Optimization Algorithms for RES Operation Application With Utilization of Programmable Logic Controlers

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Abstract: **The energy systems which consist RES will take a leading place in the energy world in future. From the one side the participation of RES (Renewable Energy Sources) and energy storage devices will increase the flexibility of the energy system and will offer new services at the energy market. From the other the probabilistic work of the RES lead to uncertainty in their production and may cause difficulties in the energy system operation. This two reasons together with the variety of RES and storage opportunities rise the necessity of building reliable algorithms for optimization of their work and their interoperability. Also concerning the future plans for energy systems development all energy systems including electricity, gas, heat, etc. should collaborate each other which increase the complexity of the algorithms for controlling the different systems. Usually, the optimization algorithm is part of MES (Manufacturing Execution Systems) or MOM (Manufacturing Operations Management) systems and they are executed in computers using different types of operation systems. In this article and approach for utilization of programmable logic controller as and algorithms holding devices is proposed. The utilization of the PLCs for such type of tasks will lead to improved performance of the algorithms and will increase the reliability and the speed of the algorithms. As the PLCs are relatively standard devices this will lead also to improved possibility for interoperability between different systems.**

Keywords: intelligent house, Programmable Logic controllers, Demand side management, solar energy production

I. Introduction

Concerning the new regulations of the European Union the citizens are marked in the center of the European goal for clean energy generation [1]. From one side EU stimulate the installation of small generation facilities. The current legislation stimulate the utilization of generation units for households if they are used for their own needs. In Bulgaria, a limit of 30 kW generation power for PV is presented. This lead to obvious benefits to the citizens. Installing small generation facilities may effect on the prices of the electricity paid as in case of self-consumption many grid taxes can be avoided. From the other side increasing number of small generation facilities makes difficult the electricity system control from the side of DSO and TSO. Some issues in using of large number of small generation are the problems with voltage and frequency control and presence of harmonics injected in the common electricity system [2]. Concerning the EU analyses main generation systems are roof based PV [1]. This means that in such case the time of the generation will not coincides with the time of consumption (usually the peak production from the PV is about the middle of the day but the peak of the consumption is in the evening.) From the other side investing in solar generation is still expensive if it is not donated from the government or from the EU funds. This reasons rise necessity to install renewable power sources from the one side and to limit their generation up to the consumed power in the house from the other. It is obvious that the generation utilities will not have so effective impact without electricity, heat or chemical energy storage system. Of course, in case of heat or chemical storages, additional transformation units will be necessary. This analyses shows the complexity for utilization of the large variety of opportunities like different generation units (PV, wind, hydrogen), different storage units (electrical, heat and chemical) and different types of consumption units and to synchronize them for best possible performance. In this case, there is necessary to install control system to synchronize the behavior of power sources (one or many), storages and the house loads.

II. Description of the Problem

This development presents a laboratory design of a PV system with electrical storage and thermal loads equipped with PLC based optimal control system. The goal is to maximize the utilization of the produced energy from the PV observing the technical parameters of the loads and the storage.
In the house two types of loads are presented:

- Fixed loads – which could not be controlled
- Flexible loads – which could be controlled

The flexible loads are two types depending on the applicable control algorithm:

- ON/OFF control – mainly loads related to heating and hot water generation
- Continues control – variable loads (ventilation system and devices with remote mode selection or remote control opportunities

In this case, the total load consumption of the house could be resented as:

$$P_L^T = P_{FL} + P_{FLL}^R + P_{FLL}^{CC} \tag{1}$$

Where

P_L^T - is the total load of the house

P_{FLL}^R - is the total load of the flexible loads with on OFF control

P_{FLL}^{CC} - is the total load of the flexible loads with continuous control. Different implementation of the home control system could be found as it is shown in [5], [6] and [7].

For this research presents realization of loads optimization control using programmable logic controller (PLC) is chosen. The optimization procedures are calculated in the PLC and the control signal is applied to the loads connected to small capacity PV generation unit. The goal is to ensure maximal

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utilization of the PV capacity with the existing house loads. In this use case returning energy to the grid is forbidden.

