Flexible load control in electric power systems with distributed energy resources and electric vehicle charging

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Abstract: **This article presents an approach for flexible loads control in power systems with integration of electric vehicles (EV) and distributed generation for power system regulation. A control system with monitoring and control capabilities is proposed as a possible solution of the main problematic issues related to EV charging. IEC61850 standard is covered for data transfer between local and global monitoring systems. An optimization problem for load shift control depending on technical and market conditions is defined and solved. The approach is widely applicable for various EV charging and distributed energy resources (DER) considering control algorithms, smart charging, EV and DER hosting capacity extension, EV interoperability testing, smart grid power management, monitoring and other power system problems.**

Keywords: **electric loads management, electric vehicle charging control, electric loads optimization, flexible electric loads, DER control in electricity markets**

I. INTRODUCTION

The present world tendency shows increasing values of consumption and production of electricity [1]. Although the major amount of the electricity is produced of fossil fuels and gas the share of the renewables generation increases rapidly during the recent years. Additionally the goal to decrease CO_2 emissions leads to increasing the part of electric vehicles.

The electric vehicle (EV) charging devices promise to be one of the most significant challenges for the contemporary microgrids and distribution networks [3,4,7,9]. The European Commission urges the members to increase their efforts in development of proper EV charging infrastructure. Chargers are loads which influence significantly on the electric network parameters [3, 9]. Due to the fact that the electrical networks have been already built and the upgrades are difficult, new charging control and energy management strategies have to be found in order to enable adequate integration of the electrical vehicle charging devices into the network. At

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has a very good potential to offer novel power balancing and grid support services, by providing dispatchable load or generation [3,4,5,9]. Combining EV with distributed energy resources (DER), like photovoltaic generation (PV) offers a promising opportunity of having both flexible load and flexible production in one and the same electric subsystem.

The legal and market rules also stimulate the usage of PVs and EVs in the energy systems. Many publications are focused on the integration of PVs and EVs in energy system [3, 6, 7].

This article presents implementation of a control system for managing the integration of PVs and EVs in the electrical power system in terms of the legal and market regulation rules.

At the present energy markets there are two main trading schemes:

1. Regulated markets where the prices of the electricity are fixed usually dividing 24 hour period in several tariff zones;
2. 24 hours ahead free market scheduling and contracting the energy at fixed intervals. Usually the interval is fixed at 1h or 15 minutes.

In both schemes minimization of the costs is a matter of defining and solving an optimization problem which depends on the treading scheme, market prices and the flexibility of the consumers connected to the power system.

Significant problem in utilization of PVs and EVs as flexible load is finding appropriate way to control the loads under the technical and market constrains.

Concerning the findings of the “IndustRE” project [1, 2] the most suitable business models for combining Variable Renewable Energy (VRE) and Flexible Demand (FD) are:

- ***Business models type A: Reduced energy bills by shifting consumption***

A.1 Time of use tariff or price rates, e.g. night rate offered by a supplier.

A.2 Dynamic pricing signals emitted from the supplier.

A2.2 A supplier owning VRE plants benefitting from the FD to balance.

A2.3 On-site renewable energy and possibility of netting demand.

A.3 Management of consumption in response to wholesale electricity prices by acceding directly to the market or through a supplier/aggregator.

A.4 Reduced network charges due to lowering peak demand.

• ***Business models type B: Offering flexibility services to the power system***

B.1 FD offering reserve capacity, either directly or through an aggregator.

B.2 FD responding to signals sent by the Balancing Responsible Party (BRP), who tries to balance their demand-generation portfolio.

B.3 Other services to the system, such as: investment deferral, congestion management, among others.

The investigation shows that such business models are strongly applicable in the EU countries [2].

This article is focused on the investigation of a way to realize load shift control and power production limitation depending on 24 hours ahead forecast schedule and protective load limitations.

