Multi-Objective Reactive Power Dispatch in Distribution Networks using Modified Bat Algorithm

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***Abstract*—Integration of distributed generation in power system challenges operation and management of power distribution network. This paper presents Modified Bat Algorithm for Optimal Reactive Power Dispatch (OPRF) of distributed generation for voltage support in distribution network. An objective function with constraints of voltage, DG reactive power , thermal limits of lines is presented. A modified IEEE 37 node test feeder with variable generation was used to validate the proposed algorithm. A co-simulation setup was used in which electric grid was developed in Power system tool (DigSILENT PowerFactory) and Modified Bat Algorithm was developed in Python. Results showed that Modified Bat Algorithm is quite effective for voltage profile improvement and loss minimization**

***Index Terms*—Distributed Generation, Voltage Regulation, Modified Bat Algorithm, Co-simulation**

NOMENCLATURE

t_{max}	Maximum number of iterations.
N	The number of bats in the swarm.
D	Dimension of the problem.
v_i^t	Velocity of i^{th} bat at t^{th} iteration, where $i \in [1, N]$ and $t \in [1, t_{max}]$.
x_i^t	Position of i^{th} bat at t^{th} iteration.
A_i^t	Pulse amplitude of i^{th} bat at t^{th} iteration.
r_i^t	Rate of pulse emission of i^{th} bat at t^{th} iteration $r_i^0 \in [0, 1]$.
f_i^t	frequency of emitted pulse of i^{th} bat at t^{th} iteration.
α, γ	Constants that determine the rate of convergence, where $\alpha \in [0, 1]$ and $\gamma > 0$.
C_n	Acceleration constants for bats to propel them towards optimal solution C_n where $n \in [1, 4]$.
x_b^t, $x_{b_i}^t$	Global and personal best solution of the i^{th} bat respectively at t^{th} iteration.
x_w^t, $x_{w_i}^t$	Global and personal worst solution of the i^{th} bat respectively at t^{th} iteration.
W^t	Inertia weight coefficient at t^{th} iteration $\in [W^l, W^u]$.
G, B	Tuning parameters for inertia weight.
U_k, u_k	Actual and per unit voltage at the k^{th} bus.
$u_{max,min}$	Maximum and minimum voltage in the network.
δ_{kl}	Voltage angle difference between the k^{th} and l^{th} bus.
P_{g_k},P_{d_k}	Active power generation and demand at k^{th} bus.
Q_{g_k},Q_{d_k}	Reactive power generation and demand at k^{th} bus.
θ	Upper and lower power factor limits for generators.
S	Equipment loading as percentage of nameplate rating.
^{u}, ^{l}	Super scripts donate upper and lower limits for a parameter.
ζ	Amplification constant.

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I. INTRODUCTION

The share of distributed generators (DGs) in the power generation is gradually increasing. Major reasons behind this growth are; economic, environmental and political interests [1] [2] [3]. Increasing share of renewable energy resources has resulted in decreasing share of conventional fossil energy in power generation [4].

Presence of a large number of DGs in power distribution network, however, also complicates distribution control and management. As a significant number of DGs are connected at the distribution side of power grid, it may alter the direction of power flow in distribution systems. Reverse power flows can disturb the conventional operation procedures, including voltage management and protection [5] [6].

Reverse power flows make voltage control a challenge in both planning and operation of distribution networks. Volt/Var control is one possible solution for voltage regulation. It caters to both under and over voltages as reactive power is either supplied or absorbed depending on the voltage at the point of common coupling. The objective of vol/var control is to supply electricity while ensuring the voltage at the PCC remains within the bounds prescribed by standards such as EN 50160. Volt/var control in conventional distribution grids is relatively simple and generally involves switched shunt capacitor banks which acts on local information and control commands [1]. However, DGs can be used to contribute for voltage regulation at point of common coupling by controlling DG reactive power output and this can help in reducing the negative effects caused by its own penetration.

Thus, volt/var control problem can be translated into optimal dispatch of reactive power of DGs. This problem has got attraction of various researchers and a lot of research work is going on this topic and various methods of Optimal Reactive Power Dispatch have been proposed in the literature. In [7], authors presented voltage regulation algorithm on the basis of multi-agents to provide voltage support in distribution network. Agents communicates with each other and decide reactive power set points for the DGs to stabilize the voltage. In [8] Multi-agent based fuzzy inference system (FIS) was presented for optimal reactive power dispatch using Particle Swam Optimization. In [9] the authors, presented an optimization procedure in which an objective function was developed and minimized. Objective function consists of sum of the costs that distribution network operation in terms of network power losses, local generation and shunt capacitors banks reactive power production, reactive power imported by the HV network. The authors considered Reactive power output of DG and OLTC position as control variable. In [10] ,the authors proposed a day-ahead coordinated dispatch method of reactive to achieve optimal power flow, minimize power losses, and minimize operation of switching of capacitor banks.