The used laboratory equipment consist of PV generation unit with a capacity of 5 kW, batteries with a capacity of 200Ah, 5 heating units with total load of 7,6 kW and programmable logic controller (PLC). The PLC communicates with the PV invertor through Modbus TPC communication to gain the information about PV generation capacity.

The invertor is set to work without returning energy to the grid and works in one of the following modes:

1. Mode with energy excess – in this mode the PV capacity is greater than the used power. In this mode batteries are charged if the SoC is less than 100%
2. Mode with lack of energy – in this mode the PV supply the missing energy from the batteries down to SoCmin, where SoCmin is the limit of the batteries
3. discharge or from the grid up to the total power of the invertor. If the total power of the loads exceeds the total power of the invertor than some of the loads should be connected directly to the grid.

In confirmation of the selected modes typical household load profile in Bulgaria given in [9] shows that the moments of peak consumption do not coincides with the moments of energy production (Fig. 1).

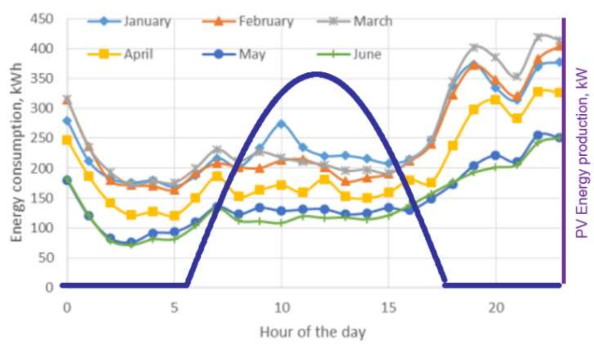


Fig. 1. Daily household consumption profile vs PV production.

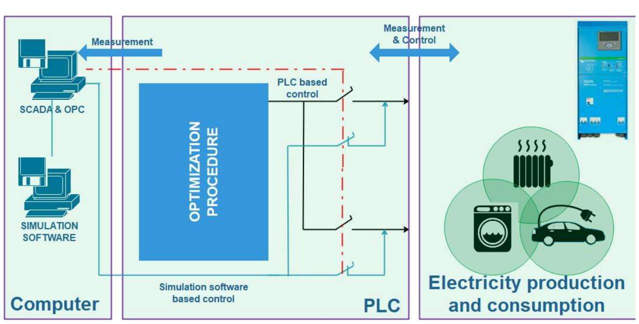


Fig. 2. Laboratory Facility structure.

In respect to ensure best performance of the house electricity system the following test facility is built as it is shown on Fig. 2 and consists of 3 elements PLC for realization of optimization and control algorithms, SCADA for facility visualization and supervisory control and simulation software for data development. The designed algorithms are tested using simulation software before they are implemented in the PLC.

III. CONTROL SYSTEM APPLICATION

The control system is designed to use programmable logic controller for execution of the control algorithm. The program in the PLC consists of the steps shown on the Fig.

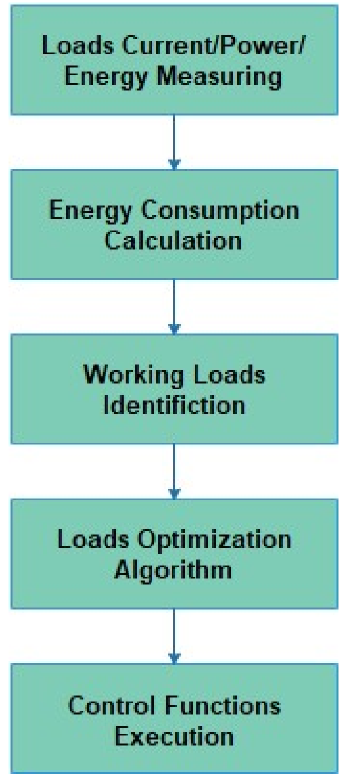


Fig. 3. PLC working algorithm.

