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Particle swarm optimization based reactive power coordinated control of distributed generation and voltage controlled devices

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In recent days, the research on reactive power coordination among Distributed generation (DG) and voltage controlled devices (VCDs) becomes popular and attracting researchers. The penetration of DG in distribution networks (DNs) increases the switching operations of under-load tap changer (ULTC) and shunt capacitors (Schs). This paper proposes a new control method in which the output voltage of DG dispatched cooperatively along with ULTC and Schs by estimating the load one day in advance. Reduction of switching operations of voltage controlled devices (ULTC and Schs) and power loss in distribution networks are the main objectives of this paper. The objective function is formulated as multi-objective function including the constraints of DG, ULTC, Schs and grid. Particle Swarm Optimization (PSO) method is proposed to solve the multi-objective function. The proposed method is designed and implemented with MATLAB for dispatchble DG. Simulation studies demonstrate that the objective can be achieved under various grid conditions.

Keywords: *Distributed generation (DG), Voltage controlled devices (VCDs), Under-load tap changer (ULTC), Shunt capacitors (Schs), Particle swarm optimization (PSO).*

1.0 INTRODUCTION

In recent years, the involvement of Distributed generation (DG) in Distribution Networks (DNs) becomes more popular. The effective involvement of DG affects the operation of DNs in terms of steady state voltage fluctuations. The traditional reactive power control approach is not effective [1]. Donnel reported that after the DG integration into distribution network, ULTC and Automatic Voltage Regulator (AVR) switching operations increased by more than three times[2]. In [3], ULTC and Schs are controlled by Supervisory Control and Data Acquisition (SCADA), with the integration of DG these voltage controlled devices switching operations are increased up two times. This affects the life of voltage controlled devices and also causes steady state voltage fluctuations in DNs.

In [4], ULTC and Schs are optimally coordinated using dynamic programming algorithm to control steady state voltage fluctuations considering the power loss. In [5], dynamic programming algorithm is used to determine optimal dispatch schedule of ULTC and Schs considering voltage deviations of all the nodes. In [6], genetic algorithm is used to determine the optimal schedule of the Schs and ULTC. These papers considering ULTC and Schs, the concern of DG on ULTC and Schs not considered. In [7], it is reported that the conventional control set points of Schs on DNs are to be revised to accommodate the influence of DG. Vivan and Karlsson proposed coordination method for ULTC, Schs and DG to minimize the power loss in DNs, In this case the effect of induction and synchronous machine based DGs are used[8]-[9]. Freitas et al., reported a detailed comparative analysis between synchronous and

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induction machine based DGs. However, these papers not included the capability of DGs for voltage control in distribution networks(DNs).

Li et al., proposed an adaptive control method for DG, in this method the reactive power of DG is controlled according DNs voltage fluctuations [11]-[12]. In addition, DG owners and Independent power producers (IPPs) have devised regulations that require to participate in grid voltage control [13]. In [14] and [15], ADINE and DG Demonet concept was proposed, in which DGs operate together with VCDs to increase the level of penetration.

This paper proposes a new control method based on the above observations. In which DG actively participates in the coordination process along with ULTC and Schs based on a day-head load forecast. Switching operations of VCDs and Distribution network power loss are the main objectives of proposed method.

2.0 PROBLEM FORMULATION

Simple radial distribution network is considered for problem formulation purpose and is shown in Figure 1.

In Figure 1 transformer (Tr) controls the entire distribution voltage and distributed generation (DG) is capable of injecting or absorbing the required reactive power. For simplification, we assumed that the power loss in transformer is negligible and loads on distributor are treated as constant loads. Sending bus voltage, receiving bus voltage and power loss can be expressed in-terms of tap position, number of substation capacitors connected, number of feeders capacitors connected and reactive power of DG.

