switches that are considered for opening as the input or the independent variable set. Therefore, the variable 'x' in objective function is to minimise the total number of switching operations between any two consecutive time intervals so as to minimise the mechanical stress on the switches as formulated in (1). Further, a set of restrictions needs to be applied in the selection of switches in order to maintain the radiality of the network and to prevent islanding of any of the network components. Hence the following reconfiguration constraints are applied to avoid the selection of infeasible switch sets [29].

- The total number of switches selected for each particle is equal to the number of loops formed when all the tie switches and sectionalising switches are closed.

$$\boldsymbol{X}_i = [X_{i,1}, X_{i,2}, \ldots, X_{i,d}, \ldots, X_{i,D}] \quad (11)$$

where, D = Total number of loops in the network; $\boldsymbol{X}_i$ = vector of switch indices for ith particle.
- The dth element of the particle X_i must belong to the dth loop or mesh.

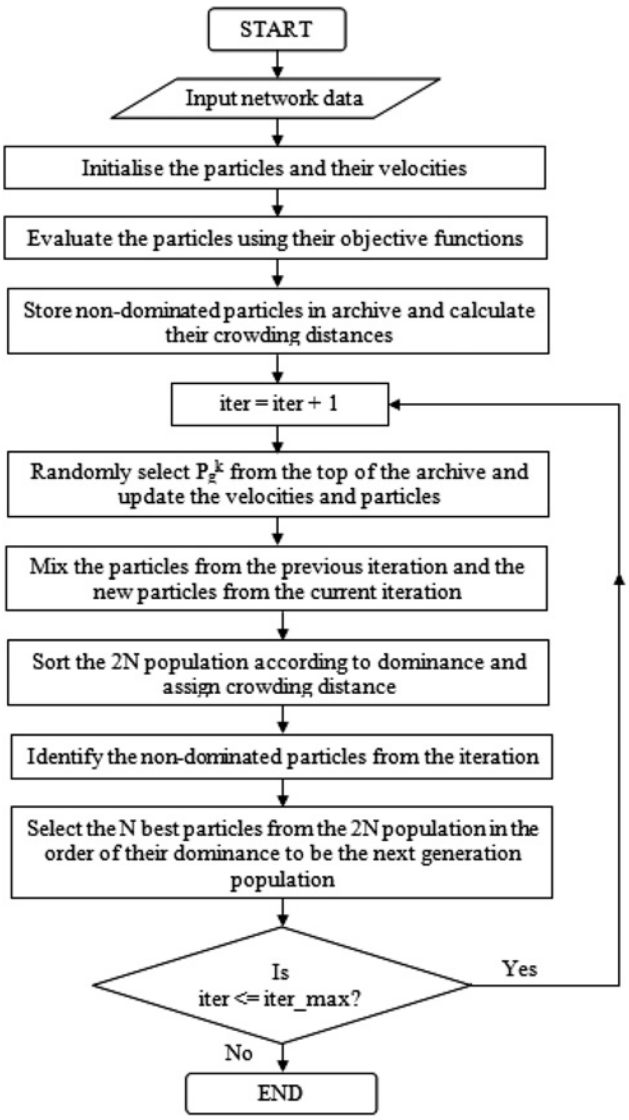

Fig. 3 *Flowchart of the proposed method for implementation of NSPSO for network reconfiguration*

- Only one switch from a branch string or vector common to any two loops can be opened. For instance, only one switch from vector L_{12} or L_{13} can be open at a time as in Fig. 4.
- Likewise, only one switch from a continuous branch string or vector between any two nodes can be open. For example, only one switch from vector L_{33} can be open.
- All branches intersecting on a common node cannot have any open switch in them at the same time. For instance, L_{12}, L_{13} and L_{23} intersect at node $\boldsymbol{c}$. Hence, at least one of the vectors cannot have an open switch in it at any given time.

Further, in this work, for avoiding the selection of unfeasible switches, the following algorithm has been proposed:

- Collect all switch indices for dth loop for the selection of dth element.
- Find out any branch vectors in the dth loop that have already been open. Remove from the collection all the switch indices belonging to the already opened branch vectors.
- Find out all nodes connected to the dth loop that have more than two branch vectors intersection. Find out the intersection branch vectors which already have an open switch in them. If all but one branch vector have open switch, remove from the collection the switch indices to the intersection branch vector that belongs to the dth loop.
- Make sure that one of the switch indices from that collection gets selected for the dth element.

