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FUZZY-PI CONTROL OF WATER PUMPS MODELLED BY HYBRID BOND GRAPHS

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Abstract. *This paper establishes a complex highly nonlinear model of a submersible pump station with three pump aggregates, in the water factory NAISSUS in Niš, using the theory of bond graphs. To verify the model accuracy there are performed several simulations in the software package Dymola. To reduce power consumption of the pumps and to eliminate the need for classic switching tables, herein, we propose the fuzzy-PI controller. The obtained experimental results confirms the effectiveness of the proposed control logic and the power required for the pump station is significantly reduced.*

Key words: *Bond graphs, Pump station, Fuzzy-PI control, Switching tables*

1. INTRODUCTION

Modelling and simulation is crucial in the design and analysis of engineering systems. In the analysis and design of engineering problems, the most important thing is to perfectly know the process of technology. The success of the use of computer based tools to assist in the design, control, monitoring and modeling of these systems is critically dependent on the ability to develop accurate models for simulating, and verifying system behaviour. Moreover, it is well known that the quality of the designed control method directly depends of the model accuracy. In literature, several methods for obtaining model of the plant could be found.

The bond-graph method is a modeling approach where component energy ports are connected by bonds that specify the transfer of energy between system components [1]. In another words, the bond graph presents a method for obtaining dynamical models of

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different engineering systems. They are further developed in [2], [3], and now this method can be successfully implemented in practice [4]-[7]. As one example of practical realization, it is shown in [8], [9] that bond graphs can be used for system modelling. In this paper we present the bond graph modelling of submersible pumps plant in water factory Naissus in Niš. Installation of frequency converter on each of them reduces the peak and "polishes" voltage, and in that way the possibility of an induction motor burning out is also reduced. In [10], we introduced orthogonal filters in order to additionally reduce voltage sag effect, causing by starting large motors. There, we considered only one pump, and the other two were neglected. Herein, we go one step forward and consider the whole plant, consisted of three parallel-pumps. Their working cycle is described in the switching table.

Dymola is a commercial modeling and simulation environment based on the open Modelica modeling language (an object-oriented, declarative, multi-domain modeling language for component-oriented modeling of complex systems). The BondLib library, firstly presented by Cellier in [11], is designed as a graphical library for modeling physical systems using the bond graph metaphor. This library contains the basic elements for analog electronic circuits, translational and rotational mechanical systems, hydraulic and thermal systems. So, we come to the idea to simulate obtained model of three submersible pumps in Dymola. There are several advantages, in the sense of simulations, in comparison to the other simulations software widely used. For example, presenting simulation results is much more simpler than in Simulink, because you can show every signal from model without inserting new blocks (graphs, to workspace blocks, etc.).

In the control process area, the majority of real processes is rather complex and difficult to model and control [12]. Having this in mind, we need a simple advanced control alternative as fuzzy logic control [13], [14]. The application of fuzzy logic to a wide range of control applications has made possible the establishment of intelligent control in these areas [15], [16]. The main advantage of FLC in comparison to the other control techniques, lies in the fact that it provides a good support for translating the heuristic knowledge of the skilled operator (expressed in linguistic terms) into computer algorithms. Fuzzy control could be successfully applied for solving real problems [17-21], previously not tackled due to their complexity or to lack of information. However, FLC is usually applied with poor analytic knowledge of their behaviour and only in simple configurations. To overcome this problem, in the last two decades, there is a great effort to combine various control techniques into one single controller. In that way, the obtained controller outline their individual strengths and suppress drawbacks. FLC-PI controllers are quite simple, though they are the most widely used in practice and provide similar results to conventional controllers.

In this paper, we derived the model of a submersible pump station with three pump aggregates by using the bond graph modelling approach. The obtained model is then realized in Dymola software environment and after that it was transferred as a block to the Simulink. Further, the process of controller design is carried out in Simulink. The water level and the difference between the water level, measured by sensor, and the output variables with switch ON-OFF function of the submersible pumps are used as input information to the proposed controller. A fuzzy control system, applied to an induction motor, is fed by a PWM three phase voltage inverter. To verify the proposed control scheme we performed several digital simulations, and the obtained results confirm better system performances in regard of reducing power required for the pump station.

