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Application of the Hybrid Bond Graphs and Orthogonal Rational Filters in Sag Voltage Effect Reduction

D. M. Trajkovic[1], V. D. Nikolic[1], D. S. Antic[2], S. S. Nikolic[2], S. Lj. Peric[2]
[1]University of Niš, Faculty of Mechanical Engineering,
Aleksandra Medvedeva 14, Niš, Serbia
[2]University of Niš, Faculty of Electronic Engineering,
Aleksandra Medvedeva 14, Niš, Serbia
stanisa.peric@elfak.ni.ac.rs

***Abstract*—This paper presents the application of hybrid bond graphs in modelling and simulation of submersible pump in the water factory NAISSUS in Niš. The obtained model is used as a plant model for control problem reflected by voltage sag effect, caused by starting large motors. In order to improve the performances of the pump, we introduce the new control method based on the orthogonal filters of Müntz-Legendre type. The genetic algorithm is used to obtain the parameters needed for filter realization. Finally, the simulation results confirmed good system performances of the given control and it is shown that voltage sag effect is significantly reduced.**

***Index Terms*—Bond graphs, genetic algorithms, filters, modelling.**

I. INTRODUCTION

The introduction of advanced technology into wide range of engineering systems necessitates the use of computer based tools to assist in the design, control, monitoring and modelling of these systems. The success of all these tools is critically dependent on the ability to develop accurate models for simulating, and verifying system behaviour.

Bond graphs represent an efficient tool for system modelling [1], [2]. The concept of bond graphs was first developed by Paynter [3]. The main idea was further developed by Karnopp and Rosenberg [4], [5], and now this method can be used in practice [6]–[9], which is in particular interest of this paper. The fundamental advantage of bond graphs is in central physics concept-energy (bond graph consists of components which exchange energy using connections; these connectors represent bonds). The effort (voltage, force, pressure, etc.) and the flow (current, velocity, volume, flow rate, etc.) are generalization of the similar phenomena in physics. The factors which characterize the effort and flow have different interpretations in different physical domains (mechanical, electrical, hydraulic, thermal, chemical systems). Bond graph models can be used for simulation of some complex systems in order to obtain better performances related to defined criteria. The main problem herein is reflected by sag voltage effect, caused by starting large motors, so the authors of this paper come to the idea to reduce it using some advanced control techniques.

Genetic algorithms [10] are optimization technique based on simulating the phenomena that takes place in the evolution of species and adapting it to an optimization problem. These techniques apply the laws of natural selection onto the population to achieve individuals that are better adjusted to their environment. The population is nothing more than a set of points in the search space. Each individual of the population represents a point in that space by means of his chromosome. The individual's degree of adaptation is given by the objective function. Applying genetic operators to an initial population simulate the evolution mechanism of individuals. "Survival of the fittest" philosophy is used to speed up the evaluation process.

During the past several years, we have developed some new concepts of orthogonality using mathematical transformations in complex domain [11]–[14]. From the necessity for mathematical tools for analysis of complex dynamical systems, orthogonal filters were derived. They can be used for the analysis of real technical systems: modelling and analysis of DC servo drive [11], modelling of system for electrical energy distribution [13], dynamic stability analysis of nonlinear structures [15], [16], etc.

In this paper we present the modelling of submersible pumps in water factory Naissus in Niš using hybrid bond graphs. Installation of frequency converter reduces the peak and "polishes" voltage, and in that way the possibility of an induction motor burning out is also reduced. On the other hand, the voltage sag is still oversized, so we introduce the Müntz-Legendre type orthogonal filter to reduce it additionally, thus saving electricity. Genetic algorithm is used to obtain the necessary parameters of this filter.

II. PLANT DESCRIPTIONS

The pump station, shown in Fig. 1, a, is used to distribute

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the untreated water to the infiltration units. It consists of three identical submersible pumps 70 UPP 30, produced by Jastrebac in Niš, and independent suction tubes. The pump and motor parts are connected into a compact unit, while the impeller with rotor is mounted on the common shaft. The UPP submersible pumps are designed with fixed impeller blades adjusted to desired angle according to the technical characteristics. The parameters of submersible pump are: flow Q=312-315 m^3/s, head of the pump H_p=5.5-4.2 m, efficiency coefficient η=0.845-0.818, *NPSH*=7.9-7.4 m.