II. TEST CASE

A representative simulation test case of existing 0,4 kV, 21 bus distribution network of a village near Sofia, Bulgaria is presented (fig. 1) [15,16,9].

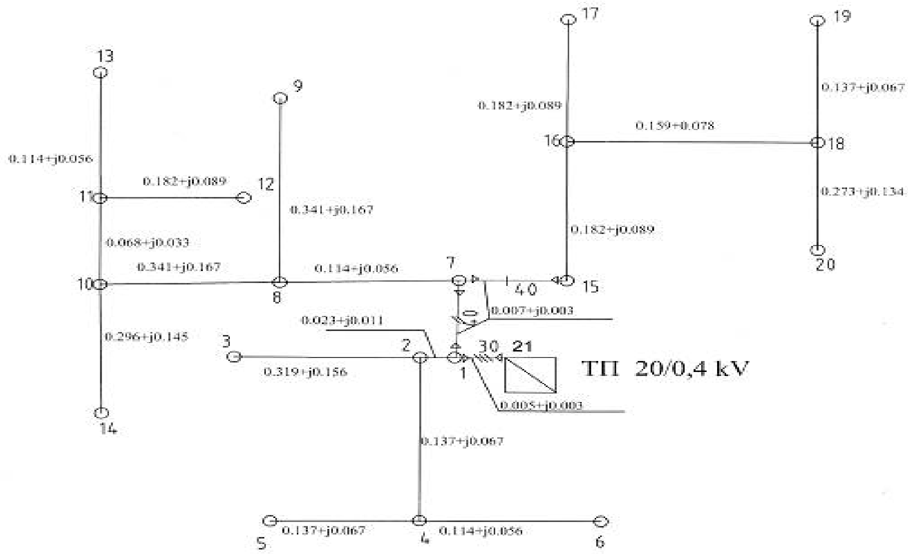


Fig.1 One-line scheme of the tested system

The network (fig. 1) has uniformly distributed, symmetric, predominantly active inflexible domestic load.

The minimal and the maximal domestic load without EV charging are P_{min}=33,2 kW and P_{max}=110,8 kW respectively. Two inverters tied photovoltaic generators with flexible production are interconnected at bus 10 and at bus 18. A photovoltaic generator G1 with nominal power P_{G1}=30 kW is connected at bus 10. A photovoltaic generator G2 with nominal power P_{G2}=50 kW is connected at bus 18.

A presence of 10 electrical vehicles with flexible loads totaling 7% of the vehicles in the village is assumed. The average daily run per vehicle is 64 km achieved using 13,2 kWh. A probabilistic distribution of the EV charger placement, starting moment of the charging and the initial SOC is applied similarly to the purpose in [8]. It is supposed that most of EV users will start the charging after returning home after work which occurs most probably at 18:30h.

The system has preliminary defined 24 hours ahead schedules for domestic loads, EV loads and PV genera-

$$P_t = P_c - P_{PV} \quad (1)$$

where

P_t is the total power of the system

P_c is the total power consumed by the electrical loads in the system

P_{PV} is the total power produced by the PVs.

In this case

$$P_c = P_{dl} + P_{EV} \quad (2)$$

where

P_{dl} is the total power of the domestic loads,

P_{EV} is the total power consumed by the EVs.

If P_{SH} is the scheduled power according the 24 hours ahead market and $P_c = P_{SH}$ in the best case then

$$P_A = P_{SH} - P_{dl} \quad (3)$$

where $P_A -$ is available power for EV charging.