2. PLANT DESCRIPTION AND BOND GRAPH MODELS

In this section, we give briefly a description of the pump station presented in Fig.1, which is used for distributing the untreated water to the infiltration units. This plant was already considered in our previously papers [10], [22], [23], but there we considered pump station with only one submersible pump. Herein, the pump station is consisted of three identical pumping units with independent pipelines. Moreover, these models are improved by inserting the labels which denote flow and effort and by giving the appropriate equations for these labels. The pumps aggregate works between 4.2m and 5.2m. This determines the dimensions of water storage level for ON-OFF regulation of the pumps aggregate. The parameters of submersible pump are: flow Q=312-315 m^3/s, head of the pump H_p=5.5-4.2m, efficiency coefficient η =0.845-0.818, *NPSH*=7.9-7.4m. The capacity of the pump station is:

a) one pump aggregate turn on: flow - Q=312-315 m^3/sec, input power *P*=30kW,

b) two pump aggregate turn on: flow - Q=600-620 m^3/sec, input power *P*=60kW.

The model of a whole plant is divided into several sub models representing its individual parts (rectifier, inter circuit, inverter, asynchronous motor and submersible pump). In this section we will also upgrade the some bond graphs of the specified parts, already derived in [10].

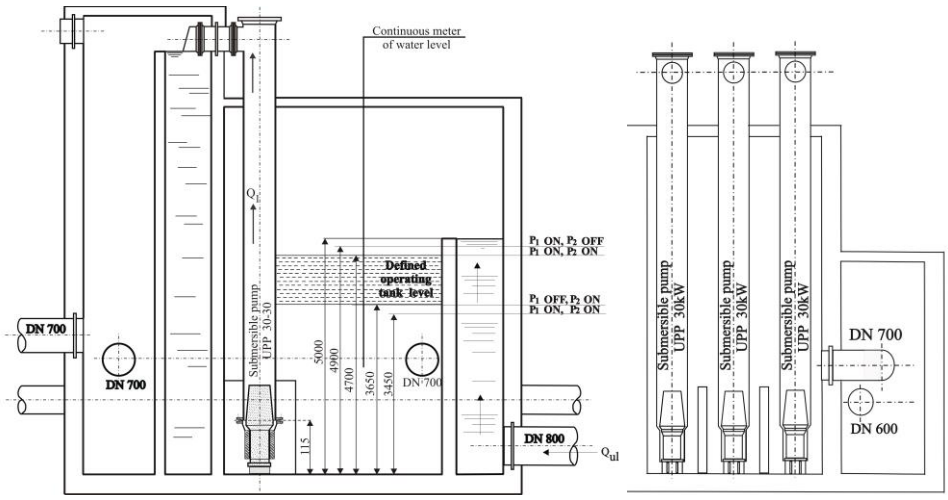


Fig. 1 Vertical section of the pump station

Following denotations are used in bond graph models: *Se*-the effort sources of voltages, *Sf*-the flow source, *TF*-the bond graphic linear transformer element; the constant is defined as the amplification of flow from the inflow to the outflow with transformation constant, *MTF*-the bond graphic modulated transformer element with transformation constant, *R*-resistors element for rotors and stators, *C*-the bond graphic linear capacitor, *I*-inductor element, effort accumulator, *MGY*-modulated gyrator element with gyration constant. There are also junction structure elements: *0*-junction and *1*-junction. The *0*-junction is a flow balance junction or a common junction. It has a single effort on all its bonds and the algebraic sum flows is null. The *1*-junction is an effort balance junction or a common flow junction. It has a single flow on all its bonds and the algebraic sum of effort is null. Further, the improved bond graph models of the individual parts of pump station are given.