In this paper a Modified Bat Algorithm is presented for optimal reactive power dispatch is presented. The paper is organized as follows; In Section II problem is formulated and objective function alongwith constraints is given. Section III presents the Modified Bat Algorithm while Section IV gives brief overview of simulation setup. Test case description are given in Section V. Section VI presents results and discussion and conclusions are given in Section VII.

II. Problem formulation

In radial distribution networks, line impedance and net active and reactive power flow result in voltage deviation. Traditionally, power flowed from transformers to load centers resulting in voltage drop along the feeder. Fig.1 is a vector representation of voltage drop phenomenon for a simple two bus system. Integration of distributed energy resources (DERs) in distribution networks can potentially cause reverse power flow, resulting in rise in voltage.

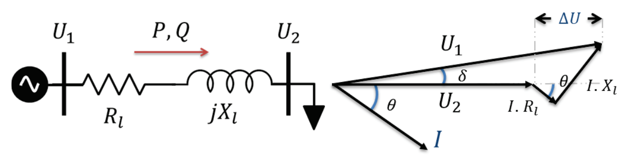

Fig. 1. Phasor diagram for a 2 bus system

Power loss through a branch is a function of branch conductance g ,voltage at either end of the conductor U_1, U_2 and difference between voltage angles δ_{12}. Total active power loss within a network can therefore be written as a summation of losses in all the branches in the network and can be calculated using Eqn (1).

$$P_{loss} = \sum g_k(U_k^2 + U_l^2 - 2U_kU_l\cos\delta_{kl}) \ , \quad (1)$$

Minimizing active power losses using optimal reactive power dispatch leads to higher voltage deviations in the network. In the active power loss minimization problem inverters distributed within the distribution network act as reactive power sources like a capacitor. This reduces net reactive power flow from the external grid, relieves capacity and reduces losses. In come cases, voltage deviation may exceed limits stated by international standards such as EN 50160 [11]. In this work, the upper u^u and lower u^l voltage limits have been at 1.05 and 0.95 p.u. respectively. To ensure voltage remains within the prescribed bounds voltage deviation can be made part of the objective function. Eqn. (2) and (3) are used in this paper to ensure voltage remains within the set limit.

$$u^{uv} = \begin{cases} u^{max} - u^u & \text{if } u^{max} > u^u \\ 0 & \text{else} \end{cases} \ , \quad (2)$$

$$u^{lv} = \begin{cases} u^l - u^{min} & \text{if } u^{min} < u^l \\ 0 & \text{else} \end{cases} \ , \quad (3)$$

The final objective function can be formulated as a weighted summation of the two objectives, namely, active power loss minimization and voltage limit violation minimization. In this work, the objective function formulated in Eqns. (2) and (3) has been weighted by as an exponential function. This ensures that if a voltage violation occurs, it becomes the dominant objective in the final objective function, ensuring voltage limits are not violated. Eqn. (4) shows the formulation of the final objective function.

$$Minimize \quad F(\vec{Q_{g_i}}) = P_{loss} + e^{\zeta(u^{uv}+u^{lv})} \quad , \tag{4}$$

Subject to,

$$\left.\begin{aligned} u^l \leq u_k \leq u^u \\ Q^l_{g_k} \leq Q_{g_k} \leq Q^u_{g_k} \\ \theta^l_{g_k} \leq \theta_{g_k} \leq \theta^u_{g_k} \\ S_{tr} \leq S^u_{tr} \end{aligned}\right\} \quad , \tag{5}$$

Standards like VDE-AR-N 4105 that cater to integration of distributed energy resources in the distribution network require distributed generators to support power factors 0.9 in MV and LV networks [12].The amount of reactive power a distributed generator can dispatch is limited by inverter rating. Inverter reactive power limits have been calculated using $\pm\tan[\cos^{-1}(\theta)]P_{rated_i}$, where $\theta = 0.9$ and inverter active power ratings, P_{rated_i} have been listed in Table I. Active power output of renewable energy resources is stochastic and the power factor constraint ensures that inverter operates between 0.9 and 1 power factor. Power factor limit is a function active power generation rather than rated power and can be calculated using the same equation by replacing P_{rated_i} with P_{G_i}. Thermal ratings of lines and equipment such as transformers should not be exceeded as it adversely affect their performance and lifespan. This is formulated as the final constraint in Eqn. (5).

