OPTIMIZATION OF PHOTOVOLTAICS ACTIVE POWER CURTAILMENT IN LOW VOLTAGE NETWORKS BY USING ARTIFICIAL BEE COLONY METHOD

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ABSTRACT

Rapidly increasing share of photovoltaics in electricity generation that are connected on the low voltage network can cause overvoltages and reduce reliability of power supply due to their stochastic daily generation curve that don't coincide with the consumption curve. Distribution system operators have to manage distribution networks in a way to ensure prescribed reliability of power supply and electricity quality to all customers. In this paper, an optimization method for coordinated active power curtailment has been developed by using Artificial bee colony method. The method is made as a three-phase model due to unbalanced loading of low voltage networks. The proposed method should increase the capacity of the network for connection of larger share of photovoltaics which enables more customers to become producers. The generation and consumption daily curve should be more balanced so it is also expected that voltage profile of the network will be improved.

INTRODUCTION

In last two decades total installed capacity of photovoltaics in a world is in constant growth. It is predicted that total world installed capacity in 2020th will be over 700 GW [1]. Photovoltaics generation depends on the current insolation of panels which changes due to daily sun movement, change of seasons and current panel shading caused by clouds or some other objects. Because of these factors, photovoltaics are considered as intermittent sources whose generation curve has stochastic nature and is hard to be predicted. Due to their characteristic generation curve, the peak generation occurs in the middle of the day while peak consumption usually occurs later in the afternoon. In low voltage networks with high penetration of photovoltaics in some periods total generation can be greater than the total load which results in voltage raise that can exceed the upper permissible limit. On the other hand, in the periods of low generation of photovoltaics or when there is no generation at all, the same networks have to satisfy the conditions of the permissible voltage drop at its ends. These reasons represent the greatest technical limitation for connecting the larger share of photovoltaics on a certain low voltage network.

To increase the capacity of low voltage network for connection of larger share of photovoltaics many methods of voltage regulation have been proposed. One of the most perspective is the active power curtailment [2]. Regulation of active power in low voltage networks has a great impact on voltage due to large X/R ratio. Active power curtailment can be implemented locally as a function of inverter or remotely and centralized from the substation MV/LV level. Centralized method is more effective because of coordinated monitoring and control but it requires communication infrastructure.

In this paper an optimization method for coordinated active power curtailment has been developed by using Artificial bee colony method. The method is made as a three phase model due to unbalanced loading of low voltage networks. The optimization method has two objective functions. The first is maximization of total active power that photovoltaics can deliver in network at a certain moment, provided that voltages in all nodes are below the upper permissible limit, and the second is the minimization of power losses. The main goal of this method is to satisfy producers' will to maximize their profit by maximization of total power plant generation and distribution system operator's will to raise the network efficiency at the same time. The proposed method should increase the capacity of the network for connection of larger share of photovoltaics, which enables more customers to become producers. The generation and consumption daily curve should be more balanced so it is also expected that voltage profile of the network will be improved.

The method is tested on a real low voltage network example by simulating high penetration of photovoltaics and its impact on electrical conditions in case when there is no voltage regulation and in case when the proposed method is implemented. In the results, the comparison of voltage profiles, power losses, active power reduction and the increase of the network capacity before and after application of the proposed method should represent all its benefits and achieved goals.

COORDINATED ACTIVE POWER CURTAILMENT

Fig. 1 shows a simplified review of a customer with roof installed photovoltaic (prosumer). Electric meter measures the difference of the object electricity consumption and generation.

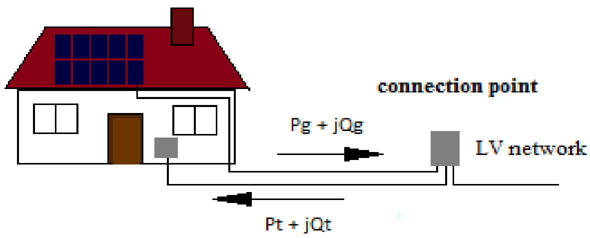

Fig. 1 Simplified model of a prosumer with roof photovoltaic

Voltage difference caused by the prosumer in the connection point can be calculated as (1) [3]:

$$\Delta U = I(R + jX) = \frac{S^*}{U_{net}^*}(R + jX) = \frac{PR+QX}{U_{net}^*} + j\frac{PX-QR}{U_{net}^*} \quad (1)$$

From the equation (2) it is obvious that voltage at connection point can be regulated by regulation of network voltage, reduction of line impedance and regulation of active and/or reactive power of the prosumer.