2.1. Bond graph model of rectifier and inter circuit

Two components can be connected by a power bond-bond thus giving them the same effort and flow. The corresponding bond graphs equations of rectifier and inter circuit for *1* and *0*-junction are:

$$1:\begin{cases} e_3 = e_1 - e_2 - e_4 \\ f_1 = f_2 = f_3 = f_4 \end{cases} \tag{1}$$

$$0:\begin{cases} f_5 = f_2 \\ e_2 = e_5 \end{cases} \tag{2}$$

In Fig. 2, the bond graph model of inverter and inter circuit is presented.

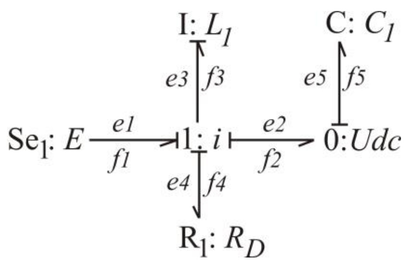


Fig. 2 Bond graph model of the rectifier and inter circuit

2.2. Bond graph model of inverter

The bond graph model of the whole inverter unit can be modelled as it shown in Fig. 3.

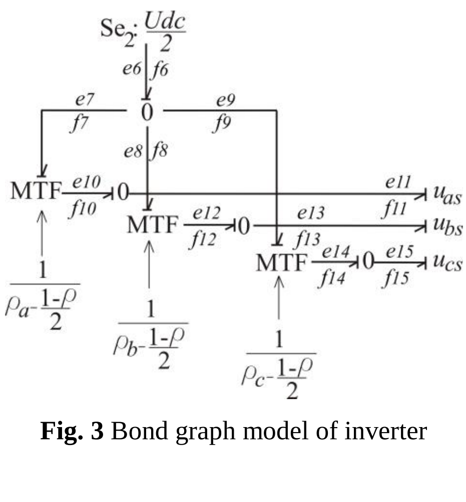


Fig. 3 Bond graph model of inverter

The equations which describe the efforts and flows from Fig. 3 are written in the following form:

$$0:\begin{cases} e_6 = e_7 = e_8 = e_9 \\ f_6 = f_7 + f_8 + f_9 \\ e_{10} = e_{11};\ f_{10} = f_{11} \\ e_{12} = e_{13};\ f_{12} = f_{13} \\ e_{14} = e_{15};\ f_{14} = f_{15} \end{cases} \tag{3}$$

$$MTF:\begin{cases} e_{10} = \left(\dfrac{1-\rho}{2}\right)e_7;\ e_{12} = \left(\dfrac{1-\rho}{2}\right)e_8 \\ e_{12} = \left(\dfrac{1-\rho}{2}\right)e_9;\ f_{10} = \left(\dfrac{1-\rho}{2}\right)f_7 \\ f_{12} = \left(\dfrac{1-\rho}{2}\right)f_8;\ f_{12} = \left(\dfrac{1-\rho}{2}\right)f_9 \end{cases} \tag{4}$$

2.3 Bond graph model of asynchronous motor

A generalized dynamic model of the induction motor consists of an electrical sub-model to implement the three-phase to two-axis (3/2) transformation of stator voltage and current calculation, a torque sub-model to calculate the developed electromagnetic torque, and a mechanical sub-model to yield the rotor speed [10]. For constant machine speed and load, angular frequency of all variables is equal to the frequency of the rotating field. By using Park transformation, all variables (voltages, currents and fluxes) in synchronously rotating reference frame appear as constants. The asynchronous motor in *d-q* model is presented by well known equations, which can be found in [10]. The corresponding bond graph model of asynchronous motor described by these equations is shown in Fig. 4.