III. Modified bat algorithm

The original bat algorithm is a population based metaheuristic algorithm inspired by the behavior of micro bats [13]. Micro bats like sonar emit loud pulses and use the returning echo to detect surfaces that help them navigate and hunt. Some species are even capable of modulating the frequency of the pulses. Each pulse lasts a few milliseconds the frequency typically ranges between 25 kHz and 100 kHz which lies in within the inaudible part of the spectrum for humans. This is fortunate as bats can emit pulses with amplitudes as high as 110 dB.

In [14] two modifications to the original bat algorithm have been suggested. In the original bat algorithm, the velocity update of a bat is a function of the difference between the current position and the best known solution. Each iteration bats try to minimize this difference while simultaneously trying to find a better solution. The first modification suggests adding bad experience components to the velocity update equation, so that each bat tries not only to move towards the best known solutions, but also move away from worst known solutions. The suggested modification aims at improving the rate of convergence and exploration capabilities of the algorithm. The second modification suggests using a non linear inertia weight component with initial value $W^0 = W^u$ that converges to $W^t \rightarrow W^l$ as $t \rightarrow t_{max}$, where both $W^l, W^u \in [0, 1]$ and $W^l < W^u$. The aim is to assign dynamic weighs to previous velocity and the calculated deviation when updating the new position. Parameters $G \in [1, 20]$ and $B \in [1, t_{max}]$ in Eqn. (10) provide control over transition between global and local search and can be tuned for a specific optimization problem. Eqns. (6) to (**??**) are used to upadte the frequency of emitted pulse, inertia weight and bats' position and velocity.

$$f^t_i = f^l + (f^u - f^l).u[0, 1] \quad , \tag{6}$$

$$W^t = 1 - \left[\frac{1}{1 + e^{\frac{B-t}{A}}}(W^u - W^l) + W^l\right] \quad , \tag{7}$$

$$\begin{aligned} v^t_i = W^t v^{t-1}_i + (1-W^t)[C_1(x^{t-1}_i - x^{t-1}_b) + C_2(x^{t-1}_i - x^{t-1}_{b_i}) \\ + C_3(x^{t-1}_w - x^{t-1}_i) + C_4(x^{t-1}_{w_i} - x^{t-1}_i)].f^t_i \quad , \end{aligned} \tag{8}$$

$$x^t_i = x^{t-1}_i + v^t_i \quad , \tag{9}$$

Where,

$$A = \frac{t_{max} - 1}{G} \quad , \quad G \in [1, 20] \quad , \quad B \in [1, t_{max}] \quad , \tag{10}$$

To improve local search capabilities of the algorithm Yang has proposed random walk close to the good solutions, which increases chances of finding an even better solution. This is achieved by using Eqn. (). Where, $\bar{A}^t$ is the average amplitude of all bats at tth iteration.

$$x^t_{new_i} = x^t_{old_i} + u[-1, 1]\bar{A}^t \quad , \tag{11}$$

As bats close in on their prey, they reduce the amplitude of the emitted pulse so that they can maintain an element of surprise. The rate of emission is increased to ascertain the precise location of a moving prey. This behavior has been mathematically modeled using Eqns. (12) and (13). It is important to note that as $t \rightarrow \infty$, $A^t_i \rightarrow 0$ and $r^t_i \rightarrow r^0_i$.

