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Multi-objective differential evolution algorithm-based pricing model in power market for demand-side response

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Abstract. In terms of the pricing of electric power, the impacts of energy utilization efficiency and energy consumption in power production are factored in. First and foremost, a multi-objective optimization model is established for maximum economic benefit and minimum environmental pollution. The model adopts the co-integration analysis of electricity demand and electricity price to characterize the consumer behavior under certain power pricing strategy, and adopts the cost-profit model to characterize the producer behavior. The consumer and producer behaviors are modeled as the constraint. Secondly, given that the traditional multi-objective optimization algorithm is not highly precise in optimizing, in this paper, a multi-objective differential evolution algorithm based on population congestion is designed to optimize the parameters of quantization varying filter. Eventually, the proposed algorithm is demonstrated feasible through the simulation experiment in the standard calculating examples and the actual calculating examples.

Key words. Multi-objective optimization, Differential evolution, Pricing in power market, Congestion.

1. Introduction

In recent years, the shortage of seasonal energy in China has made energy issue a hot topic. Rational energy pricing has an important impact on rational utilization of energy, economic development and environmental protection. On the one hand, excessive energy pricing will curb enterprise capacity and hinder economic development. On the other hand, low energy prices will lead to resource abuse and environmental pollution, reduce the production enthusiasm of energy producers and

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exert negative impact on the long-run development of economic society, which cannot be overlooked. In the meantime, the linkage of global energy markets caused by economic globalization has increased the complexity of energy pricing. Therefore, rational energy pricing has important influence on the long-term stable development of China's economy and society.

Data analysis of several developing countries in Asia indicates that there is a causal relationship between energy pricing and economic growth and energy consumption. Literature [3] studied energy pricing from the perspective of environmental protection; Literature [4-5] studied the impact of energy pricing on energy efficiency; Literature E6 studies the impact of energy pricing on energy consumption; Literature [7] studies the empirical relationship between energy price change and economic growth based on data analysis from 1995 to 2005; Literature [8] studied the influence of oil price on all economic variables in China.

The above researches focus on a certain aspect of the impact of energy pricing on social environment, whereas factor out the complex impact of energy pricing strategy on all aspects of socio-economic environment. Thus it is impossible to give a rational energy pricing guidance for all aspects of society. Literature [9] proposed a framework model of power management in developing countries; Literature [10] qualitatively analyzed China's electricity pricing reform and further reform goals since 1978, pointing out that the government-led pricing mechanism should reflect the change of market supply and demand timely and encourage the competition and technical innovation when the price of electricity has not been released from the market; In literature [11] the multi-objective optimization model was established, and the optimal energy pricing strategy of Pareto was given in an assumed autarkical urban system, using CO2 emissions and consumer spending to describe the environmental impact and economic impact of energy pricing. Yet in this literature, the model adopts a lot of simplifying assumptions, such as a closed urban system, and a single energy supplier that supplies all the energy in the city. It is difficult to fully consider the complex impact of energy pricing in real social context.

On the foregoing basis of the literature analysis, this paper takes power resource as the research object and considers the influence of power pricing strategy on energy utilization efficiency and energy consumption in power generation. The multi-objective optimization model is established, and the annual optimal pricing strategies of the year 2008 $\sim$ 2010 are given. The current situation of China's electricity market is compared with the suggestions proposed by relevant research institutions for the future pricing of electric power. Eventually, the model proposed in this paper is demonstrated correct and rational.

2. Multi-objective optimization model for power pricing

2.1. Model of variable relation for power pricing

The rational pricing strategy should aim at the comprehensive effect of social environment. In recent years, China's electricity price reform has been committed to promoting economic and social development while meeting environmental protection requirements. Therefore, optimal power pricing strategy can be modeled as multi-objective optimization problem. Energy pricing is a way to give consumers and producers the environmental and economic responsibility of producing and using energy, by charging a fee. Rational energy pricing should conform to the development rules of market economy, guide consumers to consume reasonably, stimulate production and encourage the producer to carry out technological innovation. Therefore, the social environmental effect of electric pricing can be reflected by the influence of electricity pricing on consumers and producers. Establish a consumer behavior model for the former and establish a producer behavior model for the latter. Combining the results of two sub-models, this paper evaluates the influence of electricity pricing on economic and social environment, as shown in Fig. 1.

