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A Method for Cost Minimization Applicable to Load Centers Containing Distributed Generation

Č. V. Zeljković, *Student Member, IEEE*, N. Lj. Rajaković, *Senior Member, IEEE*, and S. J. Zubić

***Abstract*--Distributed energy resources (DER), located close to end use loads, have the potential to meet consumer requirements more efficiently than the existing centralized grid. In this paper, a specific scenario is considered, where the consumer center uses distributed resources to meet a part of its energy requirements, while the rest of the needed electricity is purchased from the utility distribution company. In order to minimize total consumer costs, a robust optimization algorithm based on a search method has been developed. The main outputs of this algorithm are optimal dispatch between distributed resources generation and the electricity purchased from the utility as well as the particular contribution of every on-site generating unit in the dispatch schedule. The algorithm was tested using several characteristic simulations and two basic areas of its application have been discovered – optimal dispatching of existing distributed energy resources and economic evaluation concerning installation of new generating facilities.**

***Index Terms*--Optimization methods, Power generation dispatch.**

I. Nomenclature

n	Number of distributed generating units
i	Index of generating unit ($i \in \{1,2,..,n\}$)
j	Index of cost type
m	Number of time intervals per month
h	Index of time interval ($h \in \{1,2,..,m\}$)
t	Simulation time step
L	Investment lifetime
d	Discount rate
S_k	Amount of savings for k^{th} year
A_i	Annuity index of i^{th} unit
$P_L(h)$	Total load demand during the h^{th} interval
$P_{PU}(h)$	Power purchased during the h^{th} interval
P_{PU}^{MAX}	Monthly peak demand of purchased electricity
P_{PU}^{TMAX}	Temporary assumption of monthly peak demand of purchased electricity during the search process
$P_{DER}(h)$	Total DER production during the h^{th} interval
$P_i(h)$	Power of i^{th} DER unit during the h^{th} interval
P_i^{INS}	Installed power of ^{ith} unit
E_i	Emission coefficient of i^{th} generating unit
C_{PU}^{kWh}	Power utility volumetric rate
C_{PU}^{kW}	Power utility demand rate
C_i^{kWh}	Equivalent kWh fuel costs of i^{th} unit
$C_i^{DER-FIX}$	Integrated fixed costs of all DER units
$C_i^{DER-VAR}$	Integrated variable costs of all DER units
C_i^{CAP}	Capital costs of i^{th} unit
$C_i^{O\&M-FIX}$	Fixed operation and maintenance costs of i^{th} unit
$C_i^{O\&M-VAR}$	Variable operation and maintenance costs of i^{th} unit
$C_i^{TAX-FIX}$	Fixed tax costs of i^{th} unit
$C_i^{TAX-VAR}$	Variable tax costs of i^{th} unit
C_{ET}	Emission costs

II. Introduction

ON-SITE power generation can do a lot of favors for the consumer. The increase of supply reliability and voltage stability are some of the technical aspects. But what is more interesting to the consumer is that the use of on-site distributed energy resources (DER) can bring direct economic benefits [2], [3], [4], [5].

In this paper, the specific scenario is considered, where the consumer center uses local distributed resources to meet part of its energy requirements and the rest of the needed electricity purchases from the utility distribution company. An optimization algorithm is presented with the total costs minimization as the main goal.

The electric utility tariffs and the DER costs included in the objective function are in coherence with real conditions in Bosnia and Herzegovina and the neighboring Balkan countries. By using minor modifications the presented procedure can be adapted to the other surroundings.

Čedomir V. Zeljković is a research and teaching assistant at the Faculty of Electrical Engineering, University of Banja Luka, Bosnia and Herzegovina (e-mail: cedomir@etfbl.net).

Nikola Lj. Rajaković is a full professor at the Faculty of Electrical Engineering, University of Belgrade, Serbia (e-mail: rajakovic@etf.rs).

Siniša J. Zubić is a research and teaching assistant at the Faculty of Electrical Engineering, University of Banja Luka, Bosnia and Herzegovina (e-mail: zubic@etfbl.net).

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The algorithm is based on a search method and for that reason is capable of dealing with non-smooth generator cost functions as well as with *max* function that is necessary for peak demand costs modeling.

III. Electricity Pricing Models

The first step in any economic calculation for a distributed generation project is a careful analysis of the cost of electricity and/or fuel that will be displaced by the proposed system. In this section, the focus is on electric utility rate structures, which are critical factors for customers evaluating a DER project, intended to reduce electricity purchases.