5 System studies

5.1 Validation of optimisation technique

Though, NSPSO is not a contribution of this paper but it has been applied on this type of problem to assess performance in comparison of the results of [14] to see its effectiveness. Here, DNRC is performed using discrete particle swarm optimisation algorithm.

The objectives considered are minimisation of the power loss, the number of switching operations and deviations of bus voltages from their rated values subjected to system constraints and IEEE 33-bus network, see Fig. 4, and is taken as the test system without DG installation. The detail of the Pareto front solutions produced by applied NSPSO as well as MOPSO techniques in [14] are presented in Table 1 on the same test system. The first nine results obtained by NSPSO method is same as obtained in [14] and hence, these are not shown here for sake of space. However, from tenth and onwards results are better than [14], where five particles (rows 1–5) from NSPSO are more dominant than [14].

Thus, it is seen that the applied NSPSO technique is capable of producing more dominant Pareto set solutions than method suggested in [14]. Therefore, it can be concluded that the applied NSPSO method in this work is suitable for further studies related to multi-objective network reconfiguration.

5.2 Results and discussions of proposed optimal network reconfiguration by using NSPSO

The NSPSO-based network reconfiguration is implemented considering DG penetration in the network and 24-hour variation categorised in six periods for load and DG generation profiles for a particular day.

Further, DG power factor is optimised for reactive power generation in addition to network reconfiguration for improvement of network performance. Moreover, DG's power factor is also optimised to reduce real power wastage, which caused by its operation at other than unity/constant power factor to support network voltages. The effectiveness of the proposed approach is demonstrated through comparison of the network performance by four cases, where the cases-2 and 4 are the suggested schemes in this work. Table 2 represents various case studies carried out in this work.

Further evaluating the effectiveness of the proposed scheme, load increase is considered in the IEEE 33-bus network, which is attributed to future demand increase. The load increase is assumed to be uniform throughout the system and periods. The energy loss for each time frame is calculated by running load flow for each period considering the average load and DG output for the corresponding period for the network configuration selected through the optimisation for the given time frame.

The parameter settings for NSPSO are set to $\varpi^{\max} = 0.9$ and $\varpi^{\min} = 0.3$, while acceleration coefficients c_1 and c_2 are at 2.0. The population size and iteration are 50 and 50, respectively. The set of input variables, i.e. the opened switches and the operating power factor for the DGs, for each of the cases and for each time period/frame is presented in Tables 3–5. For case-1 and case-2, no reconfiguration is considered but tie switches-33 to 37 are kept open at all times and are hence not mentioned in the tables. Further, for case-1 and case-3, each DG's operating power factor is considered to be unity at all times and are also mentioned in corresponding tables. However, it is assumed that power factor of DGs would be allowed to vary between 0.8 lagging to 1.0 as case may be. It is also assumed that the average power output of solar PV based DG is zero for hours between 0:00 to 6:00 and for 21:00 to 24:00 h of the day; while the output is very small for