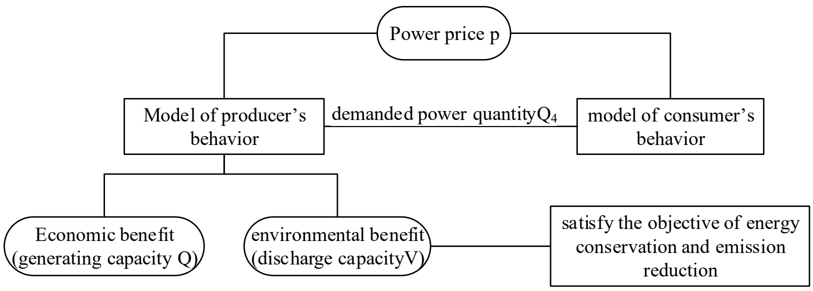

Fig. 1. Relation between power pricing and economic environment variables

Consumer behavior is influenced by price and consumption ability. As the result of Johansen co-integration test indicates, there is a co-integration relationship between demand for electricity consumption, GDP (reflecting consumption capacity) and price of electricity. In other words, changes in the price of electricity and GDP will affect the change of electricity demand, and there is a long-term stable equilibrium between the three variables. Therefore, based on the literature [12] and the relevant statistics of 1994-2010, this paper establishes a long-term equilibrium relationship between electricity demand, GDP and the sales price of electricity, which is denoted as:

$$I_{Nqt} = 0.7702 I_{Nqt-1} - 0.057 I_{Npt} + 0.1355 I_{Ngt} + 0.049\,. \tag{1}$$

Where I_{Nqt} refers to the growth rate of power demand of the year, I_{Nqt-1} refers to the growth rate of power demand one year before, I_{Npt} denotes the average growth rate of power demand of the year, and I_{Ngt} refers to the growth rate of GDP of the year.

2.2. Model of producer's behavior

Generally, the producer pursues the maximization of profit. Such profit is determined by consumption, price and production cost. Power resources are essential for life. It is a special commodity. Consumption and price have their own characteristics. On the one hand, under any pricing strategy, its consumption will not fall below a certain limit (to meet the electricity consumption of basic living); On the other hand, government intervention has a significant impact on energy prices, so energy prices will not rise indefinitely. In addition, technological innovation in the production process can improve production efficiency and reduce enterprise cost and increase profit. A rational energy pricing policy would encourage companies to increase profits through improving production processes.

In China, power resources are state-owned resources, and the power production process is largely guided by the government. However, for the producers of power resources, i.e. power generation enterprises at the end of the power supply system, including state-owned enterprises such as China Huaneng, and small-scale private power plants, their production behavior is still directly linked to the benefits. According to relevant reports, in the case of low profits and even long-term losses, some power generation enterprises use negative production to avoid losses, which is the important cause of the power supply gap.

In this regard, the impact of power pricing on producers can be translated into maximization of profit in meeting basic consumer demand and government price constraints. Profits from power generation companies include profits from the sale of electricity and from technological innovations. The profit growth of technological innovation can be described by establishing knowledge storage model. Through setting the profit maximization as the optimal target, and restricting the basic electricity demand and pricing scope, and the cost profit model can be established to describe the production behavior of power generation enterprises. Fig. 2 presents the relationship between the variables of producer's producing behaviors.