The three-phase motors have protection class IP 68 and insulation class F. The rotor assembly is guided by antifriction bearings lubricated by grease. The shaft sealing is performed by two mechanical seals. The motor is started up in star position, and the stator windings are equipped with thermal protection. Three-phase asynchronous motor is connected with frequency controller, as it can be seen in Fig. 1, b, and it has the degree of protection IP54 (T-OFF/ON=15 s.). Oil frequency controller work is based on information from the level sensor.


a) b)

Fig. 1. a – the pump station; b – Regulation of the induction motor with frequency regulator.

The model of whole plant is described by models of its individual parts (rectifier, inter circuit, inverter, asynchronous motor and submersible pump). In the following sections, these components are modelled using bond graphs.

III. Modelling of PWM Voltage Inverter using Bond Graphs

High cost of electricity required frequent regulators in designing and reconstruction of the pump stations. The most common method to control the voltage output of electrical motor is to use a variant of pulse width modulation (PWM). By changing the frequency and voltage of electric power, it is possible to control motor speed and, simultaneously, nominal motor torque in the range of regulation. The speeds of the synchronous and asynchronous motors are controlled by the frequency of the applied voltage.

In order to regulate the asynchronous motor, it is necessary to have voltage or current source with variable amplitude and frequency. The frequency converter is used for the realization of a variable speed electrical drive with induction motor. The diode is an uncontrolled component and it conducts current if positively biased while blocking it if negatively biased. The rectifier flattens the pulsating voltage in the voltage inverter.

The filter has a dual role: it reduces the voltage harmonics on the inverter input that enters the rectifier and limits harmonic current i. The network inductance is used as inductance of the LC filter. A diode is used in series with U_{dc} to ensure that i_{dc} through the circuit cannot reverse. DC intermediate circuit (LC filter) voltage inverter is shown in Fig. 2.

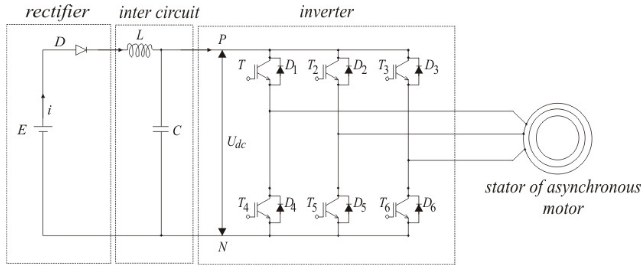

Fig. 2. PWM voltage inverter.

Mathematical model of DC intermediate circuit is written with the assumption that the current is continuous. LC filter can be described with the following differential equations:

$$\frac{di}{dt} = \frac{E - U_{dc}}{L} - \frac{1}{T}\int_0^T EdT, \tag{1}$$

$$U_{dc} = \frac{1}{C}\int idt, \tag{2}$$

where E is electromotive force, L is inductance, C is capacitance, U_{dc} is voltage of the inverter, T is time period.

Irreversible process is represented by dissipative element, R. The Se, L, C, I, and R elements exchange energy via ports. To connect more than two basic elements together, a junction structure is required. Junction typically allows an arbitrary number of components to be connected together. Energy can be represented as stored effort and stored flow. The effort source Se_1 enters electromotive force, as starting information in rectifier. Junction with the identical flow 1 presents input current through electrical circuits. They preserve continuity of power by adhering to generalized forms of Kirchhoff's current and voltage laws, which define 1-junction. Input energy is divided into inductor L, capacities C, and diode R_D. Corresponding bond graph is shown in Fig. 3.

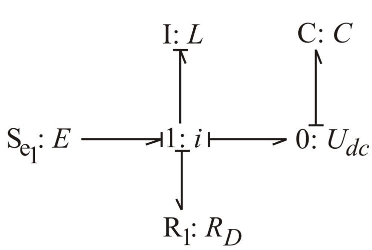

Fig. 3. Bond graph of a rectifier and inter circuit.

The inverter frequency is the last stage of the regulator, before induction motor connected in star and the point where it takes the final adaptation of the output voltage. The main components are controlled semi-conductors, placed in pairs into three branches. The thyristor is a controllable turn-on component which blocks current in both directions without a gate firing signal. If the thyristor is positively biased and a gate firing signal is present, it will conduct until the surrounding circuits force the current to reverse. An example of the last group of components is the transistor which may be turned on while blocked, if it is positively biased, using a continuous gate firing signal. If the signal is stopped, the transistor will block even though it is still positively biased.