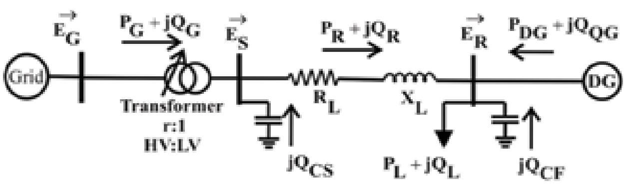

FIG.1 SIMPLIFIED SINGLE LINE DIAGRAM FOR PROBLEM FORMULATION

Based on the analysis, the optimization problem can be formulated as

$$\min, J = \sum_{h=1}^{X} \begin{pmatrix} C_{Ploss} P_{loss}^{h} + C_{Tap} \left| Tap^{h+1} - Tap^{h} \right| \\ + C_{SS} \left| NSC^{h+1} - NSC^{h} \right| + \\ C_{Feeder} \left| FC^{h+1} - FC^{h} \right| \end{pmatrix} \quad ...(1)$$

The following constraints are taken for solving the multi-objective function.

$$V_{\min} \le \left| V_i^h \right| \le V_{\max} \quad ...(2)$$

$$PF_{\min} \le \left| PF_{DG}^h \right| \le PF_{\max} \quad ...(3)$$

$$Tap_{\min} \le Tap^h \le Tap_{\max} \quad ...(4)$$

$$0 \le FC^h \le FC_{\max} \quad ...(5)$$

$$0 \le NSC^h \le NSC_{\max} \quad (6)$$

Where i =1,2........NB

h=1, 2.......NT

The variables used in equations (1) - (6) are defined as follows:

C_{Ploss} Total power loss cost-weighting factor

C_{Top} ULTC cost weighting factor

C_S Substation capacitors cost weighting factor

C_{Feeder} Feeder capacitors cost weighting factor

P_{loss}^h Total power loss at time h

$\left| V_i^h \right|$ Voltage magnitude of bus i at time h

$\left| PF_{DG}^h \right|$ Power factor of DG at time h

$\left| Tap^h \right|$ ULTC tap position at time h

FC^h Number of feeder capacitors at time h

NSC^h Number of substation capacitors at time h

X, NT Number of time intervals

V_{min}, V_{max} Minimum and maximum voltage limits

PF_{min}, PF_{max} Minimum and maximum power factor limits of DG

Tap_{min}, Tap_{max} Minimum and maximum tap position limits of ULTC

FC_{max}, NSC_{max} Maximum number of capacitors at feeder and at substation respectively

NB Number of buses in the system

The multi-objective function has four parts, the first term represents cost of distribution network power loss, the second term represents cost resulting from switching loss of ULTC, and the remaining terms represents cost resulting from switching operations of Schs at substation and feeder respectively. ULTC is more expensive device; therefore, in this paper cost weighting factors of ULTC and power loss are more as compared with Schs.

3.0 PARTICLE SWARM OPTIMIZATION

Particle Swarm Optimization (PSO) algorithm is very popular for optimizing the objective function. This algorithm has favourable performance as compared with other heuristic algorithms [16]-[17]. In this paper, we preferred PSO for minimizing the multi-objective function.

Particle swarm optimization method works on particle movements. Initially all the particles are starting from a random position and moves randomly with relative velocities, then updating their positions based best particle position decided in the previous iteration. The description of PSO can be mathematically modelled as

$$Y_i^{k+1} = round\left(w.Y_i^k\right) + round\left(\begin{matrix} c_1.rn(0,1). \\ \left(P_i^k - X_i^k\right) \end{matrix}\right)$$

$$+ round\left(c_2.rn(0,1).\left(G^k - X_i^k\right)\right) \quad ...(7)$$

$$w = w_{\max} - \left(w_{\max} - w_{\min}\right) * k / k_{\max} \quad ...(8)$$

$$X_i^{k+1} = X_i^k + Y_i^k \quad ...(9)$$

Equation 6 is velocity update equation in which first term indicates the inertial behaviour of i^{th} particle and the remaining terms represents cognitive and social behaviours of a particle that changes particle velocity by its self-experience and knowledge of swarm collection respectively. *nr(a,b)*Indicates random value which varies uniformly within the range of [a,b] and round accounts for ULTC and Schs discretized operation.$P_i^k$and G^k responsible for movement of particles towards optimal value. ULTC, Schs and DGs inertia weights were taken as 3,2 and 0.040. The round functions just for the operation of ULTC and Schs not for the DG voltage variations. In this work there are four optimizing parameters, first one is power loss reduction and the remaining three are switching operations of ULTC and Schs. The proposed algorithm is written in the following steps.