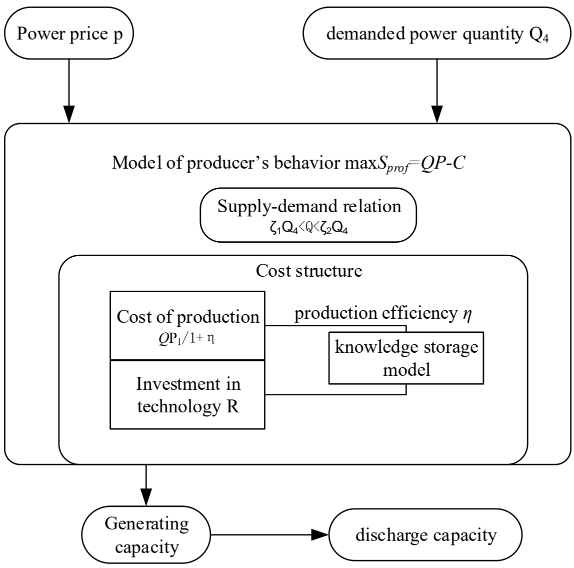

Fig. 2. Model of producer'

(1) Calculation of corporate profit: The cost of production is divided into two parts: production activity cost and technology investment, in which the technology

investment will reduce the production cost. Thus, the overall cost of production can be defined as:

$$C = \frac{QP_r}{1+\eta} + R\,. \tag{2}$$

Where Q refers to the output of energy, P_r is the unit production cost, R denotes the technology investment, η indicates the decline of investment led to by the technological investment.

The estimation of parameter η can be measured by the improvement of energy production efficiency. Coal is the most important energy source for power generation in China. According to the literature [4], the energy efficiency of primary energy consumption (coal consumption) per unit of GDP is used to measure energy efficiency. Thus, the following equation is attained:

$$\eta = (E_t - E_{t-1})/E_t\,. \tag{3}$$

Where E_t and E_{t-1} denote the energy efficiencies of the t and $t-1$ years. To quantitatively estimate energy efficiency, and knowledge storage model is built. The research and development funds over the years are adopted to indirectly calculate the technical knowledge stock, and the energy utilization efficiency is predicted by the knowledge stock. The research and development of technology is characterized by hysteresis, timeliness and spillover. As the technical funds of the first year are invest to the t' year, these funds shall be overall transformed into the technical knowledge stock. As time goes on, the techniques shall be progressively weeded out. That is to say, the corruption ratio δ exists. Additionally, a technological advance will lead to the emergence of other new technologies, which is measured by ratio of technical spillover, ϕ. In this regard, the knowledge storage model shall be established.

$$T_0 = \frac{R_{0-t'}}{r+\delta-\phi}\,. \tag{4}$$

$$T_t = T_{t-1}\,(1-\delta+\phi) + R_{t-t'}\,. \tag{5}$$

Where T_0 represents the amount of technical knowledge accumulated in the base year; R_t represents the amount of investment in technology research and development.

As acquired from literature [4, 16], when $t' = 3$ and $\phi = t'$, the relationship between knowledge accumulation T and energy utilization efficiency E is defined as:

$$\ln E_t = -0.379 \ln T_t + 4.705\,. \tag{6}$$

(2) Restrictions on the production of power enterprises. Due to the particularity of electric power, the power generation shall be directly regulated by the government, and the power production is subject to the following basic restrictions.

Production is basically consistent with social demand:

$$\varsigma_1 Q_d \le Q \le \varsigma_2 Q_d\,. \tag{7}$$

Where Q_d indicates the amount of electricity demanded by the society, ς_1 and ς_2 are the parameters uncovering the social acceptance levels.

The production shall satisfy the requirement of environmental protection:

$$V_p \leq V_s\,. \tag{8}$$

Where V_s refers to the discharge capacity restricted by the relevant national standards; V_p indicates the discharge capacity of enterprise, which is in direct proportion to the output of enterprise, the discharge capacity per unit production shall be reduced with the investment of technical investment. Thus, it is indicates that:

$$V_p = Q\gamma/(1+\eta)\,. \tag{9}$$

Where γ refers to the discharge capacity per unit production.

Limit of enterprise technology investment quota. The enterprise technology investment decision is restricted by the enterprise's own operating condition and capital strength, which is expressed as:

$$R \leq \varsigma_3 S_{prof}\,. \tag{10}$$

Where S_{prof} represents the annual profit of enterprise.