An inverter converts the DC voltage into three phase power system. Each inverter half-bridge consist of two transistor-diode pairs which will be opened and closed alternatively, meaning whenever T_1 is open, T_4 is closed, and vice versa. Assuming that each transistor-diode pair behaves like an ideal switch, they may be modelled using 1-junctions while 0-junctions are used to model the switching of the terminal voltages between the DC-link voltages ($U_{dc}/2$) and ($-U_{dc}/2$) for switching power junction.

Switching block is part of the bond graph which contains the following structures element: 0, 1 and MTF. Causal analysis is applied to both state and diode switches (Fig. 4). The vertical branch is treated as a buck–boost inverter.

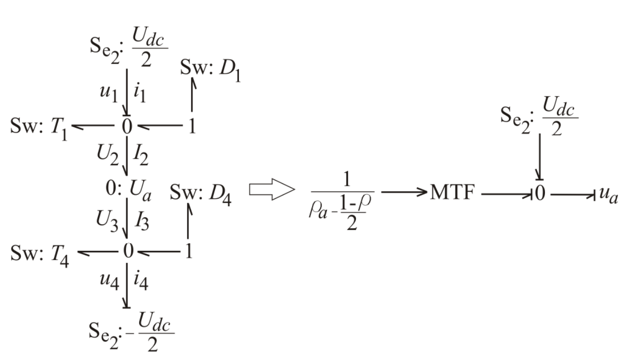

Fig. 4. Bond graph branch of inverter.

$$\text{If switch } T_1 \text{ is open}: \begin{cases} u_1 = 0, \\ i_2 = 0, \end{cases} \tag{3}$$

$$\text{If switch } T_1 \text{ is closed}: \begin{cases} u_1 = U_2, \\ i_2 = I_1, \end{cases} \tag{4}$$

$$U = \frac{1}{T}\sum \int_{i=1}^{N} u_i dt . \tag{5}$$

Mean values of output variables are:

$$U_1 = \frac{1}{T}\int_0^T u_1(t)dt = \frac{1}{T}\int_{\rho T}^T U_2 dt = \frac{U_2}{T}(T - \rho T), \tag{6}$$

$$I_2 = \frac{1}{T}\int_0^T i_2(t)dt = \frac{1}{T}\int_{\rho T}^T I_1 dt = \frac{I_1}{T}(T - \rho T), \tag{7}$$

$$U_1 = U_2(1-\rho), I_2 = I_1(1-\rho), \tag{8}$$

where ρ represents the inverter duty ratio. Symmetrical placement of Sw=OFF intervals at the edges of each half carrier cycle is intentionally planned for obtaining optimal waveform quality [5]. The inverter duty ratio can be rewritten as $\rho^*=M=(1+\rho)/2$, yielding

$$U_2 = \frac{2U_1}{1-\rho}. \tag{9}$$

The PWM inverter has a lower commutation count, but at the expense of a slightly poorer waveform quality, caused by the no centering of active states within each half carrier cycle. The output voltages are represented by the following expressions and modulation index:

$$U_a = Mcos(\omega t) + U_{off} - \frac{1-\rho}{2}, \tag{10}$$

$$U_b = Mcos\left(\omega t - \frac{2\pi}{3}\right) + U_{off} - \frac{1-\rho}{2}, \tag{11}$$

$$U_c = Mcos\left(\omega t + \frac{2\pi}{3}\right) + U_{off} - \frac{1-\rho}{2}, \tag{12}$$

where

$$U_{off} = -0.5\left(\max(U_a, U_b, U_c) + \min(U_a, U_b, U_c)\right) \tag{13}$$

is used for equalizing the lengths of null states placed at the start and end of a half carrier cycle, with 15% increase in linear modulation range. Ratio of modulated transformation is

$$\rho_a = M\cos\left(\omega t \pm j\frac{2\pi}{3}\right), j = 0,1,\dots. \tag{14}$$

Having in mind the previous analysis, the bond graph model of whole inverter unit can be modelled as it is shown in Fig. 5.

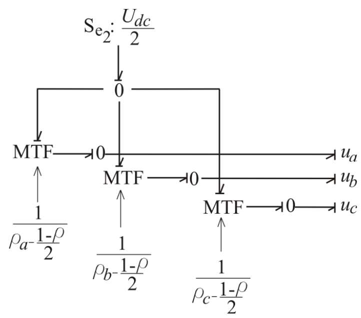

Fig. 5. Bond graph model of inverter.