Then the total power consumed by EV charging

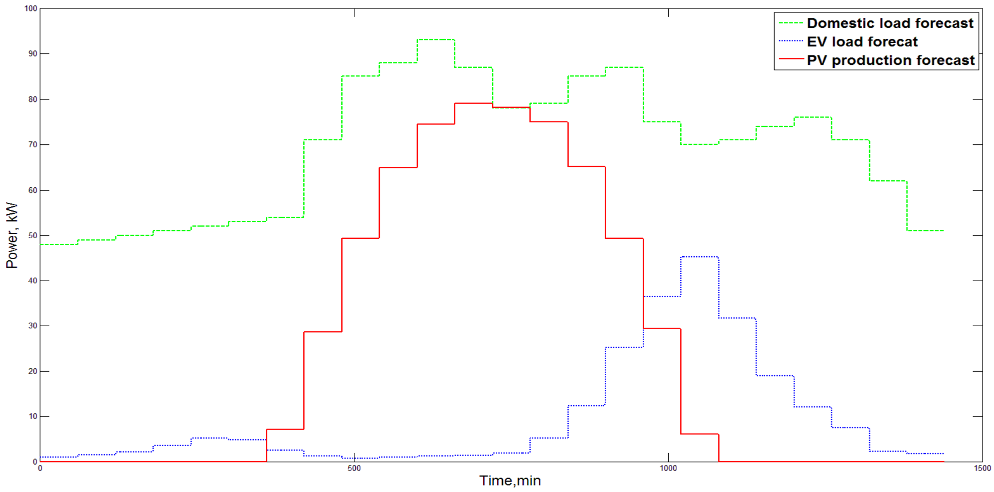


Fig.2 Domestic load, EV load, PV production 24h ahead schedules

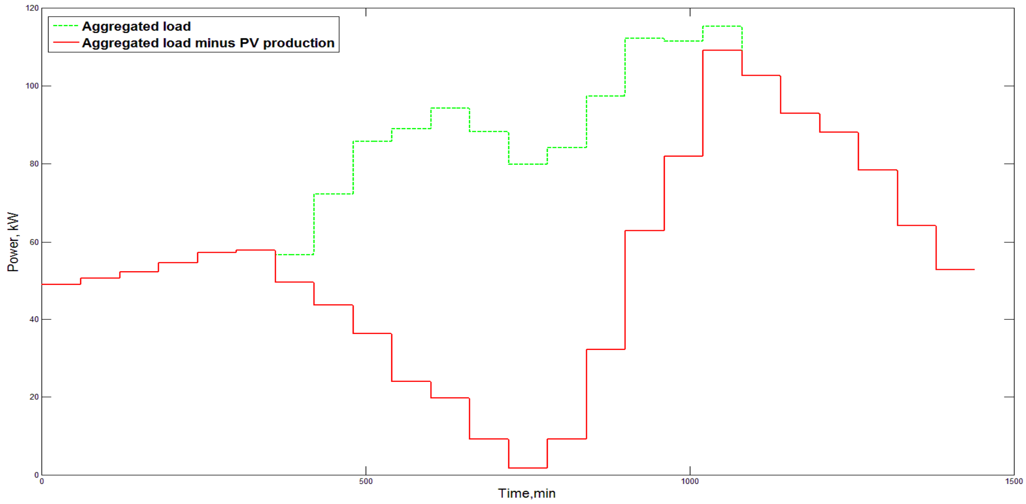
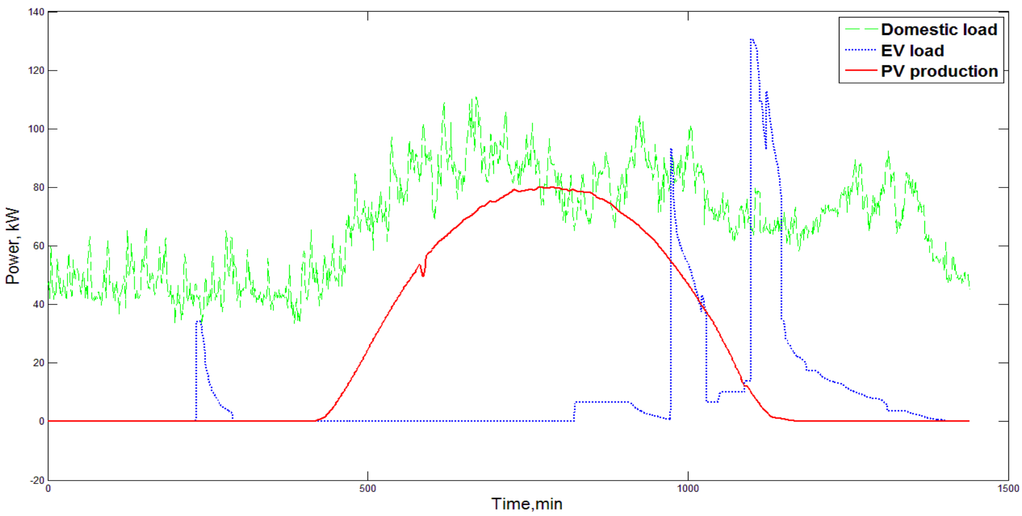