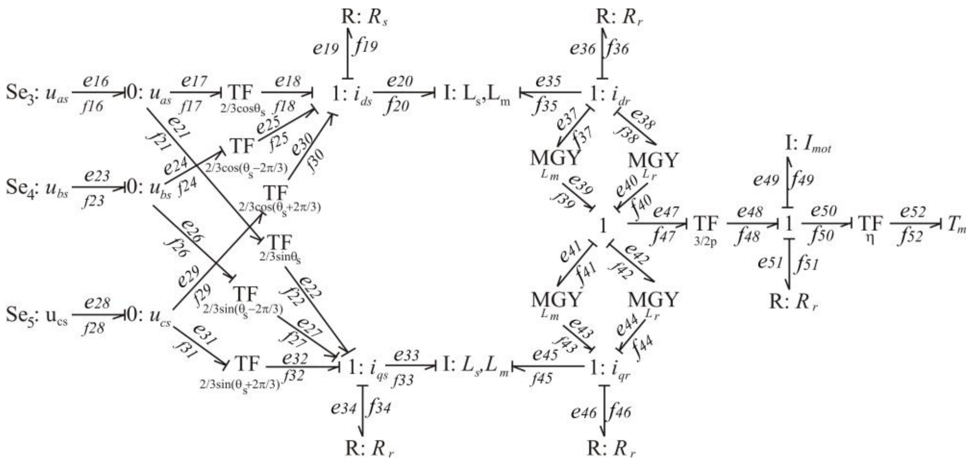


Fig. 4 Bond graph model of d-q asynchronous motor

Characteristics of a *1*-junction are given in following equations:

$$1:\begin{cases} e_{20}=e_{18}+e_{19}+e_{25}+e_{30} \\ \underline{f_{20}=f_{18}=f_{19}=f_{25}=f_{30}} \\ e_{33}=e_{22}+e_{27}+e_{32}+e_{34} \\ \underline{f_{33}=f_{22}=f_{27}=f_{32}=f_{34}} \\ e_{35}=e_{36}+e_{37}+e_{38} \\ \underline{f_{35}=f_{36}=f_{37}=f_{38}} \\ e_{47}=e_{39}+e_{40}-e_{41}-e_{42} \\ \underline{f_{47}=f_{39}=f_{40}=f_{41}=f_{42}} \\ e_{45}=e_{43}+e_{44}-e_{46} \\ \underline{f_{45}=f_{43}=f_{44}=f_{46}} \\ e_{49}=e_{48}-e_{50}-e_{51} \\ f_{49}=f_{48}-f_{50}-f_{51} \end{cases} \quad (5)$$

The corresponding bond graph equations for the *0*-junction are given in the expression:

$$0:\begin{cases} e_{16}=e_{17}=e_{21} \\ \underline{f_{16}=f_{17}+f_{21}} \\ e_{23}=e_{24}=e_{26} \\ \underline{f_{23}=f_{24}+f_{26}} \\ e_{28}=e_{29}=e_{31} \\ f_{28}=f_{29}+f_{31} \end{cases} \quad (6)$$

The bond graphic linear transformer *TF* is descriptive by equations (7) and (8):

$$TF:\begin{cases} e_{18}=\frac{2}{3}\cos\theta_s e_{17};\ f_{18}=\frac{2}{3}\cos\theta_s f_{17} \\ e_{25}=\frac{2}{3}\cos\left(\theta_s-\frac{2\pi}{3}\right)e_{24}; \\ f_{25}=\frac{2}{3}\cos\left(\theta_s-\frac{2\pi}{3}\right)f_{24} \\ e_{30}=\frac{2}{3}\cos\left(\theta_s+\frac{2\pi}{3}\right)e_{29}; \\ f_{30}=\frac{2}{3}\cos\left(\theta_s+\frac{2\pi}{3}\right)f_{29} \end{cases} \quad (7)$$

$$TF:\begin{cases} e_{22} = \frac{2}{3}\sin\theta_s e_{21};\ f_{22} = \frac{2}{3}\sin\theta_s f_{21} \\ e_{27} = \frac{2}{3}\sin\left(\theta_s - \frac{2\pi}{3}\right)e_{26}; \\ f_{27} = \frac{2}{3}\sin\left(\theta_s - \frac{2\pi}{3}\right)f_{26} \\ e_{32} = \frac{2}{3}\cos\left(\theta_s + \frac{2\pi}{3}\right)e_{31}; \\ f_{32} = \frac{2}{3}\cos\left(\theta_s + \frac{2\pi}{3}\right)f_{31} \\ e_{48} = \frac{3p}{2}e_{47};\ f_{48} = \frac{3pf_{47}}{2} \\ e_{52} = e_{50}\eta;\ f_{52} = f_{50}\eta \end{cases} \tag{8}$$