To enable high penetration of photovoltaics in low voltage network it is necessary to implement some sort of active and/or reactive power regulation of photovoltaics. Due to high R/X ratio of low voltage networks, regulation of active power is more efficient. Active power regulation implies limitation of produced power that prosumers send in network in cases when the voltage raise is higher than allowed. This limitation is called active power curtailment and it can be static with upper limit or dynamic where the limitation is changing due to current network voltage. Active power curtailment can be performed locally in inverters or can be remotely from the level of MV/LV substation. Remote regulation is more efficient because it coordinates output active power of all the inverters connected on observed LV network (Fig. 2).

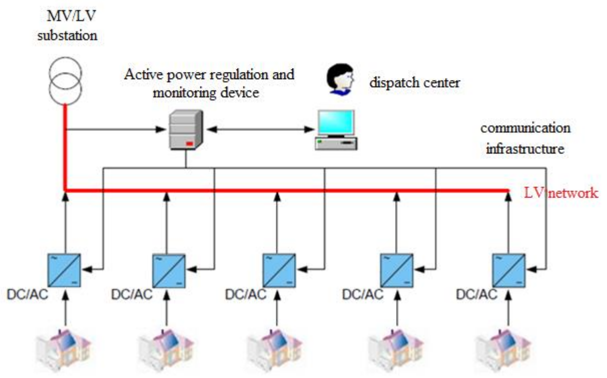

Fig. 2 Centralized system for active power regulation

In this paper an optimization algorithm for coordinated active power curtailment, which calculates total maximum active power that all observed photovoltaics can deliver in network at a certain moment with the condition that voltages in all nodes are under upper permissible limit, will be presented. For optimization algorithm, the Artificial bee colony method has been used.

ARTIFICIAL BEE COLONY METHOD

Artificial bee colony method is a metaheuristic mathematical method for solving multidimensional and multimodal optimization problems that is based on simulation of the process of food collecting of a real bee colony. Bee colony consists of a queen, drones and workers. In the process of food collecting only workers take part. They are divided on employed bees, onlookers and scouts. Scouts are randomly researching the environment for food sources. When they return to hive, they perform waggle dance in order to inform onlookers about food source quality and directions. Onlookers assess the food source quality and give the information to employed bees that go and collect the food.

In mathematical model N is a total number of bees in a colony. Food source positions represent the potential problem solution while the amount of nectar represent the solution quality. At the initial moment, half of population are employed bees and the other half are onlookers. The optimization method is divided in three phases:

1. Employed bee phase
2. Onlookers phase
3. Scout bee phase

Initialization phase

The entire procedure is cyclically repeated to the predetermined number of cycles C_{max}. Before the beginning of the cyclic process, initialization process has to be done. For every employed bee a random solution x_i is generated by using equation (2) [5]:

$$x_{ij} = x_{\min j} + random(0,1) \cdot (x_{\max j} - x_{\min j})$$
$$i = 1, \dots, \frac{N}{2} \quad ; \quad j = 1, \dots, D \qquad (2)$$

where

i – ordinal number of employed bee

x_{ij} – j[th] coefficient of D-dimensional vector x_i

D – vector dimension (equal to number of optimization parameters)

Employed bee phase

In this phase every employed bee is researching the environment of the initial generated solution to find better solution. The first step is to randomly generate coefficients j and k. Then, the new solution v_{ij} near the x_{ij} is generated by using equation (3) [5]:

$$v_{ij} = x_{ij} + random(-1,1) \cdot (x_{ij} - x_{kj})$$
$$j \in \{1, \dots, D\} \; ; \; k = \left\{1, \dots, \frac{N}{2}\right\} \; ; \; k \neq i \qquad (3)$$

Quality of solutions x_{ij} and v_{ij} are calculated by using Fitness function Fit_i (4) [6]:

$$Fit_i = \begin{cases} \frac{1}{1+f_i} & , \; f_i \geq 0 \\ 1 + |f_i| & , \; f_i \leq 0 \end{cases} \qquad (4)$$

where

f_i – objective function

Solutions are compared by using Greedy selection and only better solution is memorized. Researching of the environment of the certain solution is repeated for predetermined number of trials. If in these trials a better solution is not found, employed bee becomes scout [6].