Electric rates vary considerably, depending not only on the utility itself, but also on the electrical characteristics of the specific customer purchasing the power. The rate structure for a residential customer will typically include a basic fee to cover costs of billing, meters, and other equipment, plus an energy charge based on the number of kilowatt-hours of energy used. Commercial and industrial customers are usually billed not only for energy (kilowatt-hours) but also for the peak amount of power that they use (kilowatts). That demand charge for power ($/month per kW) is the most important difference between the rate structures designed for small customers versus large ones [2].

In Republic of Srpska (Bosnia and Herzegovina), the main two components of an electricity bill are volumetric (Bosnian Marks / kWh) and demand (Bosnian Marks / kW peak consumption per month). Time-of-use pricing is used, respecting different on-peak and off-peak rates. There is also a difference between winter and summer rates.

IV. Distributed Generation as an Option for Cost Optimization

On-site generation (distributed generation (DG)) can reduce both the volumetric and demand charges of electricity. Consumers can invest in on-site generation equipment such as reciprocating engines, gas turbines, microturbines, and fuel cells. Renewable energy technologies including solar and wind power devices are also options. Typically, on-site electricity production is most economic in parallel with utility electricity purchase. When the cost of produced electricity and heat on-site is less than the cost of purchased electricity and heating fuel separately, on-site generation is dispatched to run [3].

V. Problem Formulation

In this section, the detailed formulation of the problem is given. A summary of consumer costs is listed here, and as the sum of these costs, mathematical objective function to be minimized is formed. Fig. 1 shows functional block-diagram of the system under consideration. The traditional way for consumer energy supply is to purchase electricity from the power utility company. The alternative is to buy fuel from the market and to produce energy locally, by using own generating units.

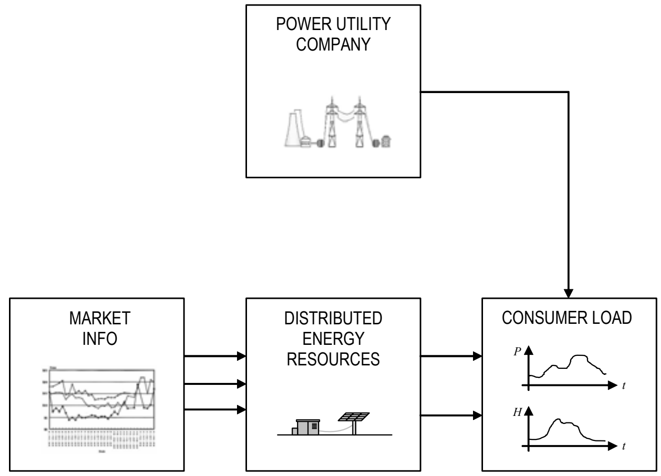

Fig. 1. Functional principle of the system being considered.

A. Basic Assumptions

For the optimization model, the following hypotheses are assumed:

- The only benefit that the consumer can achieve using distributed generation is a reduction in its energy bill. Neither reliability nor power quality benefits are taken into account.
- All data (energy loads, fuel prices, etc.) for the duration of the test period are known with complete certainty.
- The duration of the test period is one month. This assumption is reasonable because utilities mainly measure and charge peak load demand on a monthly basis.
- The distributed energy resources are not allowed to generate more electricity than the load center consumes. On the other hand, if more electricity is consumed than generated, the consumer would buy it from the utility company. No other market opportunities, such as a sale of ancillary services or bilateral contracts, are considered.
- Start-up and some other operating costs are not included [4].

B. Analysis of the Costs

In a rough analysis, two types of costs can be distinguished: the direct costs of distributed energy resources and the costs of electricity purchased. Going further, both of the two have their own specifics and can be decomposed into several components.

The costs of distributed energy resources definitely include the fixed capital costs, the fuel costs and the costs of operation and maintenance. Some legal tax payments also can be added. The costs of purchased electricity have a few components as well. As introduced in Section III, in the Power Utility of Republic of Srpska, a regulated two-element tariff is adopted, implying that the commercial and industrial consumers are billed for both the energy and the peak demand. Elsewhere, different modification of this tariff principle can be present, which can lead to slight adaptation of optimization algorithm described in the paper. The summary of the costs taken into account is shown in Table I.