STEP 1: Energy measuring and power calculation

The information of the energy production, the SoC (State of Charge) of the batteries and the power flow to the batteries is collected form the PV invertor using ModbusTCP communication between the invertor and the PLC.

Three types of measurements for loads consumed power are available in the designed measuring function of the PLC.

1. Using discrete signal

$$E_k^i = E_{k-1}^i + 1 \tag{2}$$

E_k^i is the energy consumed by the i-th load ath the moment k.

2. Using analogue measurement of the current

$$E^i(t) = \begin{cases} \int_0^{T_0} U_g I_i dt \; if \; \alpha_i = 0 \\ \int_0^{T_0} U_{PV} I_i dt \; if \; \alpha_i = 1 \end{cases} \tag{3}$$

Where

$\alpha_i = 0$ if the load is connected to the grid

$\alpha_i = 1$- if the load is connected to the PV

U_g- is the measured grid voltage

U_{PV} - is the measured PV invertor voltage

I_i – is the measured current of the i-th load

3. Smart metering – the total energy is measured directly from the smart meter.

Smart meters are actively used as measuring devices but it is not applicable for using in home control system because of system price increasing.

In this application measuring of the loads with current transformers and calculating the power using the equations (3) are used.

STEP 2: Estimating load state

The load state is given with β_i and cold be get from working schedule of the loads in the house, from the loads forecast or using identification of the current load state.

In this use case and identification of the energy consumption is used following the rule that if $\Delta E_i > 0$ for a certain period T_k then $\beta_i = 1$ for the period T_{k+1}. The duration of the period T_k is an adjustable parameter of the model.

In this research the main goal is to optimize connected to the PV without exceeding the total power of the invertor:

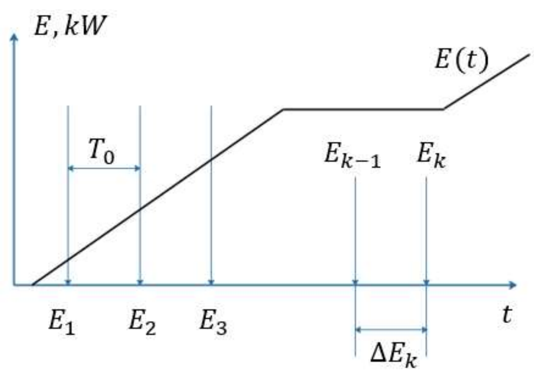


Fig. 4. Loads Energy Consumption Calculations.

STEP3: Loads optimization

In this research the main goal is to optimize connected to the PV without exceeding the total power of the invertor. Similar models showing utilization of linear programming for application in load shift are show in [8]:

1. Maximization model

$$\sum_{i=1}^{n} \alpha_i \beta_i P_i \rightarrow max \quad (4)$$

$$\sum_{i=1}^{5} \alpha_i \beta_i P_i \leq P_{max}^{inv} \quad (5)$$

2. Minimization model

$$P_{max}^{inv} - \sum_{i=1}^{n} \alpha_i \beta_i P_i \rightarrow min \quad (6)$$

$$P_{max}^{inv} - \sum_{i=1}^{5} \alpha_i \beta_i P_i \geq 0 \quad (7)$$

For the both models common limitations for α_i are available

3. Additional limitations

$$0 \leq \alpha_i \leq 1$$

$$\alpha_i - integer \quad (8)$$

Where P_i is the power of the i-th load

α_i is the independent variable in the model and shows the connectivity to the PV invertor. If α_i is connected to the PV, otherwise if β_i is 1 the load is connected to the grid. If β_i=0 then the load is in state "Idle"

P_{max}^{inv} is the maximal power of the invertor

To map the model to the PLC data equations from (4) to (8) are transformed in matrix form as follows in (9), (10) and (11):

$$\begin{vmatrix} P = [P_1, P_2 \dots P_n] \\ P = [P_1, P_2 \dots P_n] \\ P = [P_1, P_2 \dots P_n] \end{vmatrix} \quad (9)$$

The maximization model in this case will be presented as a scalar product of three vectors:

$$(A.B \ ).P \ \rightarrow max \quad (10)$$

$$A.B.\mathrm{P} \ \leq P_{max}^{inv} \quad (11)$$

For optimization algorithm a Simplex method [3] with integer variables is used. The algorithm consists of utilization of Gomory cutting panes [4].