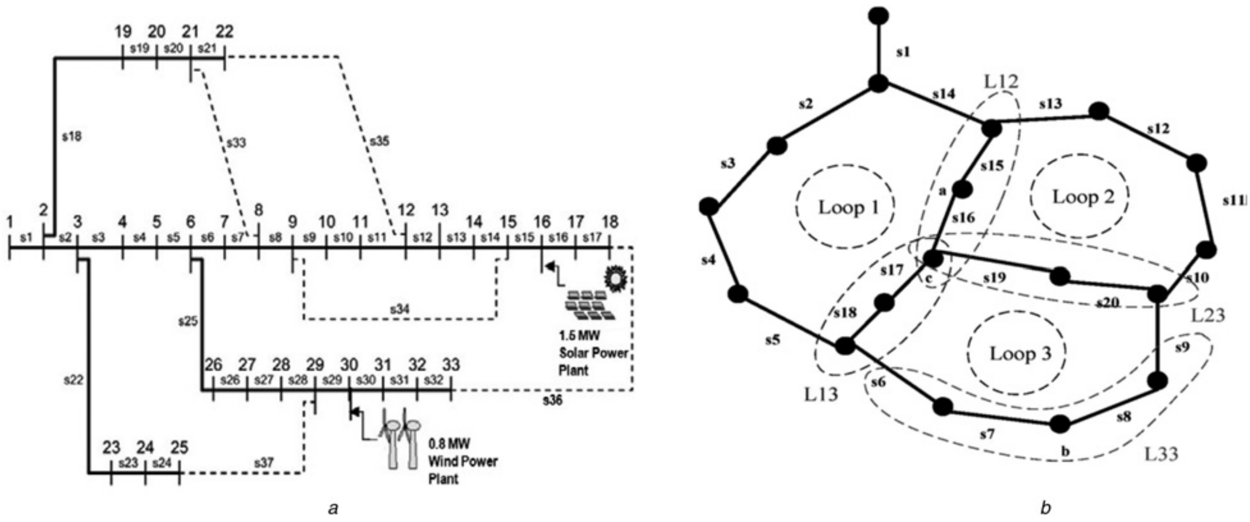

Fig. 4 *Single line diagram of IEEE 33-bus and its sample network*

a Single line diagram of IEEE 33-bus radial distribution system with DGs
b Sample network [8]

Table 1 List of non-dominated particles obtained in this work as well as in [14]

Sl. No.	Switches opened		Max. voltage deviation, p.u.		No. of switching operations		Total line loss, MW	
	Proposed work	Reference [14]	Proposed work	Reference [14]	Proposed work	Reference [14]	Proposed work	Reference [14]
1	6-11-34-37-36	7-28-33-34-36	0.0627	0.06316	4	4	0.1450	0.15628
2	7-9-14-37-36	9-28-33-34-36	0.0664	0.06334	6	4	0.1422	0.14636
3	7-11-34-37-36	7-9-34-36-37	0.0664	0.06641	4	4	0.1445	0.14615
4	7-33-34-37-36	26-33-34-35-36	0.0664	0.06991	2	2	0.1565	0.18004
5	33-8-34-37-36	27-33-34-35-36	0.0702	0.07072	2	2	0.1535	0.17727

Table 2 Different case studies

Cases	Minimisation of different objectives				Remarks
	Real power loss	Voltage deviation	Reactive power output from DGs	Network reconfigurations	
case-1	yes	yes	no (unity power factor operation)	no (tie switches always open)	basecase
case-2	yes	yes	yes (varying power factor operation)	no (tie switches always open)	to see impact of DG power factor only
case-3	yes	yes	no (unity power factor operation)	yes	to see impact of tie switches operation only
case-4	yes	yes	yes (varying power factor operation)	yes	to see impact of both varying DG power factor and tie switches

Table 3 Results of tie-switch operations and DGs power factor for cases-2 to 4 at normal load

Time duration	Case-2		Case-3	Case-4		
	Power factor of solar PV-DG	Power factor of wind DG	Switches opened	Switches opened	Power factor of solar PV-DG	Power factor of wind DG
00:00–06:00	N/A	0.8911	33-11-14-37-34	33-11-14-25-15	N/A	0.948
06:00–12:00	0.9739	0.8430	33-9-14-28-31	33-8-14-27-31	0.970	0.937
12:00–13:00	0.9647	0.9407	33-35-9-28-30	33-21-9-28-30	0.942	0.936
13:00–17:00	0.9514	0.8816	7-9-13-37-31	6-9-12-28-31	0.977	0.935
17:00–21:00	0.8765	0.8282	7-9-14-37-32	7-10-14-37-36	1	0.903
21:00–24:00	N/A	0.9186	7-9-14-37-36	7-9-14-37-36	N/A	0.897

hours 17:00 to 21:00, and is zero for the later part. Moreover, both normal as well as increased load conditions are assumed to be for 24 h time duration.