TABLE I
THE SUMMARY OF THE COSTS

Cost Type	Mathematical Formulation
DG capital costs	$C_1 = \sum_i C_i^{CAP} \cdot A_i \cdot P_i^{INS}$
Fuel costs	$C_2 = \sum_i \sum_h C_i^{kWh} \cdot P_i\left(h\right) \cdot t$
Costs of purchased electricity	$C_3 = \sum_h C_{PU}^{kWh}\left(h\right) \cdot P_{PU}\left(h\right) \cdot t + C_{PU}^{kW} \cdot \max_h P_{PU}\left(h\right)$
Costs of operation and maintenance	$C_4 = \sum_i \sum_h C_i^{O\&M-VAR} \cdot P_i\left(h\right) \cdot t + \sum_i C_i^{O\&M-FIX} \cdot P_i^{INS}$
Tax costs	$C_5 = \sum_i \sum_h C_i^{TAX-VAR} \cdot P_i\left(h\right) \cdot t + \sum_i C_i^{TAX-FIX} \cdot P_i^{INS}$
Emission costs	$C_6 = \sum_i \sum_h C_{ET} \cdot E_i \cdot P_i\left(h\right) \cdot t$

After a summation of the costs and grouping related addends the objective function is formed:

$$C = \sum_j C_j = \sum_i \sum_h C_i^{DER-VAR} \cdot P_i\left(h\right) \cdot t + \sum_i C_i^{DER-FIX} \cdot P_i^{INS} + \sum_h C_{PU}^{kWh}\left(h\right) \cdot P_{PU}\left(h\right) \cdot t + C_{PU}^{kW} \cdot \max_h P_{PU}\left(h\right) \quad (1)$$

In the equation (1), only the second addend is constant, while the others depend on a dispatch schedule. For that reason, the second addend can be designated as C_{FIX}, and the sum of the remaining three as C_{VAR}:

$$C = \sum_j C_j = C_{FIX} + C_{VAR} \quad (2)$$

It could seem to be quite simple to minimize this objective function, but the presence of *max* function induces complications for the optimization methods based on derivation. The search method is more robust and is not hindered by this fact.

With DER units already installed, the cost minimization problem is equivalent to the problem of minimizing only the variable costs. On the other hand, when analyzing investment in new generating facilities, the capital costs are necessary to be taken into account as well.

C. Constraints

The constraints are expressed in equations (3) through (6).

The balance between production and consumption must be maintained for all times, i.e. consumption is the sum of energy locally produced and energy purchased from the utility, for every time interval h:

$$\sum_i P_{DER}\left(h\right) + P_{PU}\left(h\right) = P_L\left(h\right), \quad (3)$$

P_{DER} is defined as the sum of all DER units:

$$P_{DER}\left(h\right) = \sum_i P_i\ , \quad (4)$$

According to initial assumptions, the ultimate direction of the energy flow is from the utility towards the consumer, therefore:

$$P_{PU}\left(h\right) \geq 0\ , \quad (5)$$

Finally, the lower and upper limits of output power for each generating unit must be respected:

$$P_i^{MIN} \leq P_i \leq P_i^{MAX}\ , \quad (6)$$

VI. OPTIMIZATION METHOD

In order to minimize the objective function, a suitable method was developed. In the background of the method lies a search algorithm that checks a range of variants in a disciplined manner with an appropriate resolution. Counting with the fact that a particular consumer is expected not to have a large number of DG units, “the curse of dimensionality” does not pose much threat here, and satisfactory accuracy can be achieved, within reasonable amount of time.

The block-diagram of the method is shown in Fig. 2.

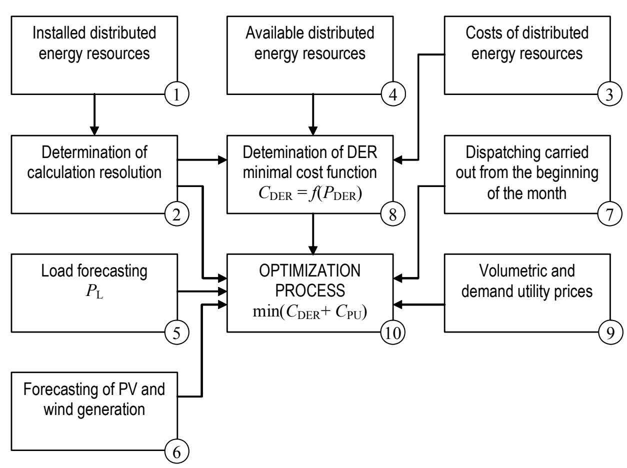

Fig. 2. Block-diagram of the optimization method.