Fig.3 Agregated loads and production 24h ahead schedules

Several batteries charging profiles are used in the simulation.The charging profile depends on the initial state of charge (SOCi) and the battery state of health (SOH) as it is shown in [3, 9, 13, 14]. The power consumption of the loads and the PV production are given on fig.4.

The calculation of the available power is given on fig 5.



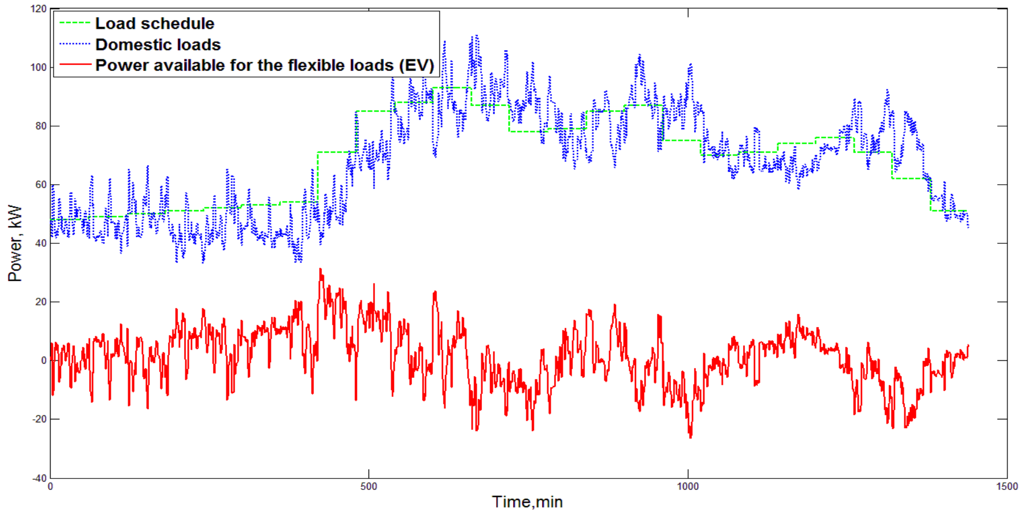


Fig.5 Available power for flexible loads over all schedule including PV production

The case study represents simulation over a typical 24 h period. The simulation time stamp is 1 minute. Based on the network data and the load, generation and charging profile data for each individual node the system parameters over the time are computed.

The following scenarios are considered:

1) *Scenario 1:* The power consumers (EVs) have no control system; uncontrolled "plug & charge" concept is applied.

2) *Scenario 2:* The power consumers (EVs) have a control system without charging mode selection. In this case the consumer cannot select if he prefers "fast" or "economic" charging. All available power of the loads is optimized by the control system.

3) Scenario 3: The power consumers have a control system with mode selection. Selecting "fast" or "economic" charging is possible.

a/ Mode 0 – Fast charging enabled which means the load become uncontrollable.

b/ Mode 1 – Fast charging disabled – the power is limited up to the maximum available.