Producer behavior optimization model. According to the optimal target and the aforementioned constraint conditions, the optimization model of energy producer behavior can be attained as follows:

$$\max S_{prof} = QP - C\,. \tag{11}$$

$$s.t. \begin{cases} C = QP/(1+\eta) + R_t \\ \ln E_t = -0.379 \ln T_t + 4.705 \\ \eta = (E_t - E_{t-1})/E_t \\ T_t = T_{t-1} + R_{t-3} \\ V_p = Q\gamma/(1+\eta) \leq V_s \\ \varsigma_1 Q_d \leq Q \leq \varsigma_2 Q_d \\ R_t \leq \varsigma_3 S_{prof} \end{cases}$$

2.3. Multi-objective optimization model for optimal power pricing

The ultimate goal of electric pricing is the maximum social benefit, including economic and environmental benefits. Power generation directly supports the development of other economic sectors, so economic benefits can be reflected in the total amount of electricity generated. Environmental benefits are reflected in the sewage discharge in the production process of enterprises. Accordingly, the electricity pricing should consider both the economic benefit maximization and the environmental benefit maximization. The multi-objective optimization model established in this paper is defined as:

$$\begin{cases} \max Q \\ \max P \end{cases} \tag{12}$$

$$s.t.\begin{cases} P = arg\ maxQP - C \\ C = QP/(1+\eta) + R_t \\ \ln E_t = -0.379 \ln T_t + 4.705 \\ \eta = (E_t - E_{t-1})/E_t \\ T_t = T_{t-1} + r_t \\ I_{Nqt} = 0.7702 I_{Nqt-1} - 0.057 I_{Npt} + 0.1355 I_{Ngt} + 0.049 \\ \varsigma_1 Q_d \le Q \le \varsigma_2 Q_d \\ R_t \le \varsigma_3 S_{prof} \end{cases}$$

3. Multi-objective differential evolution algorithm (CNMDE)

3.1. Non-dominated sorting

The initial population is sorted based on the non-dominant relationship, and a fast sorting method given in the literature [6] is adopted in this paper.

Perform the following operations for each individual p in the population P:

①Assume $S_p = \phi$, and $n_p = 0$, p refers to each individual in primary population, S_p is adopted to store the individual dominated by p in the primary population, and n_p refers to the individual amount to dominate p;

②For each individual q in P, if $p \succ q$, $S_p = S_p \cup \{q\}$ shall be attained; otherwise $n_p = n_p + 1$ shall be attained.

③If $n_p = 0$, the $p_{rank} = 1$ in individual p, and p is added to the front line of existing Pareto, i.e. $F1 = F1 \cup \{p\}$;

Perform the following operation until $F_i = \phi$:

Assume $Q = \phi$, which is adopted to store F_i;

For each individual p in F_i, the following operation shall be performed: for each individual q in S_p, perform the operation: assume $n_q = n_q - 1$. If $n_q = 0$, i.e. q is merely dominated by p, thus setting the level of q as $q_{rank} = i + 1$, and assume $Q = Q \cup q$;

④$i = i + 1$;

Assume $i = i + 1$

Assume $F_i = Q$, $2 \sim n$ front lines, $F_2 \sim F_n$, shall be attained successively.

Two parameters are added in the sorting process of this algorithm: S_p and n_p. Through the operation of definition, such algorithm shall outperform the sorting method adopted in Literature [2].

3.2. Calculation of congestion

In the differential evolution of population, individuals with relatively high fitness and relatively small density distance from other individuals are retained. r sub-objectives are given, i.e. $f_1 f_2 \ldots f_r$, the congestion of individual i refers to $P[i]_{dis}$. $P[i].m$ indicates the functional value of individual i at the sub-objective m. Thus, the congestion shall be calculated as:

$$P[i]_{dis} = \sum_{k=1}^{r} \left(P[i+1].f_k - P[i-1].f_k \right). \tag{13}$$

Normally, if the evolution scale of algorithm is N, when calculating the worst congestion, r sub-objectives shall be sorted. By this time, the v shall be calculated as $O(rN \log N)$. Given that the complexity of calculating congestion is $O(rN)$, the overall complexity for calculation of the acquirable algorithm shall be denoted as $O(rN \log N)$.