From cases-2 and 4 in Table 3, it can be observed that power factors are better in later case due to obtaining different optimal opening positions of tie switches and, hence, reconfiguration has

Table 4 Results of tie-switch operations and DGs power factor for cases-2 to 4 at 10% increased load

Time duration	Case-2		Case-3	Case-4		
	Power factor of PV-DG	Power factor of wind DG	Switches opened	Switches opened	Power factor of solar PV-DG	Power factor of wind DG
00:00–06:00	N/A	0.8446	9-14-16-26-33	11-14-16-33-37	N/A	0.929
06:00–12:00	0.8996	0.8263	9-14-28-31-33	8-9-14-28-33	0.957	0.945
12:00–13:00	0.9887	0.8518	10-12-28-30-33	6-10-21-28-30	0.964	0.919
13:00–17:00	0.9678	0.8457	7-10-13-28-31	7-31-34-35-37	0.956	0.952
17:00–21:00	0.8756	0.8261	7-9-14-28-32	7-9-14-36-37	1	0.862
21:00–24:00	N/A	0.8347	7-9-14-28-36	7-9-14-36-37	N/A	0.885

Table 5 Results of tie-switch operations and DGs power factor for cases-2 to 4 at 20% increased load

Time duration	Case-2		Case-3	Case-4		
	Power factor for solar PV-DG	Power factor for wind DG	Switches opened	Switches opened	Power factor for solar PV-DG	Power factor for wind DG
00:00–06:00	N/A	0.9203	9-14-16-28-33	11-14-15-33-37	N/A	0.967
06:00–12:00	0.8464	0.8154	9-14-28-31-33	9-14-33-34-37	0.908	0.907
12:00–13:00	0.9361	0.8948	10-13-28-30-33	6-11-12-27-30	0.982	0.958
13:00–17:00	0.9672	0.8480	7-11-14-31-37	7-9-12-31-37	0.945	0.891
17:00–21:00	0.8	0.8310	7-9-14-28-32	9-14-28-32-33	0.997	0.899
21:00–24:00	N/A	0.8339	7-9-14-28-36	7-9-14-36-37	N/A	0.874

Table 6 Optimal energy loss and minimum voltages for cases-2 to 4 at normal loading

Time duration	Case-1		Case-2		Case-3		Case-4	
	Energy loss, MWh	Min. observed voltage, pu	Energy loss, MWh	Min. observed voltage, pu	Energy loss, MWh	Min. observed voltage, pu	Energy loss, MWh	Min. observed voltage, pu
00:00–06:00	0.0623	0.9796	0.0397	0.9805	0.0522	0.9835	0.0279	0.9857
06:00–12:00	0.3202	0.9576	0.1902	0.9643	0.2405	0.9710	0.1782	0.9732
12:00–13:00	0.0920	0.9859	0.0627	0.9871	0.0493	0.9888	0.0226	0.9923
13:00–17:00	0.3560	0.9654	0.2060	0.9731	0.2640	0.9698	0.1555	0.9673
17:00–21:00	0.3118	0.9448	0.2539	0.9454	0.2319	0.9634	0.1957	0.9633
21:00–24:00	0.0916	0.9566	0.0821	0.9573	0.0671	0.9722	0.0582	0.9740
Total energy loss, MWh	1.2338		0.8346		0.9050		0.6381	

positive impacts and that's able to reduce wastage of renewable energy from solar and wind DGs.

Similarly, from Tables 4 and 5, it can be observed that overall power factors are improved even at increased loading levels due to combining together with different optimal reconfiguration of tie switches and, hence, reconfiguration has positive impacts and that's able to reduce wastage of renewable energy from solar and wind DGs. Certainly, few tie switches are opened at different time periods due to effects of load and generation profile.

Further, from Tables 4 and 5, it can be observed that DG's power factor reduced and it means DGs are producing more reactive power at increased loading conditions to support voltages. Moreover, operation of tie switches combinations are changed in each case as well as during different time periods due to changes in output power of DGs and load demand profile shown in Figs. 1 and 2, respectively. In case-2, this is more visible during peak load, i.e. during 06.00–12.00. Similarly, there is another significant drop in power factor during 17.00–21.00 when solar PV generation reduced drastically in case-2. However, after using optimal reconfigurations, both DG's power factor have improved (in case-4) compared to without reconfigurations (in case-2). Since solar PV inverter has better capability to produce reactive power and hence, it has better power factor compared with wind based DG in most of cases.

The network performance in terms of total energy loss in lines and minimum observed bus voltage magnitude for each time frame for all cases for each loading condition is presented in Tables 6–8. From Table 6, energy losses are lower for case-2 compared with case-3 in most of periods when solar/wind DGs are in use along with optimising reactive power output as well. In other words, optimal power factor scheme (case-2) is providing better results in terms of total energy loss, i.e. 0.8346 MWh over only tie switches/reconfiguration scheme (case-3), i.e., 0.9050 MWh. Further, voltage profile is well within allowable limit. Moreover, results are improved further (total energy loss reduced by 52% compared with case-1) when combining both schemes, i.e., optimal power factor and reconfiguration (case-4) compared with other cases. Similar trends are obtained at increased load conditions as shown in Tables 7 and 8.