The control system has an optimization module for load shift [10, 11, 12]. Similar optimization model with fixed load limitation and a SCADA system for data monitoring are presented in [9].

III. EXPERIMENTAL RESULTS

Some possible ways to control the loads are given in [17, 18, 19]. Two of them are:

a/ Power limitations are used as measured disturbance in a feedback process control system [18,19].

b/ An optimization problem is defined and solved periodically [17].

The first method is acceptable mostly for large industrial loads and in this test case an optimization model of type (4) is implemented.

where:

P_i - is the available power of the i-th EV;

P_A – is the total available power for EVs charging.

The minimization of (4) will result in minimization of financial loses as there is different prices for the surplus, deficient and scheduled energy registered at the free electricity market. Usually the scheduled energy is much cheaper than the other two.

The power and its time derivative constrains are given by:

$$P_i^{min} \le P_i \le P_i^{max}$$
$$\Delta P_i^{min} \le \Delta P_i \le \Delta P_i^{max} \qquad (5)$$

where:

P_i^{min}, P_i^{max} - Minimum and maximum power requirements for charging;

ΔP_i - Power change for charging of i – vehicles between two optimization cycles.

The optimization problem is solved at every 1 minute period and the power of the EVs is limited to an appropriate value. The simulation results are given on fig.6.

Adding the mode control (Scenario 3) means the following constrains should be added in the optimization model

$$if\ M_i = 1\ then\ P_i = P_i^{max} \qquad (6)$$

where M_i is the charging mode of the i-th vehicle ($M_i = 1$ means "Mode 0" is selected).

In this case the system does not limit the consumption of the load if fast charging mode is selected. The results are shown on fig.7. Usually mode selection could lead to power peaks and undesirable voltage decrease in the system. This is the reason to include protective limit of the consumed power in the control system. The result of the protection power level is shown on fig.8. The protective limit in this test case is 80 kW.

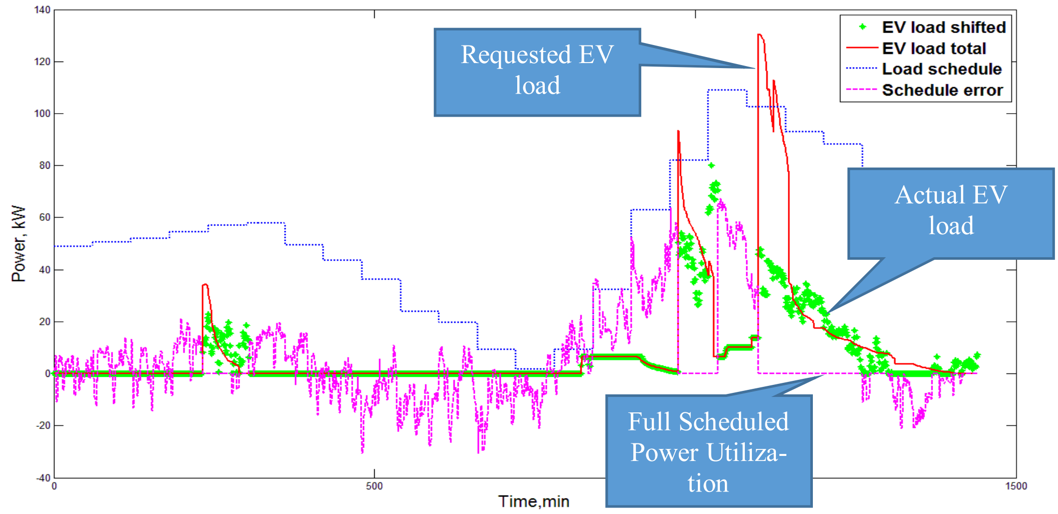


Fig.6 Load shift depending on 24 ahead market scheduling without mode selection and PV generation