Onlooker phase

Onlookers' task is to rate solution quality of all employed bees. For every solution, a probability p_i is calculated (5):

$$p_i = \frac{Fit_i}{\sum_{n=1}^{N} Fit_n} \quad (5)$$

For choosing the best solutions, the Greedy selection is used. Onlookers then become employed bees and begin to research the environment of the best solutions by using equation (3). Researching is over after finding a better solution or if a better solution is not found in predetermined number of trials [7].

Scout bee phase

This phase begins when better solution is not found in the environment of a certain solution in predetermined number of trials. Then, bee become scout, which means that the new random solution is generated by using equation (2).

By researching the environment of the potential solutions this mathematical method is very successful in avoiding local extremes if number of cycles is large enough. It is very powerful in solving even the most complex optimization problems. Disadvantage of the method is the duration of the process, which is very long like for all other metaheuristic methods.

OPTIMIZATION OF ACTIVE POWER CURTAILMENT IN LV NETWORKS WITH HIGH PENETRATION OF PHOTOVOLTAICS

In this paper, an optimization model for calculating maximum output active power of all photovoltaics in observed low voltage network with minimum power losses. The main condition is that the voltages in all nodes are lower than the upper permissible limit will be presented. The goal of this approach is to increase the capacity of low voltage network for connection of larger share of installed photovoltaic power, to maximize produced energy that could be delivered in distribution system at a certain moment, to minimize power losses in network and to ensure that the voltages of all nodes are inside prescribed limits. Thus, this method has benefits for both, the producers and the distribution system operator.

Optimization model has two objective functions. The first is to maximize total output power of all photovoltaics (6):

$$OBJ\_FUN1 = max \sum_{i=1}^{D} P_i \quad (6)$$

where

D – number of photovoltaics

P_i – active power that i^th photovoltaic deliver to the network

The second objective function is to minimize total power losses in observed network (7):

$$OBJ\_FUN2 = min \sum_{i=1}^{n} S_{loss\ i} \quad (7)$$

where

n – number of branches

$S_{loss\ i}$ – power losses of the i^th branch

In this optimization process there are two conditions. The first condition is that the output power of i^th photovoltaic has to be between minimum (P_{min}) and maximum (P_{max}) value (8).

$$P_{min\ i} \leq P_i \leq P_{max\ i} \quad , \quad i=1,\dots,D \quad (8)$$

Technically, the lowest value of P_{min} can be set to zero which means that at the certain moment, some photovoltaics couldn't deliver power to the network at all, but it can also be set to higher percentage value of the current active power produced in photovoltaic panels. The maximum value P_{max} is equal to current active power produced in photovoltaic panel but can also be set on lower percentage value. Both parameters, P_{min} and P_{max} are predetermined percentage values and are equal for all photovoltaics.

The second condition is that the voltages in all nodes has to be lower than the upper permissible value U_{max} (9):

$$U_i \leq U_{max} \quad , \quad i=1,\dots,m \quad (9)$$

where

m – total number of nodes

Optimization program is made in Matlab R2017a. Photovoltaics are modelled as P-Q nodes. For power flow calculation a three-phase model of the network is used due to frequent unbalance. Three-phase photovoltaics are symmetrically modelled due to the request of the distribution system operator.

MODEL SIMULATION TEST ON A REAL LV NETWORK

Optimization model is simulated on a real low voltage network from substation 10/0,4 kV sv. Matije in Sibinj near Slavonski Brod with 100 nodes and 82 customers (Fig. 3).