Modulated gyrator element is with the following characteristics:

$$MGY:\begin{cases} e_{39} = e_{37}L_m;\ f_{39} = f_{37}L_m \\ e_{40} = e_{38}L_r;\ f_{40} = f_{38}L_r \\ e_{43} = e_{41}L_m;\ f_{43} = f_{41}L_m \\ e_{44} = e_{42}L_r;\ f_{44} = f_{42}L_r \end{cases} \tag{9}$$

2.4. Bond graph model of submersible pump

Herein, we provide a short description of a submersible pump [10]. The characteristics of bond graphic *1*-junction, linear transformer element *TF* and modulated gyrator element *MGY*, are expressed by the following equations:

$$1:\begin{cases} e_{55} = e_{54} + e_{59} - e_{60} - e_{56} - e_{57} - e_{58} \\ \underline{f_{55} = f_{54} = f_{59} = f_{60} = f_{56} = f_{57} = f_{58}} \\ -e_{64} = e_{62} - e_{63} \\ \underline{f_{62} = f_{63} = f_{64}} \\ e_{67} = e_{65} - e_{66} \\ f_{67} = f_{65} = f_{66} \end{cases} \tag{10}$$

$$MGY:\begin{cases} e_{54} = ne_{53} \\ f_{54} = ne_{53} \end{cases} \tag{11}$$

$$TF:\begin{cases} e_{62} = Ae_{57} \\ f_{62} = Ae_{57} \end{cases} \tag{12}$$

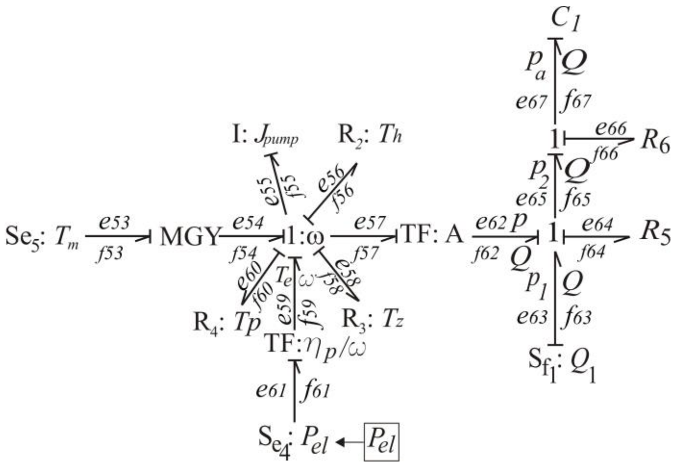


Fig. 5 Bond graph model of submersible pump

In the next step, we realized the individual bond graph models by using Dymola software package. As we already mentioned, this software tool has many advantages in comparison to the other commercial software. After simulation process, we concluded that obtained model mimics the behavior of the real plant adequately.

3. CONTROLLER DESIGN

It was shown that control sequence is very applicable for the control of some complex systems. Switching tables make clearer input combinations that lead to changes in the outputs, and therefore it is possible to write the corresponding Boolean equation. For the above described system, concretely for the tank level water, the switching table is given in Table 1. Switch blocks are used for turning on pump P3 in the case of damaged P1 or P2.

Table 1 The switching table of the three pumps

Water level in tank	Pumps		
	P1	P2	P3
H_1= 3450 mm	ON	ON	OFF
H_2= 3650 mm	OFF	ON	OFF
H_3= 4700 mm	ON	ON	OFF
H_4= 4900 mm	ON	OFF	ON

For automatic operation of such multivariable control problems, a model-based controller should be built. So, in this paper we will try to replace this table with fuzzy-PI controller. The schematic representation of the design procedure is presented in Fig. 6. It can be seen that before the design of the proposed controller we need to export the bond graph model from Dymola to Simulink environment.