3.3. Steps of multi-objective differential evolution algorithm

Set the population scale N. The maximum iteration algebra is set as *gen, the upper and lower limits of population are XVmax* and *XVmin. The population pop shall be initialized through adopting the method mentioned in chapter 2.1. Evaluate pop, non-domination sort pop and calculate the congestion of pop, assume* $i = 1$.

Select $N/2$ individuals from the pop to compose the *parent_pop through adopting binary bidding. Carry out the difference on the parent_pop (variation and interlace operation), generate pop1, and the scale of population is* $N/2$.

Incorporate the pop1 and pop to generate *intermediate_pop, carry out the non-domination sorting and calculate the congestion on the individuals of the generated pop, and select N individuals to compose the new pop following the sorting grade and congestion.*

$i = i + 1$, if $i \leq gen$, go back to Step 2; if $i > gen$, go on.

Output *pop, which is the optimal solution set of Pareto offered by the multi-objective differential evolution algorithm in terms of the problems to be solved.*

4. Experimental analysis

4.1. Standard calculating examples

The IEEE-30 system is adopted in the simulation calculation, as shown in Fig. 3. The total load is 2.834 MW, and there are 6 generator sets in the system. The node number is 1, 2, 5, 8, 11, 13. Partial units in the power system are based on the base charge, and the rated output is constant. In this paper, it is assumed that the unit 2 and unit 5 have the base charge, with the force output 0.58MW and 0.25MW, respectively. Unit 1 is adopted as the FM unit; No. 8 and No. 13 can be used as reserve capacity units. The relevant technical parameters are shown in table 1 and table 2. Assume that the unit's output cap is its rated output. When setting the limits of the output force, 50% $\sim$ 75%the maximum output of the unit shall be reckoned with. The confidence level of the climbing constraint of generator set is 1.0.

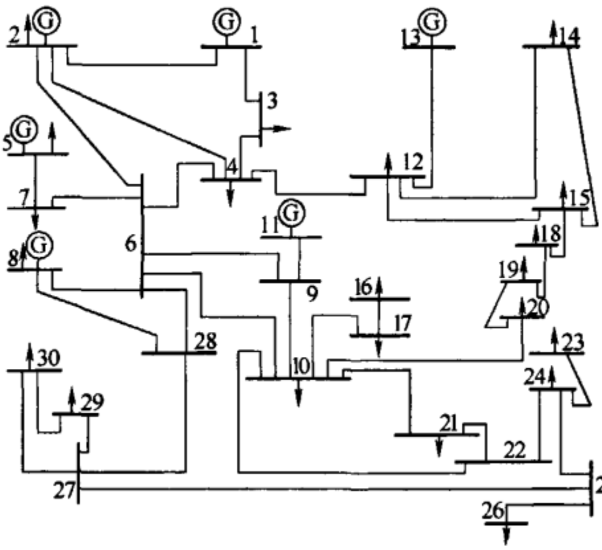

Fig. 3. IEEE-30 system

Table 1. Unit parameter of IEEE-30 node system

Unit	Upper limit of active power	Lower limit of active power	Climbing rate
1	1.39	1.30	0.030
2	0.58	0.32	0.020
5	0.25	0.20	0.010
8	0.35	0.30	0.005
11	0.18	0.10	0.010
13	0.17	0.10	0.007

Table 2. Data of reserve unit

Unit	P_i	P_{Gk}	θ_{ik}
8	0.88	0.13	0.2
13	0.97	0.08	0.1

Note: P_i is the possibility of providing reserve unit; P_{Gk} is the possible maximum reserve capacity of unit; θ_{ik} is the probability of P_{Gk}'s occurrence.

The interruptible loads of the system are node 7, 20 and 21, which pertain to the normal distribution and are mutually independent. The interruptible loads and the variance parameters are listed in Table 3. The anticipated accidents that may occur in the future of the system are listed in table 4. The price of the security support market participants is listed in table 5.