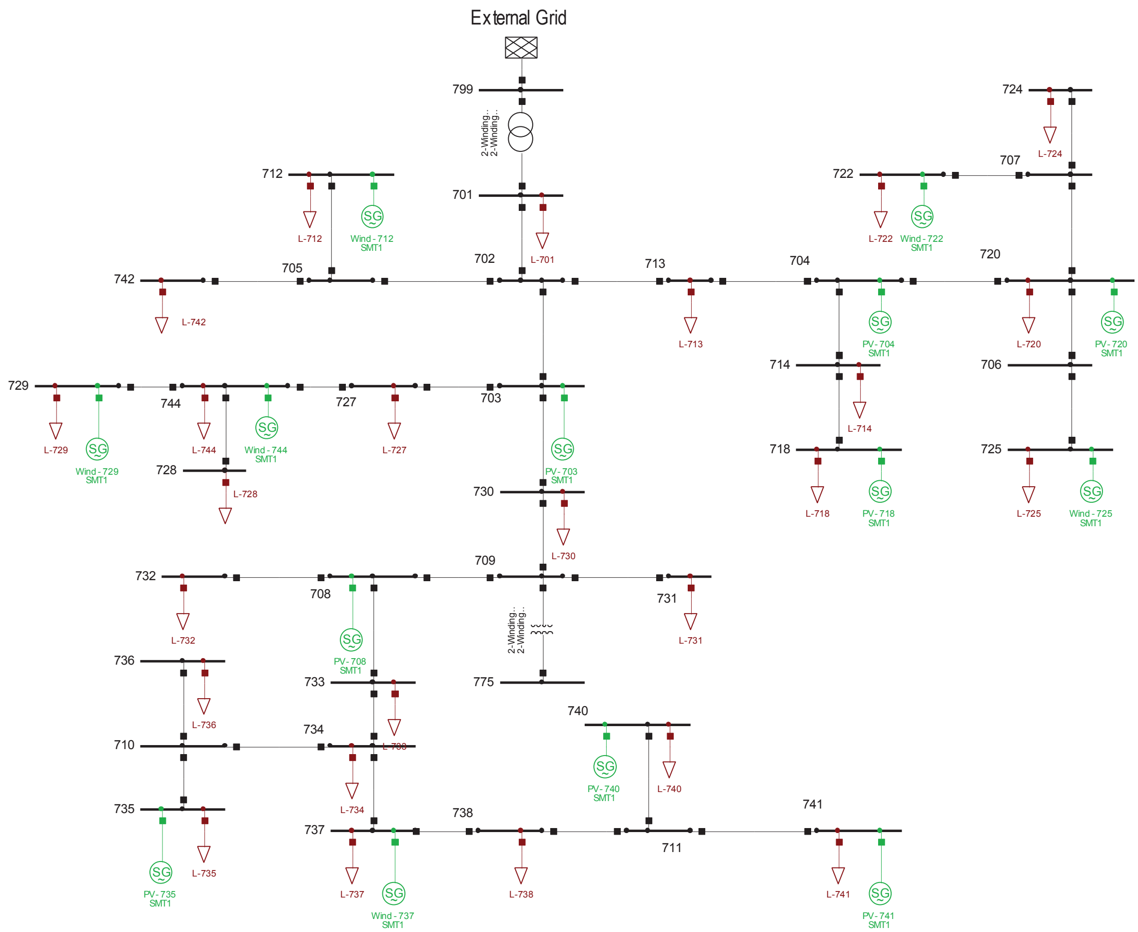

Fig. 2. The modified IEEE 37 node test feeder

$$A_i^{t+1} = \alpha A_i^t \ , \tag{12}$$

$$r_i^{t+1} = r_i^0[1 - \exp(-\gamma t)] \ , \tag{13}$$

Pseudo code for modified bat algorithm has been detailed in algorithm 1. When implementing the algorithm, each bat can have information of all bats or only neighboring bats when updating position and assessing solutions. This makes bat algorithm very powerful as can be implemented in a centralized or distributed manner.

IV. Simulation Setup

A. Tool selection

1) PowerFactory: PowerFactory is a domain specific tool for simulating, analyzing and understanding power systems [15]. The software package supports a power language called Digsilent Simulation Language (DSL) for implementing custom models and controllers while using RMS simulation. DSL however does not support matrices, which are required for implementing priority stacks for the central controller. For this work therefore, we have opted for a co-simulation approach where the power network and the local controllers for the TCLs have been implemented in PowerFactory and the central controller has been implemented in Python.

2) Python: Python is an open source high level scripting language with a large number of interdisciplinary tool boxes for optimization, signal processing, statistics, matrix calculations etc [16]. This makes it an ideal option for implementing very complex custom algorithms. An added advantage of using Python is that being a high level language, comprehensive libraries are available for external coupling which require very little effort during implementation. Using co-simulation framework these toolboxes can be used in conjunction with PowerFactory to extend its capabilities.