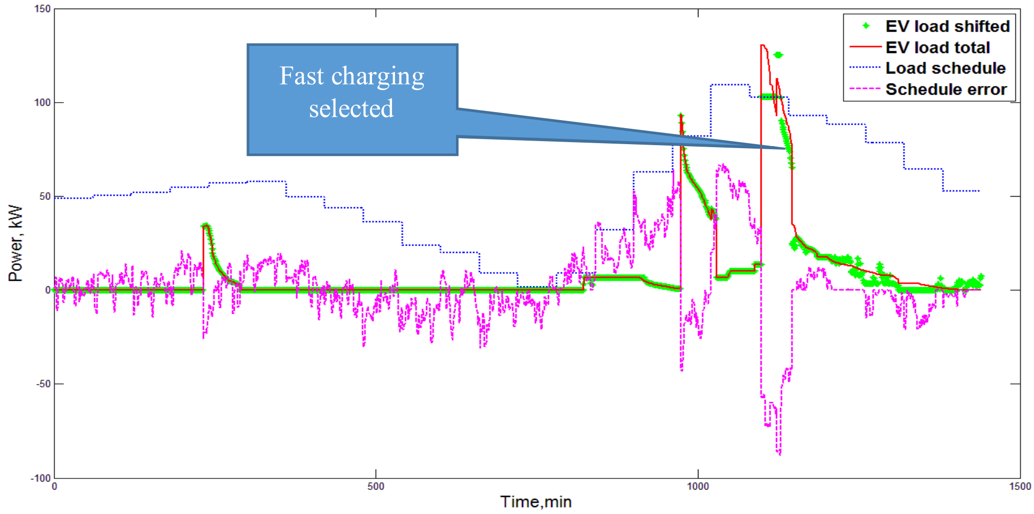


Fig.7 Load shift depending on 24 ahead market scheduling with mode selection

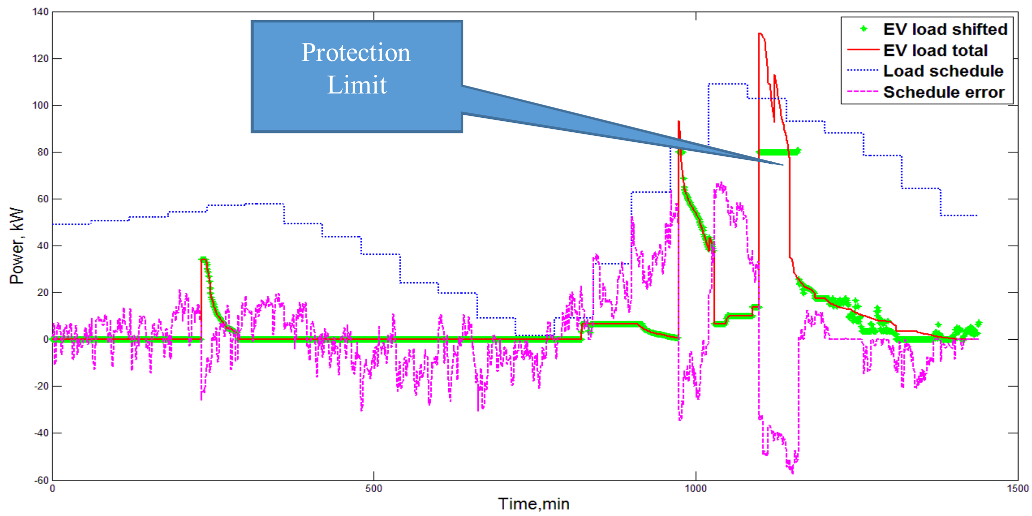


Fig.8 Load shift with mode selection and protection limit

Adding the mode selection leads to increase of the consumed power over the schedule. In this case the solution for minimizing the financial losses is to buy additional quantities at appropriate price. Fig.7 and fig.8 show presence of periods of underestimation and over- even when load shift control algorithm is applied. In this case surpluses and deficiencies can be compensated by buying or selling energy to the energy market.