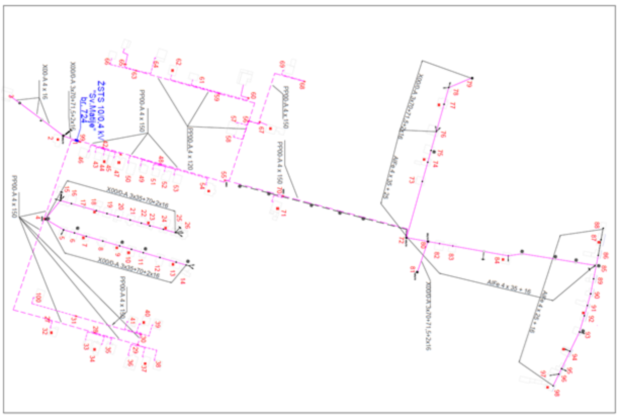

Fig. 3 Real LV network from substation 10/0,4 kV sv. Matije, Sibinj near Slavonski Brod, Croatia [8]

For the model testing 25 photovoltaics are randomly allocated. Their total installed power is 205,4 kVA. Maximum loading of the network during the day is 133,01 kVA and minimum is 33,62 kVA. Diagram in Fig. 4 represents the comparison of daily curves of total loading and total generation from photovoltaics during the ideal sunny summer day. It is obvious that the total generation significantly exceeds total loading. The highest voltage increase will occur in the period of the biggest difference between current generation and loading. In this example, this moment is at 13:30 h and it is chosen for the model simulation as the worst-case scenario.

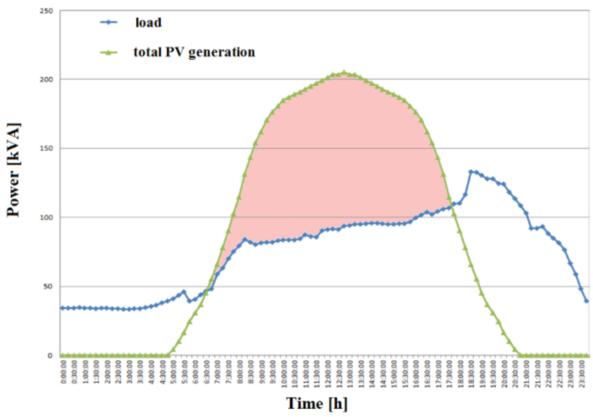

Fig. 4 Comparison of daily loading curve and total photovoltaic generation curve for the observed LV network [8]

Input parameters for the optimization process are:

Population:	**10**
Number of cycles:	**5000**
Number of trials:	**10**
$\mathbf{P_{min}}$	**0**
$\mathbf{P_{max}}$	**100%**
$\mathbf{U_{max}}$	**253 V**

Total photovoltaic power generation at the moment is 201,29 kW and total loading is 95,18 kVA. Optimum total power calculated by the proposed model amounts 182,24 kW, which means that the 9,47% of total generated power can't be delivered to the network.

Figure 5 shows the comparison of the observed network voltage profiles for each phase in case without voltage regulation and in case of application the proposed optimization model. In case without voltage regulation voltages in nodes from 85 to 98 in phases S and T are would be above the maximum allowed voltage. It would cause tripping of overvoltage protection in inverters of photovoltaics connected in nodes 87, 92, 94 and 98. In case of application of the proposed optimization model voltages in all nodes are decreased under 253 V.

Figure 6 shows the comparison of currents in all branches of each phase before and after application of the proposed method. In optimization model currents are reduced which results in a reduction of total power losses.

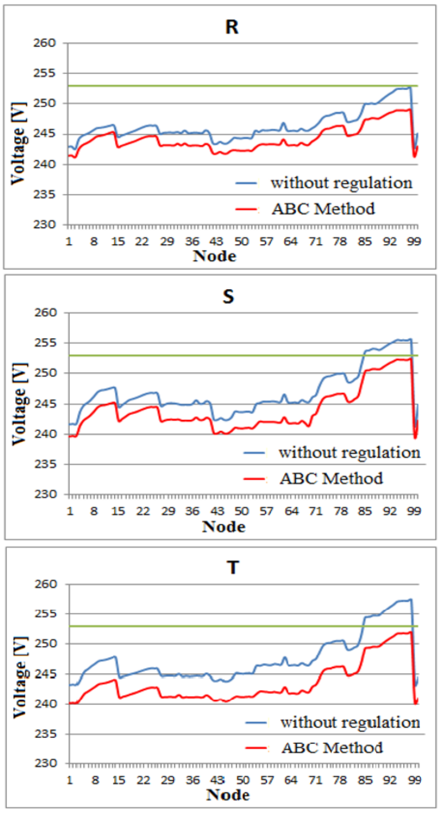

Fig. 5 Comparison of voltage profiles before and after application of the proposed method