V. Study Case

Simulation studies have been conducted on the IEEE 37 node MV test network [17] to analyze the performance of the proposed method. The network consists of

Algorithm 1: Pseudo code for modified bat algorithm

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Objective function formulation
  f(χ⃗), χ⃗ = (x_1, ..., x_d)^T
Initialize bat population at initial position x_i^0 with
  velocity v_i^0 for i ∈ [1, N]
Set frequency of pulse f_i at position x_i^0
Initialize pulse rates r_i and the loudness A_i and
  acceleration constants C_n where n ∈ [1, 4]
while t ≤ t_max do
    Adjust wavelengths λ_i for each bat and update
      their velocity v_i^t ,position x_i^t and inertia
      weight W^t
    if ū[0, 1] < r_i^t then
        Select a solution among the best solutions
          x_i^t
        Walk randomly around best solution for
          local exploration
    Generate a new solution by flying randomly
    if ū[0, 1] < A_i^t and f(x_i^t) < f(x_b^t) then
        Accept the new solutions
        Reduce pulse rate r_i^{t+1} and loudness A_i^{t+1}
          for the next iteration
    Rank bats according to fitness f(x_b^t) and find
      the best global solution x_b^t
Return optimal solution x_b^{t_max} and its fitness
  f(x_b^{t_max})
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25 loads serviced by a 2.5 MVA transformer. Fourteen DERs have been placed within the network. Node ID, active power rating and DER type have been listed in Table I. Fig 2 is a graphical representation of the modified IEEE 37 node test feeder. For the purpose of simulation normalized real 15 minute average load, PV generation and Wind generation profiles have been used. Each load has randomly been assigned either a residential or commercial load profile. Simulations have been run for a sunny day with significant wind generation only in the second half of the day.

VI. Results and discussion

The proposed method is capable of dispatching reactive power set points without violating power factor limits of distributed generators. Fig. 3 shows reactive power set points for the PV connected at node 708. Fig. 4 shows active power losses for the base case scenario and with optimal reactive power dispatch. The graph shows reduction in active power loses before, 10 am and after 3 pm. During this this time there is no voltage violation hence u^{uv} , $u^{lv} = 0$ and objective function reduces to $F(\vec{Q_{g_i}}) = P_{loss}$. During the same time a rise in voltage compared to base case can be seen in Fig. 5. This is due to inverts supplying reactive power acting as a capacitor, improving network power factor. Local supply of reactive power improves voltage. It has the added advantage of reducing net inflow of reactive power from the external grid by upto 80%. Fig. 6 shows this phenomenon. Reduced reactive power inflow reduces line congestion and reactive power loses. It also leads to significant reduction in transformer loading as can be seen in Fig.7. Before 7 am limited wind generation and no PV generation means limited reactive power dispatch capability as DERs need to operate at power factors greater than 0.9. After 3 pm increase in wind generation results in increased reactive power dispatch capability, resulting in larger reduction in active power loses and a larger voltage rise (Fig. 4 and 5). During 10 am and 3 pm, generation from both PVs and wind generators is high. Voltage deviation at the point of common coupling of a generator and the grid is a function of injected

TABLE I
Active power ratings, node ID and type of the distributed generators

Rating MW	Node	Type	Rating MW	Node	Type
0.29	703	PV	0.30	741	PV
0.27	704	PV	0.20	712	Wind
0.45	708	PV	0.41	722	Wind
0.42	718	PV	0.31	725	Wind
0.36	720	PV	0.13	729	Wind
0.33	735	PV	0.38	737	Wind
0.25	740	PV	0.37	744	Wind