Table 3. Normal distribution parameters of the active power of the interruptible load nodes

Node number	MW	MW
7	0.228	1.40
20	0.022	1.60
21	0.175	1.80

Table 4. Expected accident set

No.	Type of fault	Set of accident probability
1	three-phase shortcircuit for 19-20 circuits	0.40
2	three-phase shortcircuit for 9-10 circuits	0.20
3	No.11 unit generator tripping	0.40

Table 5. Comparison of optimization methods under different confidence levels

reserve confidence level of rotation	Condifence level of line power	Cost of optimizing security
0.900	0.920	7.2546
0.950	0.940	7.9675
0.980	0.960	8.6859
0.990	0.980	9.5213
0.997	0.990	10.2667
1.000	1.000	10.7054

The selection of the confidence level of various constraint conditions is consistent with the operating requirements of the system. If the power grid dispatch center is not willing to assume any risks but to adopt the most conservative results, the confidence level can be given as 1.0.

4.2. Actual application

Given that the optimization model established in this paper contains the sub-optimization model, the method of literature [11] is first used to solve the sub-model. Fixed electricity price, through selecting the power generation as the decision-making variable, obtains the most profitable generating capacity under such pricing model. Given the continuity of the policy, electricity pricing will not fluctuate evidently in large areas. Thus, select a series of pricing strategies, repeat the solution of the sub-model, and obtain the generating capacity under different tariff patterns in the vicinity of current power pricing. Select the power pricing leading to maximum power generation as the optimal solution for the Pareto model, i.e. the optimal power pricing.

Take the most severe cases of power shortage in 2008 and 2009 and 2010. Use lingo software to solve the optimization model. The optimal pricing, production, social demand and net output value (economic benefit) of the electricity resources from 2008 to 2010 are attained, as listed in Table 6. The actual average selling prices for 2008 $\sim$ 2010 were 523.45, 534.29, 571.44 Yuan/MW ·h. The actual power consumptions are 34, 349.95 x 109, 35 874 x 109, 41 998.8 * 109 kW· h. As indicated, the optimal pricing is slightly higher than the actual pricing. The initiative of enterprises can be stimulated, and the production of electricity can be increased by raising the price of electricity. And accordingly, the power output can be increased. In addition to the most severe shortage of electricity in 2008, the growth rates of electricity prices in 2009 and 2010 (1.82% and 3.09%) were lower than the actual growth rates (2.07% and 6.95%). It can accordingly achieve a more steady growth in the price of electricity.

Table 6. Pricing strategy from 2008 to 2010

Year	$(\mathrm{MW{\cdot}h})^{-1}$ Power price/Yuan$\cdot(\mathrm{MW{\cdot}h})^{-1}$	10^9kW·h Demanded power quantity	10^9kW·h Production quantity of power
2008	569.72	34943.02	35641.88
2009	580.19	37113.23	37855.56
2010	598.14	39969.70	40769.10

Factoring in the actual situation of the electric power market, the phenomenon of "power shortage" occurred in many areas of the country during the summer electricity peak in 2008. The research indicates that low electricity pricing is an important reason for the phenomenon of "power shortage". As the electricity regulation report of the year 2010 indicates, since 2008, China's five major power generating groups (China Huaneng, Datang, Huadian, Guodian, China power investment corporation) have been losing more than 8.5 billion yuan in cumulative losses for three consecutive years, with the total losses reaching over 60 billion Yuan. As a result, some power generation enterprises inevitably generated as little electricity as possible or generated no power, and the power price shall go up imperatively, which is consistent with the results of this paper. Hence, the model is demonstrated to be rational.

5. Conclusion

In terms of the power pricing, the influences from multiple aspects, inclusive of pricing strategy for power, the energy utilization efficiency and energy consumption, are adequately reckoned with. A multi-objective optimization model with maximum economic benefit and minimum environmental pollution is established. The following conclusions are obtained by solving the model:

(1)Electricity pricing has a direct impact on consumer behavior, and there is a long-term equilibrium between electricity price and electricity demand. If the electricity pricing changes by 5.7%, it will result in a 1% change in electricity consumption. Additionally, the changes of economic and social parameters also affect the optimal power pricing. If unit production cost increases by 1%, optimal electricity price shall increase by 0.74%. If the rate of pollution is limited by 10%, the optimal electricity price shall be up by 1.09%. This shows that the cost of energy conservation and emission reduction needs to be assumed by consumers and producers, and electricity pricing needs to reflect the cost of technological innovation to encourage technological innovation.