The crucial block was named “Optimization Process”, because its outputs are the final solutions – optimal dispatch of the available resources and the minimal amount of costs for the consumer. The other blocks represent auxiliary procedures intended for preparing and conditioning of required input data.

At the very beginning of the procedure, enumeration of all present distributed energy resources is performed (Fig. 2, block 1). The operational range from the lower to the upper power output must be defined for every DER unit. For a particular consumer this procedure is performed only once.

Determination of calculation resolution is also performed only once (block 2). Duration of the optimization procedure is sensitive to the chosen resolution. Therefore, a compromising value must be adopted, that will be harmonized with the resolution of DER output power controllers, ensuring reasonable calculation times. Apart from the calculation resolution, the time resolution is necessary to be chosen as well. The simulations described in this paper uses one-hour time step.

Enumeration of the available distributed energy resources (block 4) is another required operation, because some of the units can be out of service. The reasons can be of a planned nature (maintenance, overhaul) or accidental (outages, faults).

One of the basic assumptions is certainty of the consumer's load profile. This is not unreal hypothesis because after the series of measurements it is possible to notice regularities and predictability in the load. The corresponding block of the optimization chart (block 5) is responsible for taking user data and forming the energy demand vector respecting the calculation resolution.

Production of solar and wind power devices (block 6) has stochastic character and is forecast by taking the weather conditions into account. These renewables have the variable costs that are negligible when compared to other fuel-firing DER units; therefore the best decision is to use their full potential available. A straightforward way to model this activity mathematically is to decrease consumer load profile for the amount of renewables output. Energy storage capacities could help in the easier following the forecast production plan.

The default variant of optimization is a whole month calculation. However, the situation is complicated by the stochastic nature of DG system failures, which can happen at inopportune times during the month and lead to a growth in utility electricity peak demand. Additionally, some other changes, such as drastic oscillations of fuel prices, installation of new generating units, completion of overhaul procedures, or changes in customer load profile can occur. For that reason, the optimization algorithm is enabled to start from an arbitrary day of a month, respecting the dispatching carried out to date (block 7), i.e. temporary value registered on the peak demand meter that will not be reset till the month's end. As the month progresses, the optimal dispatching will change as any DG failures are incurred and as forecasts are updated.

In order to make search paths shorter, all DER costs are lumped together (block 8). Using dynamic programming, for every value of output power that can be covered by DER units, the cheapest way of dispatching is chosen, and C_{DER} function is created by accumulating all those minimized costs.

The central optimization process (block 10) then operates only with two cost functions, the integrated costs of the DER units C_{DER} and the utility electricity costs C_{PU}, having obligation to determine the optimal balance between the generated and purchased energy. The process can later perform an inverse dynamic programming procedure, decomposing aggregate DER production P_{DER} and creating the detailed dispatch schedule. Solving of the problem would be extremely much simpler if the electricity costs did not have peak demand element. Actually, this problem becomes simultaneous, i.e. the peak load demand which happens only once in the month significantly participate in the amount of the customer's energy bill. The flowchart of this process is shown in Fig. 3.

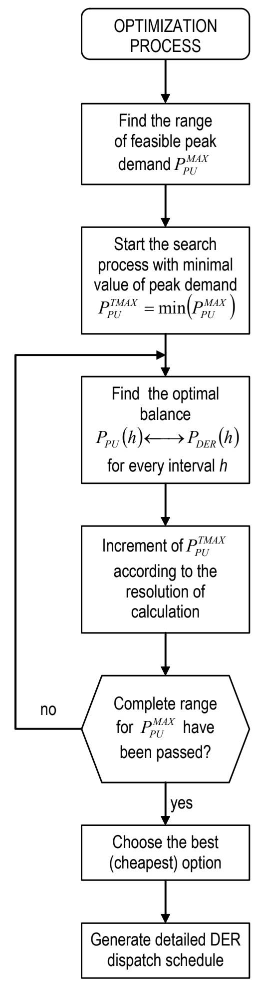

Fig. 3. Block-diagram of the optimization process.

VII. Application to Installation Assessment

The optimization algorithm can be applied to economic assessment of DER installation problem. The optimization software is fed with data for the potential generating units and the best possible dispatching solutions are determined. By comparing the new optimized costs to the previous energy costs without DG resources installed, the amount of annual savings (S_k) for every year k over the system lifetime L is calculated. Finally, taking into account the capital costs, it is looked for the positive estimation of the net present value.