Therefore, from Tables 6–8, it can be seen that the case of optimised network configuration with optimum reactive power dispatch from DGs is more effective in lowering line losses for the entire period among all other cases for each loading conditions.

A summary of comparison of the total energy saving (energy waste due to DGs operations at other than unity power factor to support voltages) for each loading condition with respect to reference case-1 is presented in Table 9. In other words, it can be observed that case-2 (32.36%) is providing better reduction in total energy loss as well as voltage profile compared with case-3 (26.65%) compared with case-1 and in normal load condition. Further, case-4 providing 48.28% energy loss reduction compared with case-1 in same normal load condition. Moreover, similar patterns are followed up in case of increased loading conditions.

An hourly minimum bus voltage profile for the entire 24-hour period is plotted in Figs. 5–7 for all loading conditions to further examine in detail the voltage output for each of the cases.

From Figs. 5–7, it could be observed that case-3 (network reconfiguration) always providing better voltage profile compared with case-2 (power factor optimisation) because former one assist

Table 7 Optimal energy loss and minimum voltages for cases-2 to 4 at 10% increased load

Time duration	Case-1		Case-2		Case-3		Case-4	
	Energy loss, MWh	Min. observed voltage, pu	Energy loss, MWh	Min. observed voltage, pu	Energy loss, MWh	Min. observed voltage, pu	Energy loss, MWh	Min. observed voltage, pu
00:00–06:00	0.0704	0.9771	0.0434	0.9780	0.0492	0.9838	0.0382	0.9850
06:00–12:00	0.3818	0.9497	0.2184	0.9574	0.2890	0.9647	0.2232	0.9704
12:00–13:00	0.0963	0.9801	0.0639	0.9847	0.0548	0.9861	0.0276	0.9891
13:00–17:00	0.4101	0.9580	0.2448	0.9658	0.2833	0.9610	0.2086	0.9637
17:00–21:00	0.4088	0.9386	0.3421	0.9393	0.2969	0.9594	0.2549	0.9588
21:00–24:00	0.1141	0.9517	0.1015	0.9525	0.0825	0.9689	0.0727	0.9703
Total energy loss, MWh	1.4815		1.0141		1.0557		0.8252	

Table 8 Optimal energy loss and minimum voltages for cases-2 to 4 at 20% increased load

Time duration	Case-1		Case-2		Case-3		Case-4	
	Energy loss, MWh	Min. observed voltage, pu	Energy loss, MWh	Min. observed voltage, pu	Energy loss, MWh	Min. observed voltage, pu	Energy loss, MWh	Min. observed voltage, pu
00:00–06:00	0.0799	0.9746	0.0549	0.9754	0.0572	0.9826	0.0485	0.9808
06:00–12:00	0.4565	0.9414	0.2741	0.9497	0.3469	0.9582	0.2672	0.9675
12:00–13:00	0.1026	0.9742	0.0604	0.9828	0.0613	0.983	0.0392	0.9847
13:00–17:00	0.4775	0.9506	0.2949	0.9585	0.3603	0.9589	0.2197	0.9624
17:00–21:00	0.5055	0.9308	0.432	0.9331	0.3646	0.9549	0.3316	0.9563
21:00–24:00	0.1393	0.9468	0.1255	0.9476	0.1004	0.9654	0.0892	0.9666
Total energy loss, MWh	1.7613		1.2418		1.2907		0.9954	

Table 9 Summary of minimum energy losses for all cases at different loading conditions

Different cases	Normal load		10% increased load		20% increased load	
	Total energy loss, MWh	Comparative loss reduction, %	Total energy loss, MWh	Comparative loss reduction	Total energy loss, MWh	Comparative loss reduction
case-1	1.2338	–	1.4815	—	1.7613	—
case-2	0.8346	32.36	1.0141	31.55	1.2418	29.50
case-3	0.9050	26.65	1.0557	28.74	1.2907	26.72
case-4	0.6381	48.28	0.8252	44.30	0.9954	43.48