IV. Bond Graph Model of Submersible Pump

The UPP submersible pumps are used for pumping clean and unpolluted water (without coarse impurities). The pumps are intended for irrigation and dewatering, as cooling pumps in power station, in water supply plants, in emergency cases (floods), for production of artificial rapids (waterfalls) in parks etc.

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. The asynchronous motor in d-q model is presented by equations:

$$U_{ds} = \frac{2}{3}\begin{pmatrix} U_{as}\cos\theta_s + U_{bs}\cos\left(\theta_s - \frac{2\pi}{3}\right) + \\ +U_{cs}\cos\left(\theta_s + \frac{2\pi}{3}\right) \end{pmatrix}, \tag{15}$$

$$U_{qs} = \frac{2}{3}\begin{pmatrix} U_{as}\cos\theta_s + U_{bs}\sin\left(\theta_s - \frac{2\pi}{3}\right) + \\ +U_{cs}\sin\left(\theta_s + \frac{2\pi}{3}\right) \end{pmatrix}, \quad (16)$$

$$\theta_s = \int_0^t \omega_s(t)\,dt + \theta_s(0); \theta_s(0) \to 0. \quad (17)$$

Indexes d and q represent the variables of stator, U_{as}, U_{bs}, U_{cs} are phase stator voltages, U_{ds}, U_{qs} are the two-axis components of the stator voltage vector. The electromagnetic torque T_{em} and mechanical torque T_m are given by

$$T_{em} = \frac{pL_m}{3}\left(i_{dr}i_{qs} - i_{qr}i_{ds}\right),\; T_{em}\eta = T_m, \quad (18)$$

where p – number of poles, L_m – stator inductance, η – coefficient of the motor efficiency. The power of the motor should be sufficient to accomplish the change of momentum T_z, and to compensate for any losses in energy transfer from the motor to fluid power. Usually, it is assumed that motor torque is balanced by hydraulic pump torque. If the start up of pump causes the transient regime, these two variables must be taken separately.

In order to obtain the mathematical model of a submersible pump, we must first define some of the necessary individual parameters. The input torque of the pump is the ratio of pump power and the angular velocity of fluid

$$T_e = \frac{P_m}{\omega} = \frac{60P_m}{2\pi n}, \quad (19)$$

where P_m represents the mechanical power of the pump, n - revolutions per minute. Moment of inertia-resistance, when starting the pump, is determined by

$$T_p = 0.0043\left(\frac{2\pi P_m}{60\omega}\right)^{1.48}. \quad (20)$$

Increase in required moment of energy due to the efforts is given by

$$T_h = \frac{\rho_w g f\left(QH_p\right)}{\omega}\eta_p, \quad (21)$$

where ρ_w - fluid density, g -gravitational constant, Q - water flow through the pump and H_p represents the head of the pump and it is defined by Q-H characteristics as

$$H_p = H_0 + AQ^2 + BQ, \quad (22)$$

where coefficient H_0=1.55 m, parameters A=-4.1989x10^{-6} and B=0.010016.

Change of angular momentum in the z-direction is

$$T_z = \rho_w Q\left(R_2^2\omega - R_1^2\omega\right), \quad (23)$$

where R_1 is circuit radius and R_2 is radius of the circuit with blades. To describe a mathematical model we use momentum equation and extended Bernoulli's equation:

$$mR_g^2\frac{d\omega}{dt} = J\frac{d\omega}{dt} = T_e - T_p - T_h - T_z, \quad (24)$$

$$\eta_p = \frac{P_m}{P_{el}} = \eta_h\eta_m\eta_v, \quad (25)$$

where R_g^2 - centrifugal moment of inertia, m - mass of rotating parts of the motor, J - moment of inertia of the rotor blades, ω - angular velocity of the fluid, η_p - overall efficiency of the pump, η_m - mechanical efficiency, η_v - volumetric efficiency, η_h - hydraulic efficiency, P_{el} - electrical power of the pump.

Inertia ratio is the relation of change efforts and acceleration of the flow. In this case it can be interpreted as the ratio of inlet pressure tube and the acceleration achieved by the mass of fluid pressure in the pipes.