Step:1 Assume all node voltages 1p.u

Step:2 Read Distribution system data and initialise PSO parameters

Step:3 Calculate power losses in Distribution network by applying Backward/Forward algorithm

Step:4 Based on load flow estimate the approximate initial positions of ULTC and Schs

Step:5 DG is located at specified bus

Step:6 Repeat step 3 and evaluate the fitness function with initial positions of ULTC and Schs

Step:7 Minimize the fitness function with minimum switching operations of ULTC and Schs

Step:8 If all the constraints are satisfied, then display results. Otherwise, go to step 6.

4.0 SIMULATION RESULTS

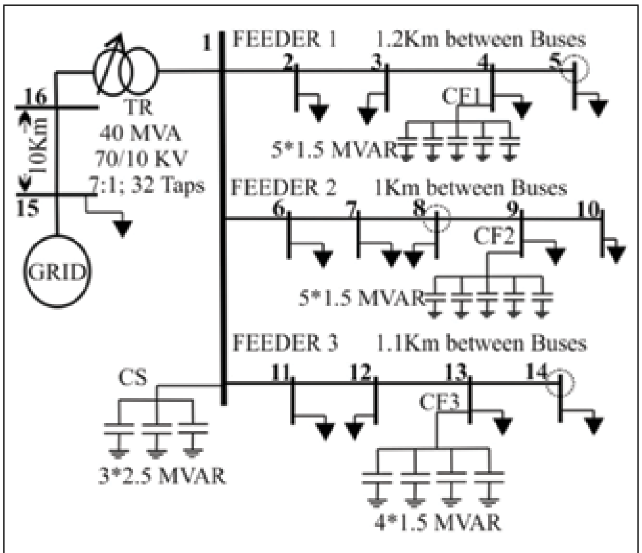

FIG.2 SINGLE LINE DIAGRAM OF TEST SYSTEM

Test system is shown in the Figure 2 and the estimated load variation of real power and reactive power on the feeders are shown in Figure 3 and Figure 4 respectively.