The algorithms for estimation of energy to buy and to sell are not considered in detail. For estimation of

1. The available quantities at the market and their prices are $< E_j^s, \beta_j^s >$

2. The energy demands and their prices are $< E_j^d, \beta_j^d >$

For data exchange with external technical and market systems IEC61850 Server is implemented (fig.9). The standard communication protocol (IEC61850) is used to guarantee the interoperability of the control system with other similar or larger power systems.

The negative values of the energy for market balancing show available quantities for sale, and the positive ones shows available energy to buy from the market. It is possible to define two additional optimization problems:

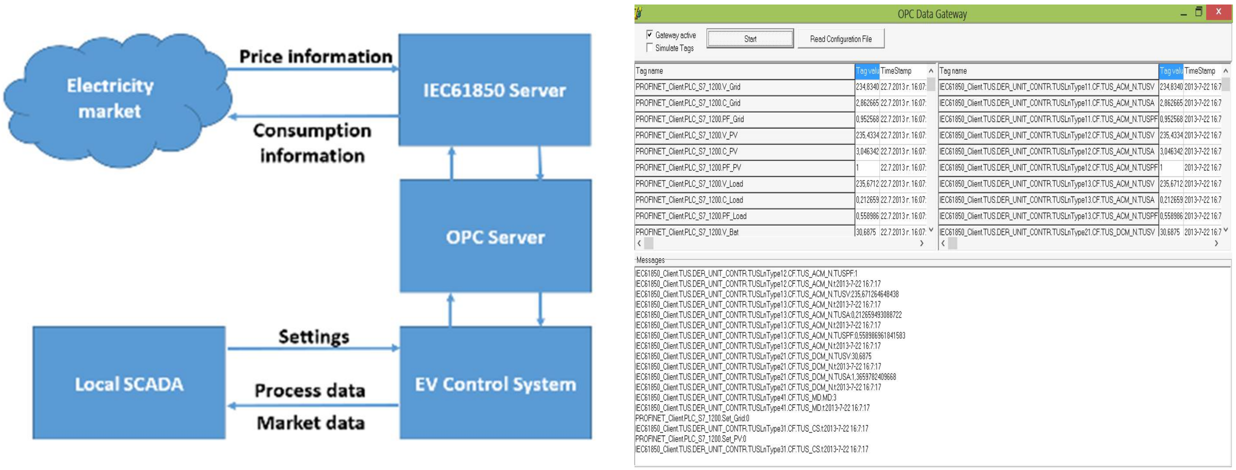


Fig.9 Information exchange system

1. Obtain the optimal prices to sell the unnecessary quantities depending on market demands.

2. Obtain the optimal quantities to buy for the additional quantities needed to the system.

In this case a flexible control with decision making for energy buying instead of load shift is achieved.

The algorithm for including the mode selection in the optimization problem and the available energy to buy from and to sell to the market is given on fig. 10

The energy surpluses could be compensated with reduction of PV production as it is shown on fig.11 The PV production reduction or selling the surpluses is a matter of estimation of the economic advantages of the system.