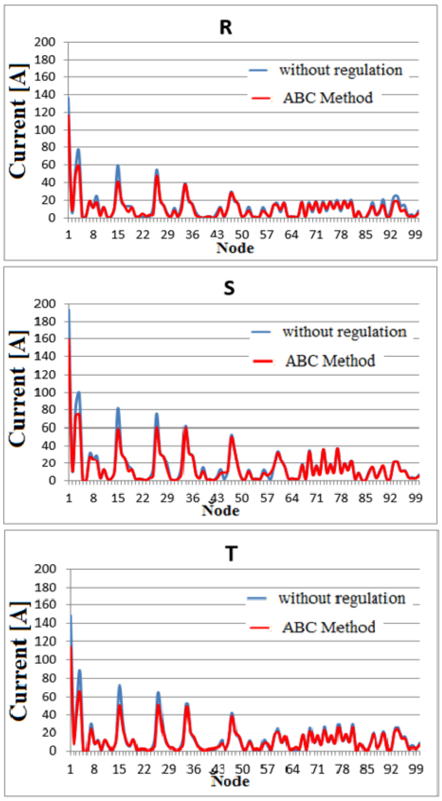

Fig. 6 Comparison of currents in all branches before and after application of the proposed method

On figure 7 current and optimum active power for each photovoltaic are compared. Above the bars is a percentage of power reduction. Most of the photovoltaics don't have significant reduction (under 10%), while other have moderate and only two have significant reduction (37,45% for PV at node 7 and 58,40% for PV at node 54).

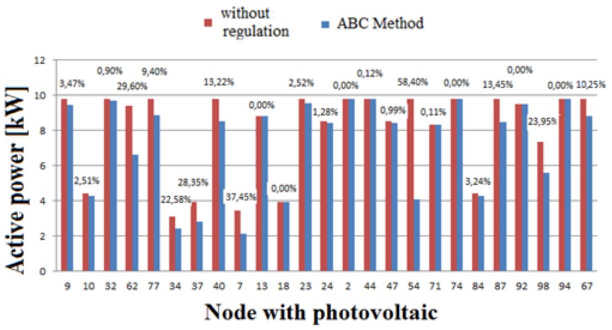

Fig 7. Comparison of total and curtailed active power of each photovoltaic

Power losses in low voltage network before application of the proposed method are 2,99% and after application are 2,23%. Total power losses reduction is 25,41%.

Test results show that all the goals of the proposed method are achieved. Electrical conditions are improved, capacity of the low voltage network for connection of larger share of photovoltaics is increased and the power losses in low voltage network are decreased. Also, curtailment of active power is not significant. Analysed case is the worst-case scenario, but most of the time there would be no curtailment or it would be lower due to photovoltaics daily generation curve and possible cloudy weather, so profitability of photovoltaics shouldn't be significantly decreased.

Advantage of the proposed model is also its flexibility because values of the parameters P_{min} and P_{max} can be set to minimize the curtailed active power.

CONCLUSION

The main problems for high penetration of photovoltaics in a low voltage network are overvoltages. To enable connection of larger share of photovoltaics in a low voltage network it is necessary to use some sort of voltage regulation methods. One of the technically most perspective methods is an active power curtailment. The main problem of this method is that the part of the produced energy can't be delivered to the network and is been thrown away. In this paper a novel optimization model of active power curtailment has been developed in order to maximize total current active power produced by photovoltaics that could be delivered to the network and to minimize power losses in a low voltage network. The goals of the proposed method are preventing overvoltages, increase of low voltage network capacity for connection of larger share of photovoltaics, minimization of curtailed power and minimization of power losses. Based on test results, all goals are achieved. The prerequisite for this method is a communication infrastructure. Disadvantage of the method is that there is no principle of fairness, which means that the curtailment is not equal for all producers as it depends on current electrical conditions in network. Equal curtailment is also possible to implement but this would cause the increase of total curtailed power and thus reduce the method efficiency. Possible solution for the curtailed power is a use of battery storages. At this moment, batteries are still very expensive, but due to fast development of the battery industry, in the near future their wider implementation in power systems can be expected.

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