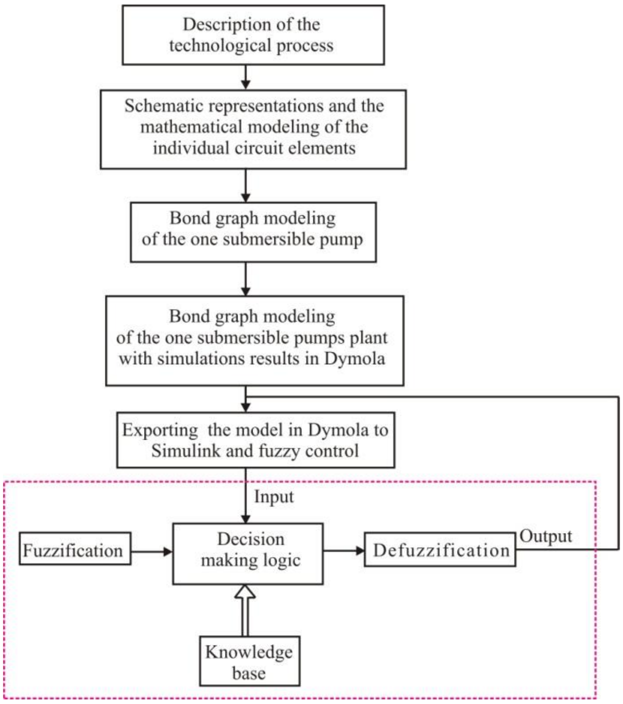


Fig. 6 Block diagram for the bond graph modeling and fuzzy logic controller

The Mamdani Fuzzy PI controller consists of two inputs; first input *inp1* represents error and the second one *inp2* is change of error (first derivative of error). Input values of fuzzy controller are positions of water level in the tank. The first input set of positions deviations consists of 4 member functions: L_1, L_2, L_3 and L_4. The second input shows the deviation from the permissible water level: negative N, zero Z and positive P. An output from fuzzy controller is voltage and it is defined as a linguistic variable as follows: *0*- turn on and *1*- turn off. The member functions for input and output are given in the Figs. 7, 8 and 9, respectively.

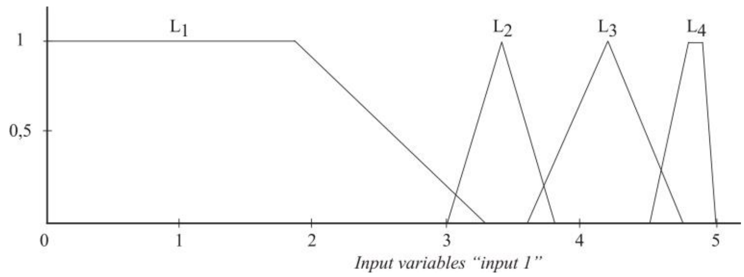


Fig. 7 Input position of the water level for both aggregates

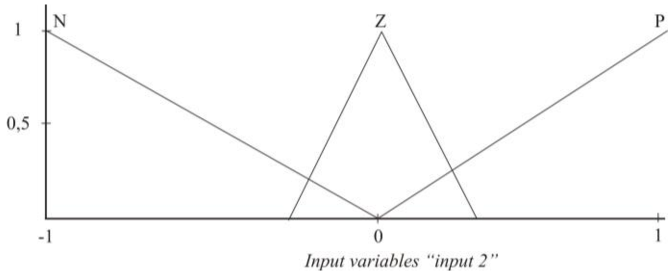


Fig. 8 Zero and positive value of the water level

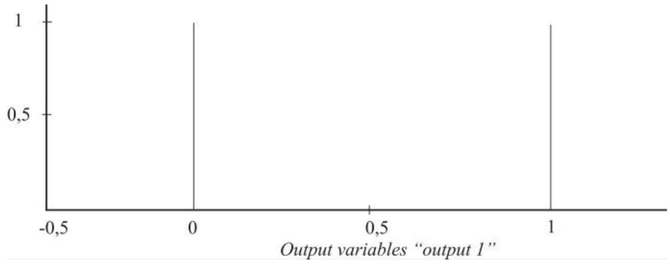


Fig. 9 Switch output

The fuzzy rules for the first pump aggregate are given as:

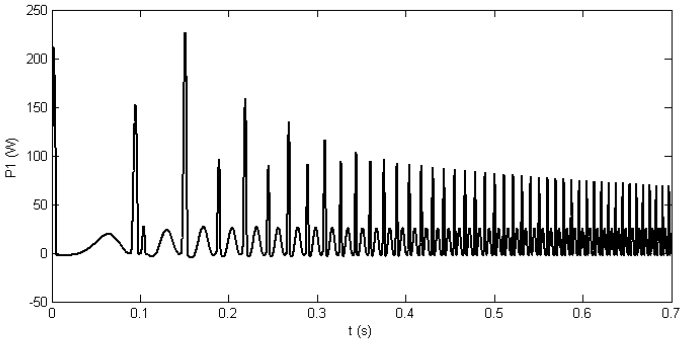
If (inp1 is L1) and (inp2 is N) then (out1 is 1),
If (inp1 is L1) and (inp2 is Z) then (out1 is 1),
If (inp1 is L1) and (inp2 is P) then (out1 is 1),
If (inp1 is L2) and (inp2 is N) then (out1 is 0),
If (inp1 is L2) and (inp2 is Z) then (out1 is 0),
If (inp1 is L2) and (inp2 is P) then (out1 is 0),
If (inp1 is L3) and (inp2 is N) then (out1 is 1),
If (inp1 is L3) and (inp2 is Z) then (out1 is 1),
If (inp1 is L3) and (inp2 is P) then (out1 is 1),
If (inp1 is L4) and (inp2 is N) then (out1 is 1),
If (inp1 is L4) and (inp2 is Z) then (out1 is 1),
If (inp1 is L4) and (inp2 is P) then (out1 is 1).

The fuzzy rules for the second pump aggregate are given as:

If (inp1 is L1) and (inp2 is N) then (out1 is 1),
If (inp1 is L1) and (inp2 is Z) then (out1 is 1),
If (inp1 is L1) and (inp2 is P) then (out1 is 1),
If (inp1 is L2) and (inp2 is N) then (out1 is 1),
If (inp1 is L2) and (inp2 is Z) then (out1 is 1),
If (inp1 is L2) and (inp2 is P) then (out1 is 1),
If (inp1 is L3) and (inp2 is N) then (out1 is 1),
If (inp1 is L3) and (inp2 is Z) then (out1 is 1),
If (inp1 is L3) and (inp2 is P) then (out1 is 1),
If (inp1 is L4) and (inp2 is N) then (out1 is 0),
If (inp1 is L4) and (inp2 is Z) then (out1 is 0),
If (inp1 is L4) and (inp2 is P) then (out1 is 0).

4. SIMULATION RESULTS

The simulation results, presenting the outputs of the three pumps, without and with fuzzy-PI control are shown in Figs. 10 and 11, respectively. Comparing the results of the required input power for pumps aggregate with and without fuzzy-PI controller we can conclude that the required input by the inverter is gradually reduced after 0.2s. This test excludes the conditions and it demonstrates the effectiveness of the proposed approach for the decoupling control between the power of the pumps and water level.



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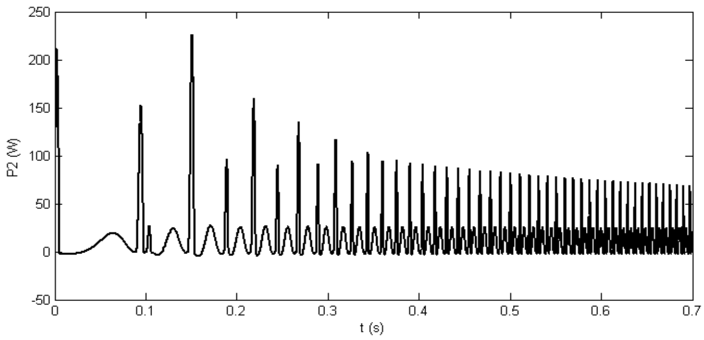