(2) This paper proposes the optimal pricing strategy for 2008, 2009 and 2010, three year with the most severe power shortages, which are 569.72580.19598.14 Yuan/(MW·h), respectively. All these optimal prices are higher than the average power price in each year. Therefore, electricity pricing should be increased appropriately to stimulate the initiative of power enterprises for power generation. The results are consistent with relevant energy and economic research results, which demonstrates the model to be correct and effective.

References

[1] N. Arunkumar, S. Jayalalitha, S. Dinesh, A. Venugopal, D. Sekar: *Sample entropy based ayurvedic pulse diagnosis for diabetics*, IEEE-International Conference on Advances in Engineering, Science and Management, ICAESM-2012, (2012), art. No. 6215973, 61–62.

[2] J. W. Chan, Y. Y. Zhang, and K. E. Uhrich: *Amphiphilic Macromolecule Self-Assembled Monolayers Suppress Smooth Muscle Cell Proliferation*, Bioconjugate Chemistry, *26* (2015), No. 7, 1359–1369.

[3] M. P. Malarkodi, N. Arunkumar, V. Venkataraman: *Gabor wavelet based approach for face recognition*,International Journal of Applied Engineering Research, *8* (2013), No. 15, 1831–1840.

[4] L. R. Stephygraph, N. Arunkumar: *Brain-actuated wireless mobile robot control through an adaptive human-machine interface*, Advances in Intelligent Systems and Computing, *397* (2016), 537–549.

[5] N. Arunkumar, V. Venkataraman, T. Lavanya: *A moving window approximate entropy based neural network for detecting the onset of epileptic seizures*,International Journal of Applied Engineering Research, *8* (2013), No. 15, 1841–1847.

[6] J. W. Chan, Y. Y. Zhang, and K. E. Uhrich: *Amphiphilic Macromolecule Self-Assembled Monolayers Suppress Smooth Muscle Cell Proliferation*, Bioconjugate Chemistry, *26* (2015), No. 7, 1359–1369.

[7] Y. J. Zhao, L. Wang, H. J. Wang, and C. J. Liu: *Minimum Rate Sampling and Spectrum Blind Reconstruction in Random Equivalent Sampling.* Circuits Systems and Signal Processing, *34* (2015), No. 8, 2667–2680.

[8] S. L. Fernandes, V. P. Gurupur, N. R. Sunder, N. Arunkumar, S. Kadry: *A novel nonintrusive decision support approach for heart rate measurement*, (2017), Pattern Recognition Letters. https://doi.org/10.1016/j.patrec.2017.07.002

[9] N. Arunkumar, K. Ramkumar, V. Venkatraman, E. Abdulhay, S. L. Fernandes, S. Kadry, S. Segal: *Classification of focal and non focal EEG using entropies.* Pattern Recognition Letters, *94* (2017), 112–117

[10] W. S. Pan, S. Z. Chen, Z. Y. Feng.: *Investigating the Collaborative Intention and Semantic Structure among Co-occurring Tags using Graph Theory.*, International Enterprise Distributed Object Computing Conference, IEEE, Beijing, (2012), 190–195.

[11] Y. Y. Zhang, Q. Li, W. J. Welsh, P. V. Moghe, and K. E. Uhrich: *Micellar and Structural Stability of Nanoscale Amphiphilic Polymers: Implications for Anti-atherosclerotic Bioactivity*, Biomaterials, *84* (2016), 230–240.

[12] L. R. Stephygraph, N. Arunkumar, V. Venkatraman: *Wireless mobile robot control through human machine interface using brain signals*, 2015 International Conference on Smart Technologies and Management for Computing, Communication, Controls, Energy and Materials, ICSTM 2015 - Proceedings, (2015), art. No. 7225484, 596–603.

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