For implementation of the algorithm in PLC is used SIEMENS S7-1200 programmed with TIA Portal v16. The programming language is SCL which give the opportunity to work with arrays and matrix.

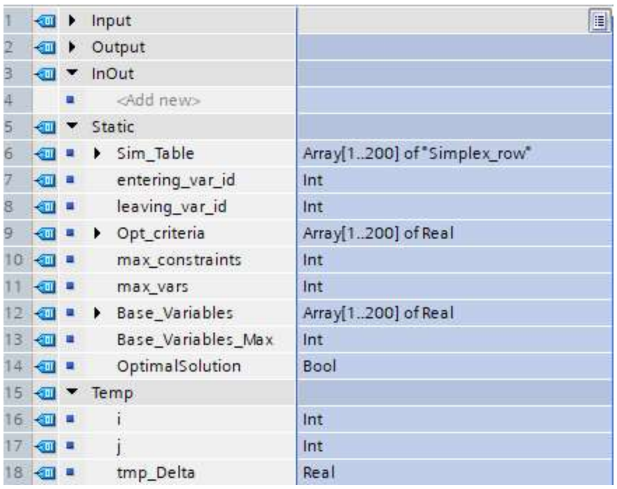
Following equations (9), (10) and (11) a simplex table with dynamical size is built in the PLC. The table is presented in Table 1.

TABLE I. SIMPLEX TABLE PRESENTATION IN THE PLC

	1	*2*	**….**	*i*	**…..**	*n*	*n+1*
1	$-\beta_1 P_1$	$-\beta_1 P_1$	….	$-\beta_i P_i$	…..	$-\beta_n P_n$	0
2	$\beta_1 \mathrm{P}_1$	$\beta_1 P_1$	…..	$\beta_i P_i$	……	$\beta_n P_n$	P_{inv}^{max}
3	$-\alpha_1$	0	0	0	0	0	0
4	0	$-\alpha_2$	0	0	0	0	0
….	0	0	…	0	0	0	0

i+2	0	0		$-\alpha_i$	0	0	0
….	0	0	0	0	….	0	0
n+2	0	0	0	0	0	$-\alpha_n$	0
n+3	α_1	0	0	0	0	0	1
n+4	0	α_2	0	0	0	0	1
…..	0	0	…...	0	0	0	1
n+i+2	0	0	0	α_i	0	0	1
…..	0	0	0	0	………..	0	1
2n+2	0	0	0	0	0	α_n	1

The proposed table is realized in PLC using the structure shown on fig.



1	Input	
2	Output	
3	InOut	
4	<Add new>	
5	Static	
6	Sim_Table	Array[1..200] of "Simplex_row"
7	entering_var_id	Int
8	leaving_var_id	Int
9	Opt_criteria	Array[1..200] of Real
10	max_constraints	Int
11	max_vars	Int
12	Base_Variables	Array[1..200] of Real
13	Base_Variables_Max	Int
14	OptimalSolution	Bool
15	Temp	
16	i	Int
17	j	Int
18	tmp_Delta	Real

Fig. 5. PLC data structure for simplex algorithm.

The data model uses up to 200 rows of the model and the size of the table is automatically calculated depending on the maximum number of variables given with the value of max_var variable.

STEP 4: Control function execution

One of the main problems reconnecting the loads to the grid or PV is that there is no possibility for frequent changing the power source because of the loads nature – frequent switching on and off can decrease the loads life and for some loads can lead to mode or program loss. For this reason contactless switching elements (SSR) are used. For this use case they are good choice as the loads characteristics are very close to active loads. The connecting principle is shown on Fig. 6.