NPV is calculated by discounting the net benefits stream into its present value:

$$NPV = -\sum_{i=1}^{N} C_i^{CAP} P_i^{INS} + \sum_{k=0}^{L-1} \frac{1}{(1+d)^k} S_k \qquad (7)$$

The feasible project with the maximal NPV will represent the best investment solution.

VIII. Simulation Results

In this section, the key simulation results are presented.

A. Basic Characteristics of the Test System

The test system is a hypothetical wood industry complex. Its load diagram was constructed by using real data taken from literature [8]. Fig. 4 shows a part of a monthly load diagram – load data for one week. It can be observed that the peak demand is reaching 1600 kW, and the minimum load is about 300 kW. There also exists the noticeable difference between weekdays and weekend days.

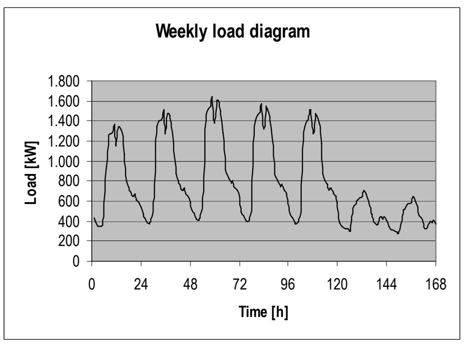

Fig. 4. The part of a monthly load diagram.

It is assumed that the consumer possesses four distributed generators denoted with G1 to G4. The first unit is the smallest and with highest fuel costs. It could be an internal combustion diesel engine. The fourth generator is the largest unit. For example, it could be based on natural gas firing. The third unit has the cheapest variable costs. It could be assumed that such power unit burns consumer's own wood waste.

Two characteristic simulations are planned: with lower fuel prices (1) and with higher fuel prices (2). The fuel prices are hypothetical. Power utility electricity prices and tariffs are in accordance with the real data from the Power Utility of Republic of Srpska for the year 2008.

TABLE II
Basic Simulation Input Data

Unit	P_{min} [kW]	P_{max} [kW]	C_{kWh} [€/kWh]$^{(1)}$	C_{kWh} [€/kWh]$^{(2)}$
G1	50	100	0,15	0,25
G2	80	150	0,07	0,11
G3	200	350	0,025	0,025
G4	500	1000	0,043	0,058

B. Simulation Results

Simulation (1) implies lower fuel costs. In the first part of simulation, the aggregate curves of DER costs are obtained. Fig. 5 and Fig. 6 show these curves for the simulation (1).

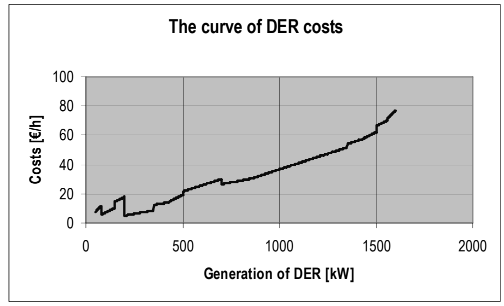

Fig. 5. The aggregate costs of distributed energy resources.

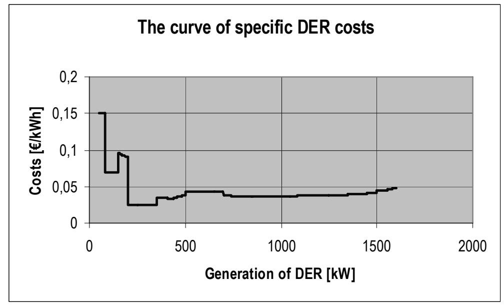

Fig. 6. The specific costs of distributed energy resources.

Fig. 7 shows the next output of the algorithm – optimal ratio between power generation of distributed resources (P_{DER}) and the electricity purchased from the utility (P_{PU}). In this case, the main supplier is on-site generation. At the same time, the utility peak demand is lower than 300 kW.

Fig. 8 presents contribution of every on-site generation unit in the dispatch schedule. The units G3 and G4 are fairly committed. Starts of the unit G2 are also needed in order to shave the load peaks and reach full optimization.

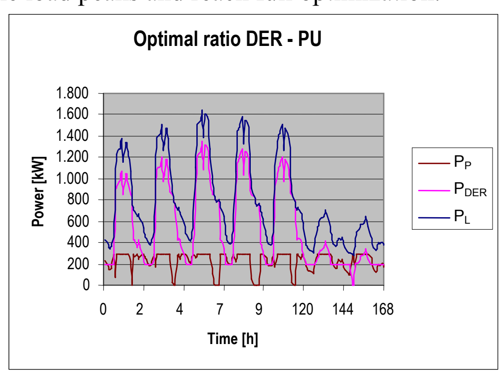

Fig. 7. Optimal ratio between DER and PU (lower fuel prices).