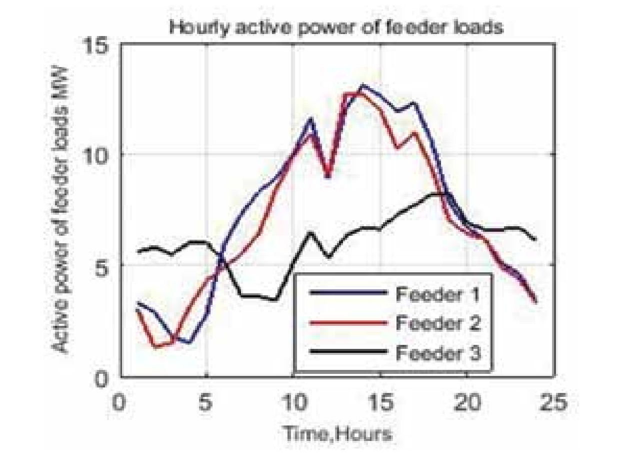

FIG.3 HOURLY ESTIMATED REAL LOAD

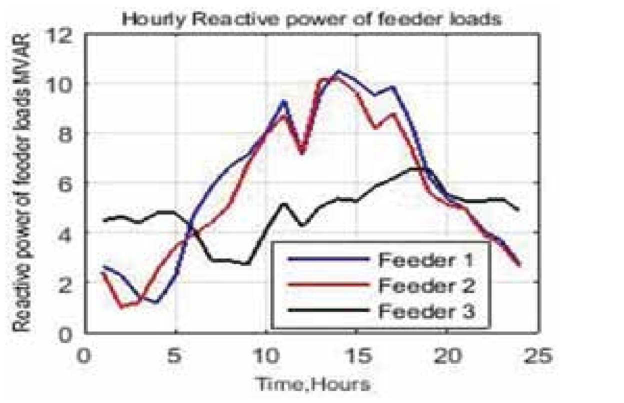

FIG.4 HOURLY ESTIMATED REACTIVE LOAD

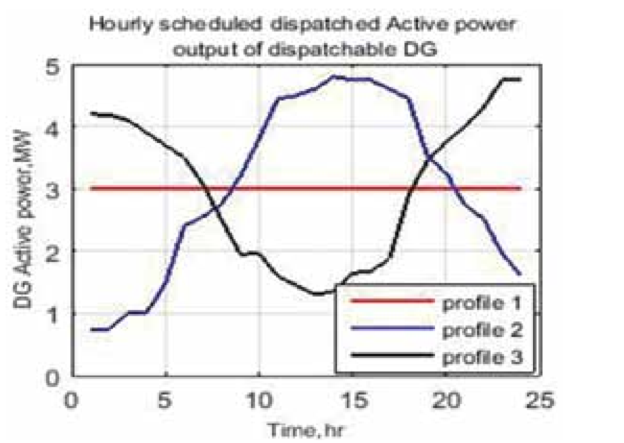

FIG.5 HOURLY SCHEDULED AND DISPATCHED ACTIVE POWER OF DISPATCHBLE DG

Hourly scheduled and dispatched DG active power is shown in Figure 5. Test system data is shown in Table.1[18]. From figures 4 and 5, peak load appears around 13:00-15:00 hours and off-peak loads appears around 2:00-4:00 hours. In this work DG real power is considered in three cases with an average power of 3MW. In profile 1 the DG power is a constant power, In profile 2 and 3 the DG power are increasing and decreasing nature respectively.

TABLE 1

TEST SYSTEM SPECIFICATIONS

Transmission Line Date		Lengh=10Km r=0.15 ohm/Km x=0.5 ohm/Km
Distribution Network Data	Feeder 1	Lengh=4.8Km r=0.12 ohm/Km x=0.35 ohm/Km
	Feeder 2	Lengh=5.0Km r=0.12 ohm/Km x=0.35 ohm/Km
	Feeder 2	Lengh=4.4Km r=0.12 ohm/Km x=0.35 ohm/Km
Transformer Data		3Φ,70/10Kv, 40MVA x-0.08pu,x/r-20
ULTC Data		At HV side, 32 steps
Shunt Capacitors Data	Substation	2.5 Mvar each
	Feeders	1.5 Mvar each
	Feeder 1 Real Load for 24 Hours in MW	3.3 2.9 1.8 1.5 2.8 5.9 7.3 8.3 8.9 10.0 11.6 8.9 12.0 13.1 12.6 11.9 12.3 10.5 7.8 6.7 6.2 5.1 4.6 3.4
	Feeder 1 Reactive Load for 24 Hours in MVAR	2.64 2.32 1.44 1.20 2.24 4.72 5.84 6.64 7.12 8.00 9.28 7.12 9.60 10.48 10.8 9.52 9.84 8.40 6.24 5.36 4.96 4.08 3.68 2.72
	Feeder 2 Reactive Load for 24 Hours in MVAR	3.0 1.3 1.5 3.1 4.3 4.9 5.5 6.4 8.4 9.9 10.9 9.0 12.7 12.7 12.0 10.2 11.0 9.3 7.0 6.4 6.2 4.9 4.4 3.3
Load Data	Feeder 2 Reactive Load for 24 Hours in MVAR	2.04 1.04 1.20 2.48 3.44 3.92 4.40 5.12 6.72 7.92 8.72 7.20 10.16 10.16 9.60 8.16 8.80 7.44 5.60 5.12 4.96 3.92 3.52 2.64

	Feeder 3 Real Load for 24 Hours in MW	5.6	5.8	5.5	6.0	6.0
		5.2	3.6	3.6	3.4	5.1
		6.5	5.3	6.3	6.7	6.6
		7.3	7.7	8.2	8.2	6.9
		6.6	6.6	6.7	6.1	
	At Bus 15	5MW.0.95 lag				

TABLE 2

DG AT NODE 5 WITH PROFILE 1 OUTPUT

CONTROL METHODS		CM	PM
LOSS(MWh)		12.35	11.65
Number of Switching Operations	ULTC	4	3
	SC	6	4
	F1C	10	8
	F2C	8	6
	F3C	4	3
Line Loss($)		988	932
Soc($)		1560	1160
Total Cost($)		2548	2092

TABLE 3

DG AT NODE 5 WITH PROFILE 2 OUTPUT

CONTROL METHODS		CM	PM
LOSS (MWh)		11.56	10.2
Number of Switching Operations	ULTC	6	4
	SC	10	8
	F1C	6	4
	F2C	8	5
	F3C	2	2
Line Loss($)		924.8	816
Soc($)		1720	1240
Total Cost($)		2644.8	2056

Distributed generation are connected at three different locations in the distribution network(at node 5, node 8 & node 14). In each case DG three profile outputs are applied and the effect of total power, switching operations of VCDs are examined. Tables 2-4 indicates total power loss and switching operations of VCDs with DG at node 5. Similarly, Tables 5-7 and 8-10 indicates total power loss and switching operations of VCDs with DG located at nodes 8 and 14.