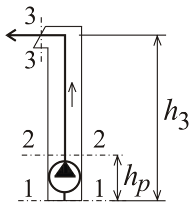

Fig. 6. Cross section of submersible pump.

If we equate the force generated by the inlet pressure to the water and the force that resists the fluid acceleration (inertia), we obtain

$$p_1 = \frac{4\rho_w l}{d_1^2\pi}\frac{dQ}{dt}, \quad (26)$$

where d_1 - radius of the pipe at the cross section 1-1 and l - length of pipe. Based on the Bernoulli's equation in cross sections 1-1 and 2-2 (Fig. 6)

$$p_1 - p_2 = \frac{g}{2}\rho_p h_p - \frac{\rho_w v^2}{2g}, \quad (27)$$

where h_p - height of pump and ρ_p - density of iron, v - velocity of fluid. For cross sections 2-2 and 3-3 extended Bernoulli's equation, which includes an energy losing due to friction, is represented in the form

$$\frac{p_2}{\rho_w} + \frac{v_2^2}{2} + gh_p = \frac{p_a}{\rho_w} + \frac{v_3^2}{2} + gh_3 + \xi_{lok}\frac{v^2}{2g} + \lambda\frac{l}{d}\frac{v^2}{2g}, \quad (28)$$

where ξ_{lok} – local resistance, p_a – atmospheric pressure. Dimensionless coefficient of friction, turbulent flow is

$$\lambda = 0.115\left(\frac{\delta}{d} + \frac{60\upsilon}{vd}\right)^{0.25}, \quad (29)$$

where: δ – roughness of the pipe, d – hydraulic diameter, υ – kinematic viscosity of water.

V. ORTHOGONAL FILTERS DESCRIPTION

The theoretical results are illustrated and validated with the real example in water industry. Complete mathematical background for designing orthogonal filters based on these polynomials can be found in [13]. In this section we give a short mathematical tool for designing Müntz-Legendre filter. In this paper we use shifted Legendre polynomials, orthogonal over interval (0, 1) with weight $w(t)$=1, explicitly defined as [13], [17]

$$P_n(x) = \frac{n!}{(2n)!}\sum_{j=0}^{n}(-1)^{n-j}\binom{n}{j}\frac{(n+j)!}{j!}x^j, \qquad (30)$$

with the following inner product

$$\int_0^1 P_m(x)P_n(x)dx = \begin{cases} 0, & m \neq n, \\ N_n, & m = n. \end{cases} \qquad (31)$$

Using these defining relations, we can design Müntz-Legendre type orthogonal filter as it is presented in [13]. This filter can be used for determining a model of real dynamical system.

It is a known fact that in practice there is often a need for some real, obtained by measuring, signal $y(t)$ to be represented in the form of the following series [11], [15]

$$y(t) \approx \sum_{i=0}^{n} c_i \lambda_i(t), \qquad (32)$$

where c_i -unknown parameters, $\lambda_i(t)$ can represent inverse Laplace transforms of the Legendre orthogonal rational functions $L_i(s)$ which are the outputs of the filter [13]. Function approximation is achieved with mean squared error (MSE) as optimization criterion

$$J = \frac{1}{T}\int_0^T \left(y(t) - y_M(t)\right)^2 dt. \qquad (33)$$

Adjustment of parameters c_i (i=0, 1, …, n) have a purpose to minimize J. For that adjustment, genetic algorithms can be used as optimization method presented in [15]. The complete block diagram, illustrating the process of modelling, is given in [11], [15].

VI. CASE STUDY

The complete bond graph of process with filter of Müntz-Legendre type is shown in Fig. 7. Practical verification of the proposed control algorithm and bond graph models is performed by digital simulation using Matlab and Simulink toolboxes. First we simulate the behaviour of bond graph model and we monitor the current and voltage values. These values have been completely matched with real one, obtained by measuring in the water factory Naissus. As we can see from Fig. 8, the obtained results without using orthogonal filter (OF) are marked with red line on both diagrams. The value of voltage is about 207 V. The main control objective is to provide lesser difference between rotor voltage and network voltage (230 V), and in such a way to reduce sag voltage effect and the current peak.