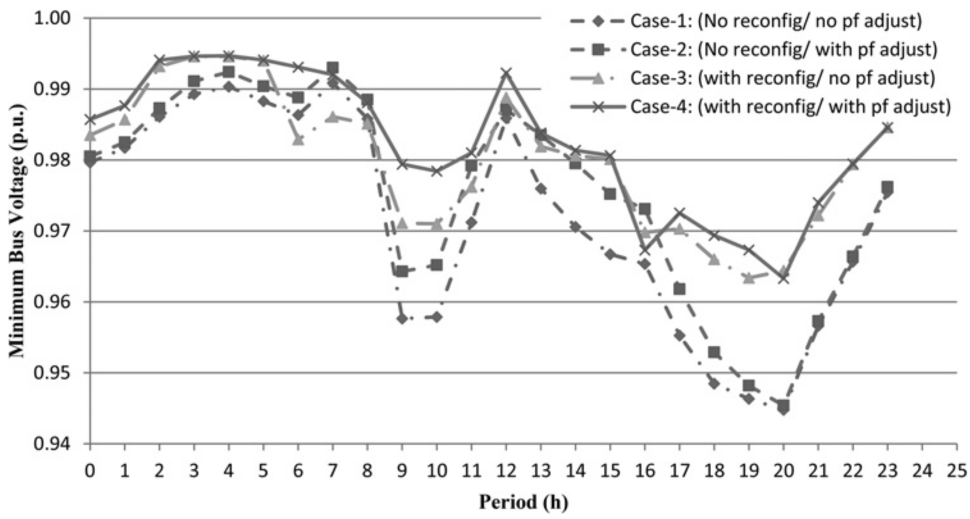

Fig. 5 *Minimum bus voltage observed for every hour of a day for all cases for nominal loading*

better sharing of reactive power among loads. Further, it is seen that although case-4 does not provide better voltage at all nodes compared with other cases but overall voltage profile throughout the time period is much better over other cases.

Although reactive power dispatch from DG contributes in reduction in power loss and voltage deviation, some active power generation from DG is sacrificed for this cause due to operation at other than unity power factor. However, this reduction in output energy generation from DGs is seen to be much less with network reconfiguration than compared to without it. This is demonstrated in Table 10 for the energy wastage of solar PV and wind type DGs for each loading case. From Table 10, it can be observed that to support voltage improvement with case-4 (tie switch operation), renewable energy waste reduced by 41.04% and 44.60 for solar and wind, respectively, compared with case-2 (with DG's output reactive power optimisation) for normal load conditions. Similar

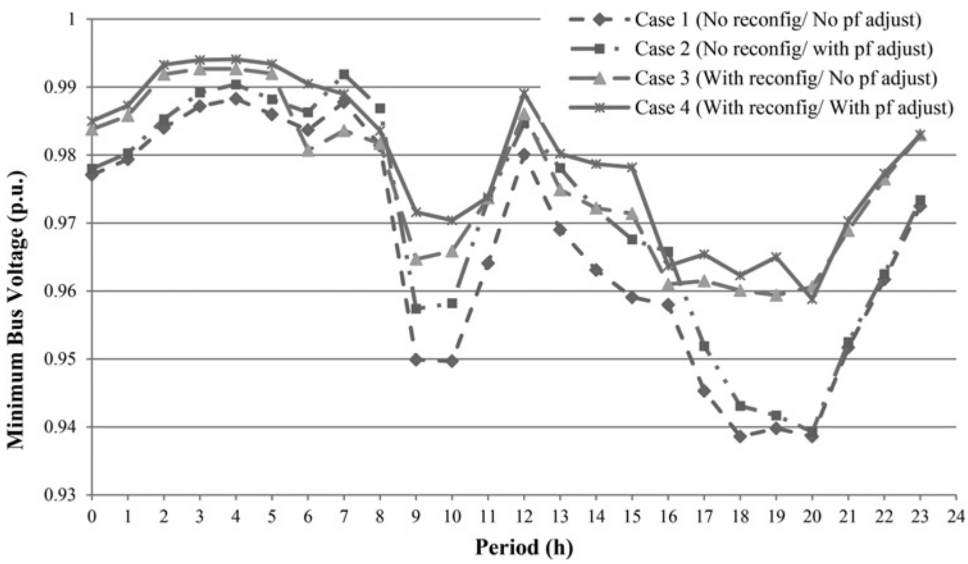

Fig. 6 *Minimum bus voltage observed for every hour of a day for all cases for 10% increased load*