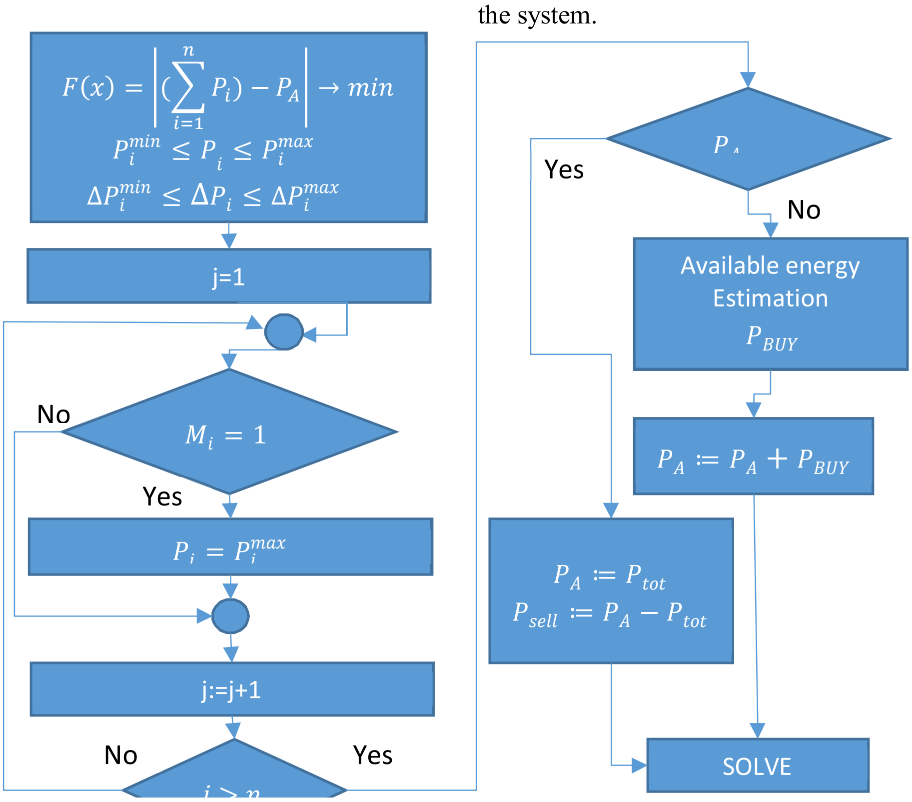


Fig.10 Load shift depending on 24 ahead market scheduling with mode selection

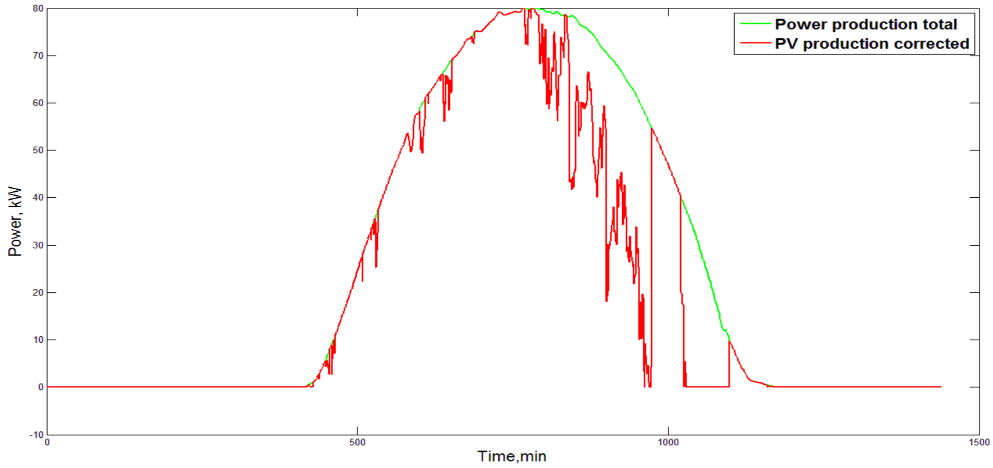


Fig.11 PV production reduction with surplus power values

IV. CONCLUSIONS

This article proposes a promising solution for use of electric vehicles and photovoltaic generation sources in the process of balancing the power system in case of free electricity market regulations. It is proven that the load shift business model is applicable having controllable electrical loads (in this case EV). The optimization models are defined and realized. The performed simulations confirm their applicability. Also the necessary conditions for data interchange are defined in respect to build flexible trading business model as an alternative of the load shift model. An algorithm for combining the load shift and flexible trading is presented. PV production limitation is also considered as possible strategy for load balancing.

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