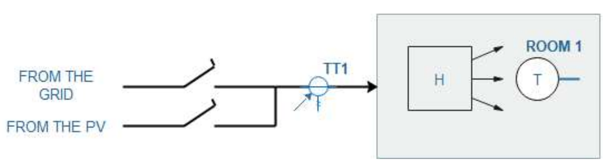


Fig. 6. Loads power supply control.

Three states of the loads are used: Connected to the grid (CG), Connected to the PV (CPV) and Idle – the load is disconnected from both sources.

To test the algorithm, simulation is done solving the problem using specialized simulation software LINGO ver.18:

The simulation code is given bellow:

```
MODEL:
SETS:
LOADS/L1..L5/: P,A;
ENDSETS
DATA:
P=2 2 1.2 1.2 1.2;
MAX_POWER=5;
ENDDATA
MAX=@SUM(LOADS(J): P(J)*A(J));
TOTAL_POWER=@SUM(LOADS(J):P(J)*A(J));
TOTAL_POWER<=MAX_POWER;
@FOR( LOADS(J):@BND(0,A(J),1));
@FOR( LOADS(J):@BIN(A(J)));
END
```

The result of simulation is given at the Fig. 7 and Fig. 9. Control signals to the loads are shown on Fig. 8 and Fig. 10.

```
     Variable           Value        Reduced Cost
    MAX_POWER        5.000000            0.000000
  TOTAL_POWER        4.400000            0.000000
       P( L1)        2.000000            0.000000
       P( L2)        2.000000            0.000000
       P( L3)        1.200000            0.000000
       P( L4)        1.200000            0.000000
       P( L5)        1.200000            0.000000
       A( L1)        0.000000           -2.000000
       A( L2)        1.000000           -2.000000
       A( L3)        1.000000           -1.200000
       A( L4)        0.000000           -1.200000
       A( L5)        1.000000           -1.200000

          Row    Slack or Surplus      Dual Price
            1        4.400000            1.000000
            2        0.000000            0.000000
            3       0.6000000            0.000000
```

Fig. 7. Simulation results for all $\beta_i = 1$.

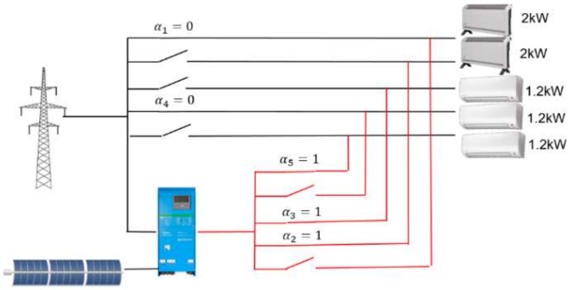


Fig. 8. Control system action all loads are active.

In the next simulation the second load L2 is excluded from the mode l and the reaction of the system is shown on Fig. 10.

Variable	Value	Reduced Cost
MAX_POWER	5.000000	0.000000
TOTAL_POWER	4.400000	0.000000
P(L1)	2.000000	0.000000
P(L2)	10.00000	0.000000
P(L3)	1.200000	0.000000
P(L4)	1.200000	0.000000
P(L5)	1.200000	0.000000
A(L1)	1.000000	-2.000000
A(L2)	0.000000	-10.00000
A(L3)	1.000000	-1.200000
A(L4)	1.000000	-1.200000
A(L5)	0.000000	-1.200000

Row	Slack or Surplus	Dual Price
1	4.400000	1.000000
2	0.000000	0.000000
3	0.6000000	0.000000

Fig. 9. Simulation results with all $\beta_2 = 0$.