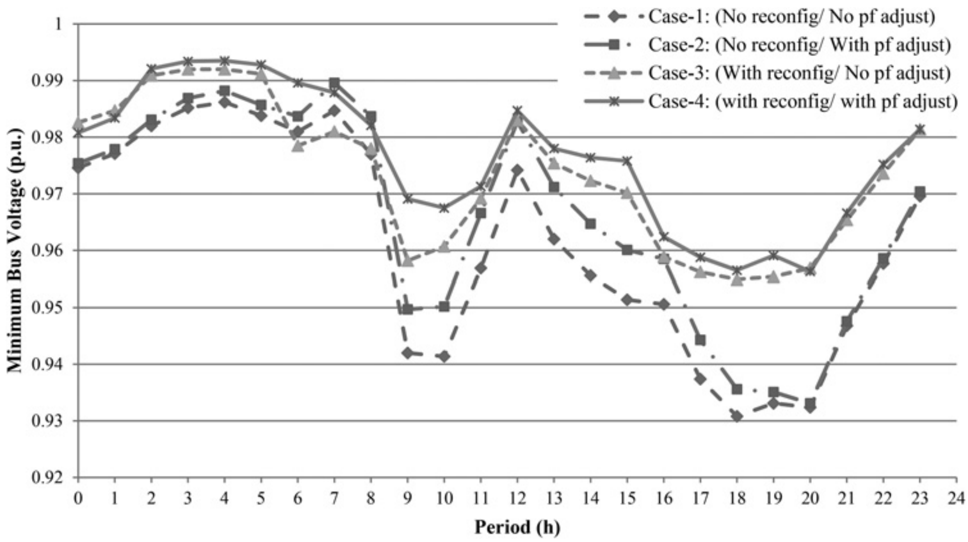

Fig. 7 *Minimum bus voltage observed for every hour of a day for all cases for 20% increased load*

Table 10 Comparison of DG energy waste due to reactive power generation to support voltages

Effects of tie switches operation on saving of energy waste from renewable DGs

Cases	Nominal loading				10% increased loading				20% increased loading			
	Energy waste from DGs, MWh		Saving in energy waste from DGs compared with case-2		Energy waste from DGs, MWh		Saving in energy waste from DGs compared with case-2		Energy waste from DGs, MWh		Saving in energy waste from DGs compared with case-2	
	PV	Wind	PV	Wind	PV	Wind	PV	Wind	PV	Wind	PV	Wind
case-2	0.4413	1.9127	–	–	0.6048	2.4084	–	–	0.9205	2.1473	–	–
case-4	0.2602	1.0596	41.04%	44.60%	0.4202	1.0814	30.52%	55.10%	0.6293	1.2204	31.63%	43.17%

trends obtained at increased load conditions as well. Hence, it could be concluded that optimal network reconfiguration would have significant positive impact on saving of renewable energy waste from DGs as case may be. Though, reduction in renewable energy waste from DGs at increased load conditions are not obtained in same proportion to normal loading but still a significant saving achieved in quantity.

6 Conclusion

In this paper, an effective algorithm proposed for reducing power losses, voltage deviation and wastage of renewable energy from optimal network reconfigurations as well as reactive power dispatch from DGs by using NSPSO. Since this proposed method applied during operating horizon and so more benefits are able to

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derive from frequent changes in network topology in combination of optimal DG's output while maintaining all parameters within limits. Test results indicated that the network performance has been improved with DNCR in terms of loss reduction and voltage profile improvement. It is also seen that reactive power dispatch from DG or network reconfiguration alone do not produce the best result, especially during heavy loading conditions due to increased load demand. However, when the two are coordinated together, they produce better network performance in terms of minimisation of power loss, voltage deviation and renewable energy wastage. In addition, network reconfigurations also help to distribute reactive power efficiently among loads so that it reduced the reactive power demand from DGs to support voltages. Thus, with proper facilities of SCADA communication and real time measurement in distribution automation, a switching schedule for optimum network reconfiguration can be generated considering the variation in load and DG output for the overall improvement in network performances.

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