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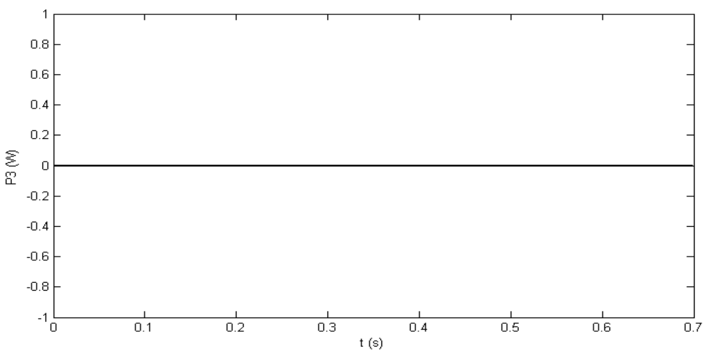
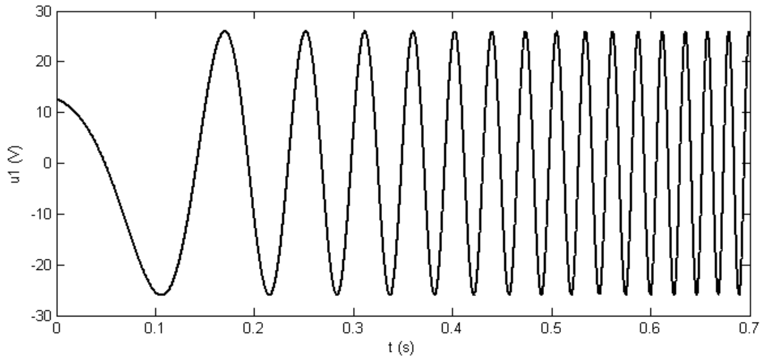


c)

Fig. 10 The simulation results without fuzzy-PI regulation.



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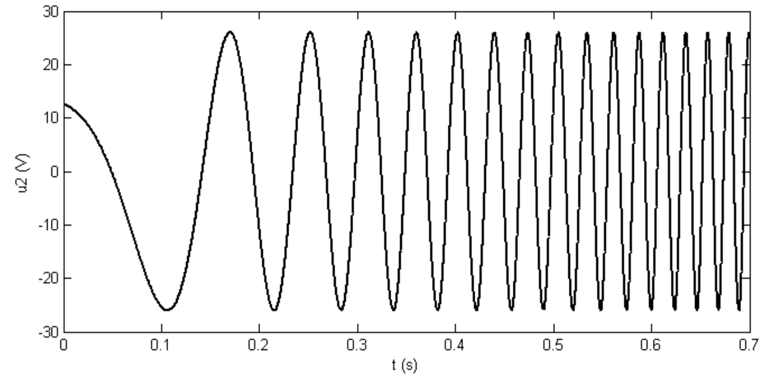

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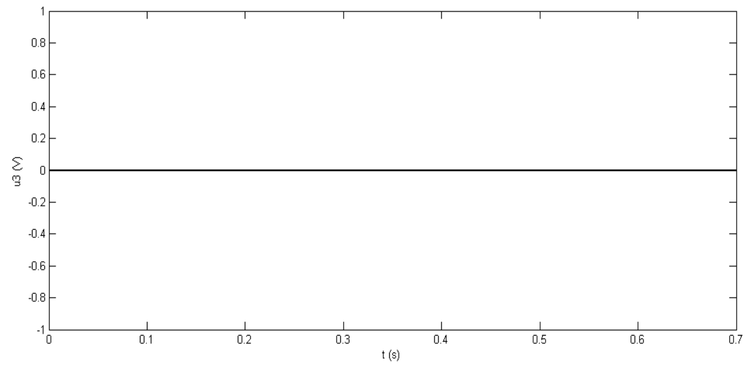

c)

Fig. 11 The simulation results with fuzzy-PI regulation.

4. Conclusion

In this paper we implemented complex analysis and developed the plant model using the concept of a hybrid bond graph modelling. Obtained model is used for controller design, based on a combination of fuzzy theory and PI control, to overcome the need for classical switching table. After simulation results, it can be concluded that the proposed solution has improved performance in the sense of reduced power required for the pump station.

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