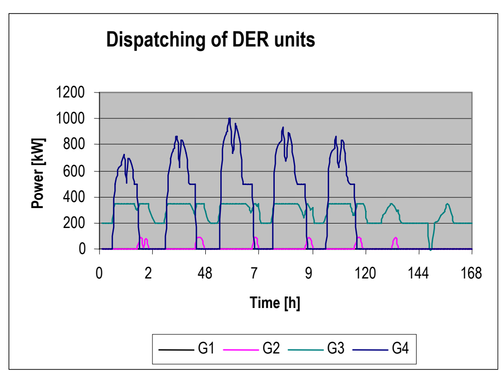

Fig. 8. Particular dispatching of the DER units (lower fuel prices).

With the fuel prices being raised (simulation (2)), the simulation results are significantly changed (Fig. 9 and Fig. 10). The test consumer is now recommended to purchase more electricity from the utility company (the peak is almost 1200 kW) and to decrease output of their own generation units. Only the cheapest unit G3 has notable commitment, but merely during the day, because lower off-peak electricity rates favor the purchase from the utility during the night.

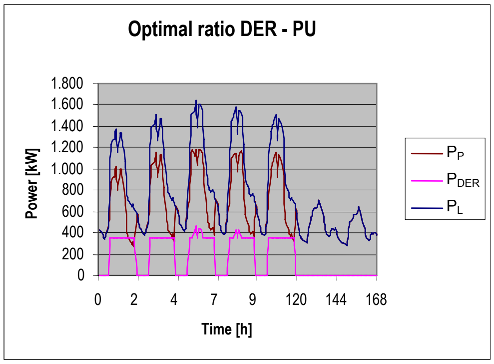

Fig. 9. Optimal ratio between DER and PU (higher fuel prices).

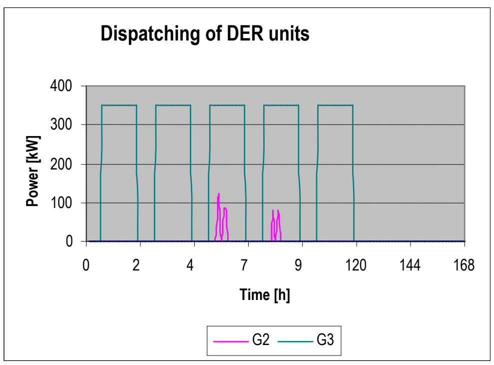

Fig. 10. Particular dispatching of the DER units (higher fuel prices).

IX. Conclusion

On-site power generation under certain conditions can bring direct economic benefits to the consumer. Aiming at maximizing these benefits, an optimization algorithm is developed. The primary output of the algorithm is optimal dispatch between distributed resources generation and the electricity purchased from the power utility. Additionally, the contribution of every on-site generating unit in the dispatch schedule is determined. The algorithm is based on a search method and for that reason is very robust and capable of dealing with non-smooth generator cost functions as well as with *max* function that is necessary for peak demand costs modeling.

However, due to accepted assumptions and limitations, there are many areas of further research to improve this model and the results.

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XI. Biographies

Čedomir V. Zeljković (S'09) received the B.Sc. (Dipl. Eng.) degree in electrical engineering from the University of Banja Luka, Bosnia and Herzegovina, in 2003, and the M.Sc. (Mr) degree in electrical engineering from the University of Belgrade, Serbia, in 2008.

Currently, he is a research and teaching assistant at the Faculty of Electrical Engineering, University of Banja Luka, working at the same time towards his PhD degree.

His areas of scientific interest are distributed generation and renewable sources in a power system, as well as power network calculations and optimization.

Nikola Lj. Rajaković (M'89 - SM'94) is a professor at the Faculty of Electrical Engineering of University of Belgrade, and senior member of IEEE.

The areas of his interest are electric power system analysis and optimization and recently, renewable energy sources and distributed generation. He is the author and co-author of several dozen articles and papers at national and international level.

Siniša J. Zubić received the B.Sc. (Dipl. Eng.) degree in electrical engineering from the University of Banja Luka, Bosnia and Herzegovina, in 2006.

Currently, he is a research and teaching assistant at the Faculty of Electrical Engineering, University of Banja Luka. His areas of scientific interest are power system protection and power system operation.