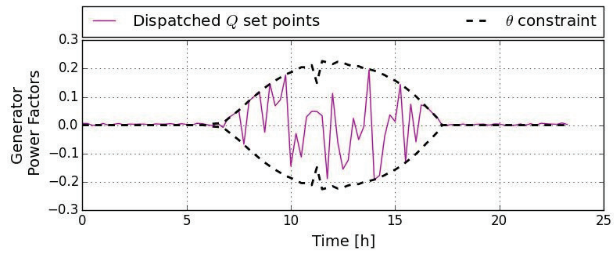

Fig. 3. Overview of the co-simulation setup

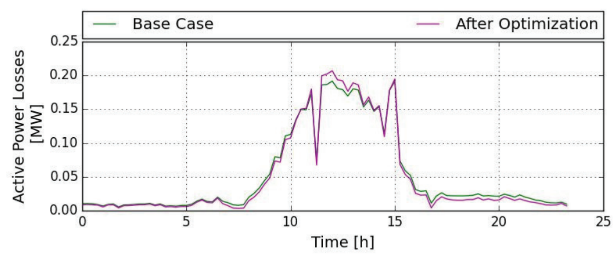

Fig. 4. Total active power loss profile

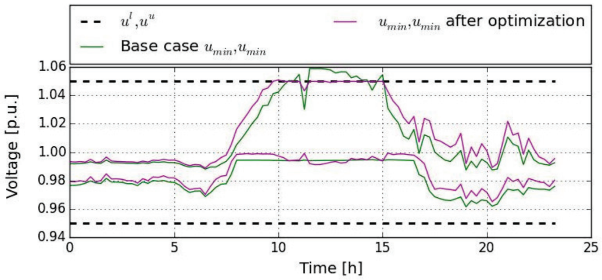

Fig. 5. Minimum and maximum voltage seen in the network

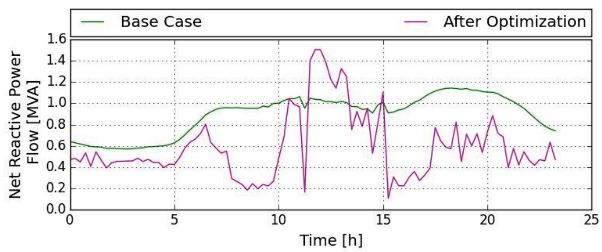

Fig. 6. Impact of the proposed method on import of reactive power from external grid

active and reactive power. Increased injection of active power results in voltage violation. As the objective function is exponentially related to voltage violation functions u^{uv} and u^{lv}, even a small violation causes $e^{\zeta(u^{uv}+u^{lv})}$ to increase rapidly. As $e^{\zeta(u^{uv}+u^{lv})} >> P_{loss}$ even for a small voltage violation, the objective function approximately reduces to $F(\vec{Q_{g_i}}) \simeq e^{\zeta(u^{uv}+u^{lv})}$. Be-

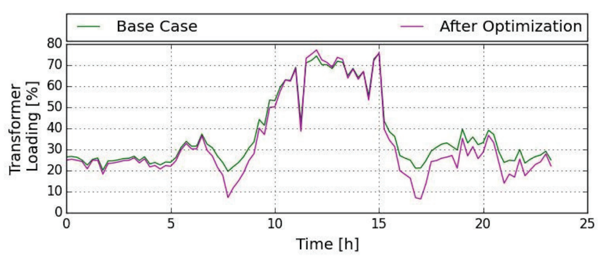

Fig. 7. Impact of the proposed method on transformer loading

tween 10 am and 3 pm, the voltage violation objective is dominant. Fig. 5 shows that the proposed optimal reactive power dispatch method can effectively mitigate voltage violations resulting from excessive generation in distribution network. Mitigating voltage rise requires inverters to act as a sink rather than a source of reactive power. This results in network power factor and increase in active power loses as can be seen from fig. 4. Inverters acting as sinks increase net reactive power inflow (Fig. 6) form the external grid. This can result in increase in

TABLE II
SIMULATION SETTINGS

Parameter	f^l	f^u	A^0	r^0	N	t_{max}
Value	-0.1	0.1	10	0.3	30	30

Parameter	G	B	α	γ	ζ	$C_{1,2,3,4}$
Value	5	15	0.9	0.9	10	[2,1,1,1]

transformer loading. Fig. 8 shows the total energy saved

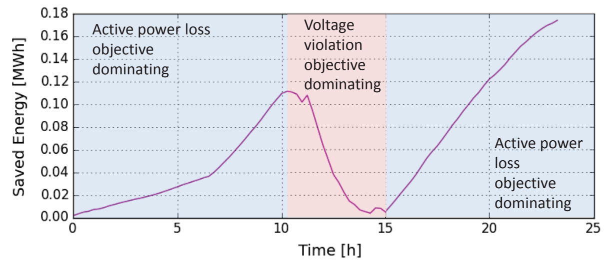

Fig. 8. Energy saved during the day

due to reduction in active power loses. The graph initially increases as P_{loss} is the dominant objective. Between 10 am and 3 pm, increase in active power losses results in a reduction in the saved energy. After 3 pm, when voltage violation is not an issue, reduction in active power losses causes the graph to rise again. Net saved energy at the end of the simulation is positive, showing it is possible to reduces loses and improve system efficiency even during days when voltage violation is an issue.