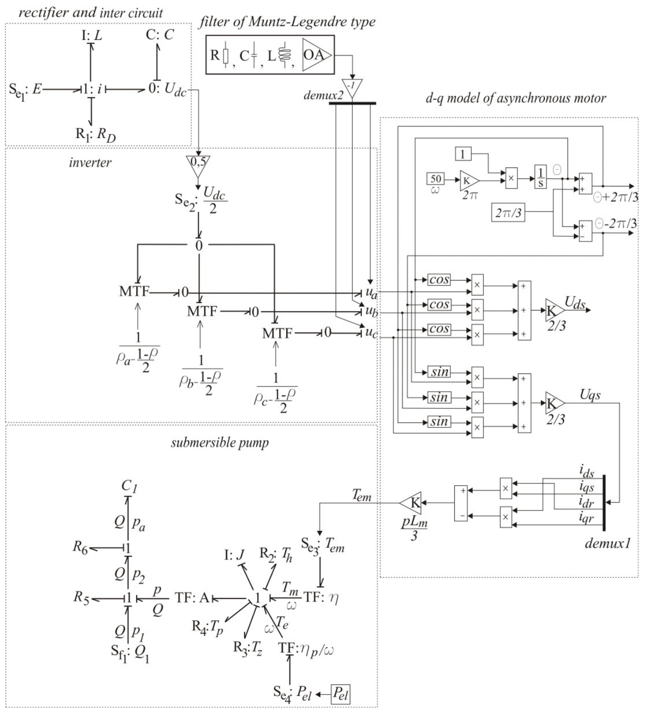

Fig. 7. Complete bond graph of the process with filter of Müntz-Legendre type.

In order to obtain the transfer function of orthogonal filter, we should make a MSE as small as possible for a chosen step input. So, relation (33) was used as the fitness function for the genetic algorithm. In our case study, model of orthogonal filter with two cascades is considered. It has five adjustable parameters s_1, s_2, c_0, c_1, and c_2. We assume that the system itself is unknown. The goal is to determine its model and transfer function. The only known data about the system is measured output (voltage on the rotor) for a given step input signal.

Genetic algorithm used in simulation has the following parameters: initial population of 250, number of generations 500, stochastic uniform selection, and reproduction with 12 elite individuals, Gaussian mutation with shrinking and scattered crossover. Chromosome has a structure which consists of five parameters above mentioned.

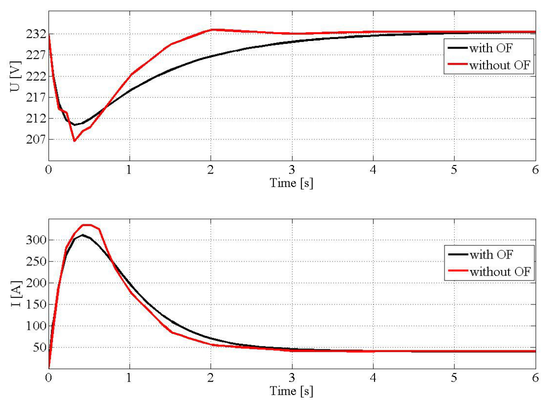

Fig. 8. Voltage and current values obtained by simulation.

Obtained experimental results for the above mentioned parameters are s_1=7.2621, s_2=0.8579, c_0=0.000421, c_1=-3.7464, and c_2=-0.4537. In such a way, we obtain the following transfer function of filter as $W(s)=(-4.2s+0.08)/(s^2+8.12s+6.23)$. The realized filter is inserted in the whole system as it presented in Fig. 7. The obtained results using OF are presented by black line in Fig. 8. As it can be seen, the proposed control algorithm slightly improves the previously simulation results. It is obvious that the use of orthogonal filters can improve performances of induction motor by reducing voltage sag effect.

VII. Conclusions

In this paper we propose the orthogonal filter for voltage sag effect reduction, caused by starting large motors used in the water company Naissus in Niš, Serbia. First, we developed the plant model using the concept of hybrid bond graph modelling, and then this model is used for control method design. The genetic algorithm is used to determine the parameters of proposed filter of Müntz-Legendre type. Finally, the performed simulations confirm the effectiveness of orthogonal filter in achieving a smaller difference between rotor voltage and network voltage.

In future work, we will consider the use of these filters in situations where the pumps work is based on predetermined algorithm. Therein, the voltage sag effect has to be reduced in a fast and high-quality way. Also, we will consider the structure that would include almost orthogonal or quasi-orthogonal filters where the gradient method can be used for determination of parameter filters.

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