TABLE 4

DG AT NODE 5 WITH PROFILE 3 OUTPUT

CONTROL METHODS		CM	PM
LOSS(MWh)		13.38	12.51
Number of Switching Operations	ULTC	4	4
	SC	6	4
	F1C	10	6
	F2C	8	4
	F3C	6	3
Line Loss(S)		1070.4	1000.8
Soc($)		1640	1080
Total Cost(S)		2710.4	2080.8

In Tables 2 to 10, CM, PM denotes Conventional method [18], proposed method respectively. Cost of line losses and switching operational cost (SOC) are calculated by considering cost weighting factor for power loss, ULTC, SC, F1C, F2C and F3C. These values are 80$/Mwh, 80$, 60$, 40$, 40$ and 40$ respectively. From the results shown in tables 2 to 10, in all the cases proposed method reduces the cost of power loss and SOC as compared with conventional method.

Equations 10 & 11 represents power loss and SOC calculation formulas.

$$Lineloss(\$) = 80 * Loss(MWh) \quad ...(10)$$

$$SOC(\$) = (80 * ULTC) + (60 * SC) + 40 * (F1C + F2C + F3C) \quad ...(11)$$

TABLE 5

DG AT NODE 8 WITH PROFILE 1 OUTPUT

CONTROL METHODS		CM	PM
LOSS (MWh)		12.64	11.01
Number of Switching Operations	ULTC	6	4
	SC	6	4
	F1C	8	6
	F2C	12	8
	F3C	2	2
Line Loss (S)		1027.2	880.8
Soc ($)		1720	1200
Total Cost (S)		2747.2	2080.8

TABLE 6

DG AT NODE 8 WITH PROFILE 2 OUTPUT

CONTROL METHODS		CM	PM
LOSS (MWh)		12.22	11.15
Number of Switching Operations	ULTC	4	3
	SC	8	6
	F1C	8	6
	F2C	8	6
	F3C	2	2
Line Loss(S)		977.6	892
Soc($)		1520	1160
Total Cost(S)		2497.6	2052

TABLE 7

DG AT NODE 8 WITH PROFILE 3 OUTPUT

CONTROL METHODS		CM	PM
LOSS(MWh)		13.68	12.53
Number of Switching Operations	ULTC	6	2
	SC	4	6
	F1C	8	6
	F2C	8	5
	F3C	3	6
Line Loss (S)		1094.4	1002.4
Soc ($)		1480	1200
Total Cost (S)		2574.4	2202.4

TABLE 8

DG AT NODE 14 WITH PROFILE 1 OUTPUT

CONTROL METHODS		CM	PM
LOSS (MWh)		13.37	12.57
Number of Switching Operations	ULTC	2	2
	SC	8	6
	F1C	8	6
	F2C	8	5
	F3C	8	6
Line Loss(S)		1069.6	1005.6
Soc($)		1600	1200
Total Cost($)		2669.6	2205.6

TABLE 9

DG AT NODE 14 WITH PROFILE 2 OUTPUT

CONTROL METHODS		CM	PM
LOSS (MWh)		13.26	12.01
Number of Switching Operations	ULTC	4	4
	SC	6	4
	F1C	8	6
	F2C	10	7
	F3C	4	4
Line Loss(S)		1060.8	960.8
Soc($)		1560	1240
Total Cost($)		2620.8	2200.8

TABLE 10

DG AT NODE 14 WITH PROFILE 3 OUTPUT

CONTROL METHODS		CM	PM
LOSS(MWh)		13.71	11.95
Number of Switching Operations	ULTC	4	4
	SC	6	4
	F1C	8	5
	F2C	10	7
	F3C	8	5
Line Loss(S)		1096.8	956
Soc($)		1720	1240
Total Cost(S)		2816.8	2196

5.0 CONCLUSIONS

This paper proposed a new control method, in which a DG output is dispatched cooperatively in coordination with switching operations of ULTC and Schs. In this paper particle swarm optimization method was proposed for minimizing the multi-objective function which is a combination of power loss and switching operations of voltage controlled devices by estimating the load one day in advance. The results demonstrated that proposed method is effectively reducing the power loss and SOC compared with conventional control method without violating the grid conditions.

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