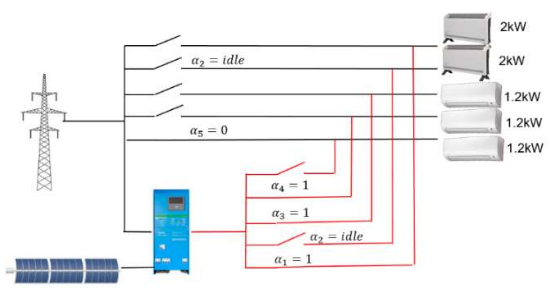


Fig. 10. Control system behavior load 2 is not active.

Solving the optimization problem with optimization algorithm and with PLC similar results are obtained.

The last step of the PLC algorithm consist of check for loads reconnection using feedback from the control signals. The feedbacks are presented at Fig. 11.

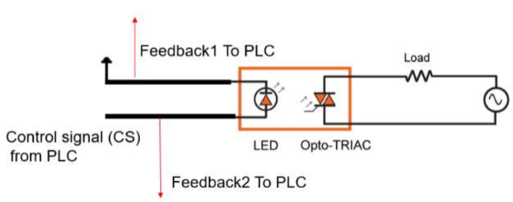


Fig. 11. Control signals feedbacks.

If the control signal is active and there is not feedback then the system will reject controlling this unit and will disconnect it for the power sources and will be placed in state “Idle”.

It is visible that in this case the system change the connected new device to the PV reconnecting the loads numbered one and two.

IV. CONCLUSION

In this research a use case with implementation of flexible control algorithm based on loads optimization is presented.

The designed facility shows the possibility to control the loads implementing advanced optimization and control technics directly in the PLC and without using computers and other supervisory devices. The results of the work are that the control algorithm is successfully applied in PLC;

The proposed structure and method improve the energy efficiency of the house with increasing the utilization performance of the PV;

This result from the algorithm realization give the base for more complex upgrade if the algorithm in the following direction:

1. Integrating in the control system more than one production and storage utility;

2. Integrating in the control system power sources with different nature (solar, wind and hydrogen);

3. Integrating energy transformation utilities and storages;

4. Implementing in the control algorithm loads forecast and loads shift technics to maximize the house energy system efficiency.

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REFERENCES

[1] Solar Energy Policy in EU and the Member States, from the perspective of the previous received, European Union 2016, https://www.europarl.europa.eu/committees/en/supporting-analyses/

[2] J. Driesen, R. Belmans, “Distributed generation: Challenges and possible solutions”, Power Engineering Society General Meeting, 2006. IEEEPower Engineering Society General Meeting, 2006. IEEE

[3] H. Taha, Operations Research: An Introduction, Pearson Prentice Hall, 2007, ISBN: 0-13-188923-0

[4] Editors: Christodoulos A. Floudas, Panos M. Pardalos, Encyclopedia of Optimization, Springer Links, 2009

[5] K.Taşdelen, O.Bingöl, Web-based Smart Home Automation: PLC-controlled Implementation, Acta Polytechnica Hungarica 11(3), March 2014, DOI: 10.12700/APH.11.03.2014.03.4

[6] C. Barz, S. I. Deaconu, T. Latinovic, A. Berdie, A. Pop-Vadean and M Horgos1, “PLCs used in smart home control”, IOP Conference Series: Materials Science and Engineering, Volume 106, International Conference on Applied Sciences 2015 (ICAS2015) 3–5 June 2015, Wuhan, China

[7] J. Bredeson, R. Benton, BMS or PLC? Controlling the Regulated Environment, BioPharm International, 2004, Volume 17, Issue 9

[8] M. Georgiev, Rad Stanev, A. Krusteva, Optimized power flow control of smart grids with electric vehicles and DER,16th Conference on Electrical Machines, Drives and Power Systems (ELMA) 2019, DOI: 10.1109/ELMA.2019.8771575

[9] N. Mihaylov, B. Evstatiev, S. Kadirova, T. Gueorguiev, T. Georgieva, A. Evtimov, “Load Profile of Typical Residential Buildings in Bulgaria”, 4th International Scientific Conference SEA-CONF 2018, doi :10.1088/1755-1315/172/1/012