On a final note, average simulation time for each time step for the given settings (Table II) was 54 seconds using a single processor. This time can be substantially reduced by using multiple cores and parallel algorithm implementation. This means that the proposed method can potentially be used in real time for reactive power dispatch in distribution networks.

VII. CONCLUSION

In this paper an optimal reactive power dispatch based method has been proposed. The formulated objective function aims at reducing active power loses while also preventing voltage violation. The proposed method has been simulated on a modified IEEE 37 node test feeder. The network has been implemented in PowerFactory while, the optimization algorithm has been implemented in Python. Simulation results show that the proposed method capable of reducing loses while also providing voltage regulation.

REFERENCES

[1] J. Barr and R. Majumder, “Integration of distributed generation in the volt/var management system for active distribution networks,” *IEEE Transactions on Smart Grid*, vol. 6, no. 2, pp. 576–586, March 2015.

[2] H. A. Khan, Z. Xu, H. Iu, and V. Sreeram, “Review of technologies and implementation strategies in the area of smart grid,” in *Power Engineering Conference, 2009. AUPEC 2009. Australasian Universities*, Sept 2009, pp. 1–6.

[3] P. Zou, Q. Chen, Q. Xia, G. He, and C. Kang, “Evaluating the contribution of energy storages to support large-scale renewable generation in joint energy and ancillary service markets,” *IEEE Transactions on Sustainable Energy*, vol. 7, no. 2, pp. 808–818, April 2016.

[4] B. Global. (2015, Feb) The bp energy outlook. [Online]. Available: http://www.bp.com/

[5] L. F. Ochoa, A. Padilha-Feltrin, and G. P. Harrison, “Evaluating distributed generation impacts with a multiobjective index,” *IEEE Transactions on Power Delivery*, vol. 21, no. 3, pp. 1452–1458, July 2006.

[6] R. A. Walling, R. Saint, R. C. Dugan, J. Burke, and L. A. Kojovic, “Summary of distributed resources impact on power delivery systems,” *IEEE Transactions on Power Delivery*, vol. 23, no. 3, pp. 1636–1644, July 2008.

[7] I. Ahmad, P. Palensky, and W. Gawlik, “Multi-agent system based voltage support by distributed generation in smart distribution network,” in *Smart Electric Distribution Systems and Technologies (EDST), 2015 International Symposium on*, Sept 2015, pp. 329–334.

[8] H.-K. Kang, I.-Y. Chung, and S.-I. Moon, “Voltage control method using distributed generators based on a multi-agent system,” *Energies*, vol. 8, no. 12, p. 12411, 2015. [Online]. Available: http://www.mdpi.com/1996-1073/8/12/12411

[9] S. Conti and A. M. Greco, “Voltage regulation through optimal reactive power dispatching in active distribution networks,” in *MELECON 2008 - The 14th IEEE Mediterranean Electrotechnical Conference*, May 2008, pp. 792–798.

[10] L. Zhang, W. Tang, J. Liang, P. Cong, and Y. Cai, “Coordinated day-ahead reactive power dispatch in distribution network based on real power forecast errors,” *IEEE Transactions on Power Systems*, vol. 31, no. 3, pp. 2472–2480, May 2016.

[11] E. Standard, “50160,” *Voltage characteristics of public distribution systems*, 2010.

[12] V. V. d. E. E. Informationstechnik, “ev: Vde-ar-n 4105: 2011-08: Power generation systems connected to the low-voltage distribution network technical minimum requirements for the connection to and parallel operation with low-voltage distribution networks,” *English translation of the VDE application rule VDEAR-N-4105*.

[13] X.-S. Yang, “A new metaheuristic bat-inspired algorithm,” in *Nature inspired cooperative strategies for optimization (NICSO 2010)*. Springer, 2010, pp. 65–74.

[14] A. Latif and P. Palensky, “Economic dispatch using modified bat algorithm,” *Algorithms*, vol. 7, no. 3, pp. 328–338, 2014.

[15] D. PowerFactory, “Digsilent powerfactory 15 user manual,” 2013.

[16] M. F. Sanner *et al.*, “Python: a programming language for software integration and development,” *J Mol Graph Model*, vol. 17, no. 1, pp. 57–61, 1999.

[17] W. H. Kersting, “Radial distribution test feeders,” in *Power Engineering Society Winter Meeting, 2001. IEEE*, vol. 2. IEEE, 2001, pp. 908–912.