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Meta-heuristic optimization algorithms for design of gain constrained state variable filter

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ABSTRACT

In conventional design method, the parameters of an active filter cannot be selected based on manufactured parameters such as E series. However, this can be feasibly obtained using optimization technique through an exhaustive search on all possible combination of preferred values of E series by providing the coding system. The exhaustive search for low pass second order filter is carried out through Meta-heuristic optimization Algorithms. The cost function for error minimization including compatible to E series and gain adaptive are used here as objective function for finding out minima through well known algorithms. The inclusion of gain constrained concept eliminates the extra op-amp cascading to state variable filter circuit which reduces the noise and dimension of cost function; in addition, improves the stability of the system. The performances of Grey Wolf Optimization (GWO), Whale Optimization Algorithm (WOA) and Sine-Cosine Algorithm (SCA), nature and physics-inspired artificial intelligence techniques are evaluated for state variable filter design considering gain constrained. Each of above algorithms is applied to filter structure and performances of them are also evaluated when filter design is realized with components selected from different manufactured E series.

1. Introduction

Conventional design methods to figure out the component values of active analog filters require the random selection of some of the component values. But this does not become feasible as less number of mathematical expressions exists compared to the number of component values. Some of the passive parameters (resistance and/or capacitance) can be blindly selected from readily available manufactured component values but other passive parameters can be calculated using well known mathematical expression. However, the calculated values may not be matched with manufactured constant values available in the market which degrades the performance of active filter. This leads to increased demand of optimization techniques for determining the component values compatible with manufactured value of the components. The analog active filter can be implemented using operational amplifiers (op-amp) with components like resistors and capacitors as a feedback. Realization with op-amp creates high input impedance, low output impedance and virtually any arbitrary gain without inductors which reduces the problems associated with inductors. Discrete components such as resistors and capacitors are available in the market and marketed in the form of series of E12, E24, E48, E96 and E192. They are manufactured in approximate logarithmic multiples of a defined number of constant values. It is necessary to optimize the selection of component values in such a way that it tightly matched with the marketed values without violating the design criteria such as quality factor, cut-off frequency and also the gain of filter. The best way to optimize the component values is the application of intelligent search methods. There are a large number of literatures available for design of 4th order Butterworth filter and state variable filter. The 4th order low-pass Butterworth filter represented by transfer function is a unity gain filter and this gain does not depend upon the component values. This requires optimizing the 4th order Butterworth filter by considering the required cut-off frequency and quality factor. However, in state-variable filter, the gain value is dependent upon cut-off frequency, quality factor and component values. The value of gain becomes affected when optimization technique is applied in consideration with cut-off frequency and quality factor only. The existing literatures [1–4] have not focussed on the gain constrained concept while applying the optimization algorithms and making compatible to E series. The gain on such state- variable filters was compensated using cascading of other gain controlled op-amp circuits. The cascade of other op-amp for gain compensation enhances noise component caused by the built-in semiconductors and resistors and thus affects the stability. In this research, effort has been made to make the gain constrained of state-variable filter while applying the optimization algorithms and make compatible to E series.

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Particle Swarm Optimization (PSO) and finite element method were applied to design the filter optimally for microwave filter design [5]. Genetic Algorithm (GA) was used to design 2-D recursive digital filter [6]. Optimization for digital filter design through PSO and Artificial Bee Colony (ABC) algorithms were presented in literature [7,8]. The component values of passive filter were selected through GA and Genetic Programming (GP) based tree representation method respectively [9,10]. Parallel Tabu Search Algorithm (TSA) was explored to carry out the design of component values of active filter which is compatible to E12 series [11]. To design digital Infinite Impulse Response (IIR) filters, Ant Colony Optimization (ACO) algorithm was used in [12]. An improved ABC algorithm was also incorporated to optimal design of filter circuit [13]. A detailed comparison study on analog passive filter design with different evolutionary methodologies was presented in [14]. An automated passive analog circuit synthesis framework using GA was explored in [15]. Unconstrained and constrained evolution LCR low pass filter was handled towards designing analog filter [16]. Differential Evolution (DE) technique was used to optimize the component values of analog filter [2]. In [3], Adaptive Immune GA was applied for determination of optimal component values of passive filter. The Clonal Selection Algorithm (CSA), PSO, GA and Immune Algorithm were successfully applied to optimal design of active filter in respective order [17–20]. State variable filter was designed using PSO without gain constrained [1]. Both state variable and 4th order Butterworth filters were designed and making compatible to E12, E24 and E96 through GA, PSO and ABC optimization algorithms [4]. In [4], the results were compared with existing literatures and represented in tabular form. The 4th order Butterworth filter was designed based on minimization of Gain Sensitivity Product (GSP) and making compatible to E12 series using Grey Wolf Optimization (GWO) and PSO [21].

Meta-heuristic optimization algorithms are becoming more and more popular and used in many fields including engineering for minimization or maximization of cost functions because of simple population based concept. Further, these are easy to implement, least chance of falling in local optimum and not requiring gradient information. It can be classified as evolutionary based, physics-based and swarm-based methods. Evolutionary based methods are inspired by the laws of natural evolution that is survival to the fittest and examples are GA, Evolution Strategy (ES), GP, Biogeography-Based Optimizer (BBO), etc. [4,22,23]. Physics-based methods uses the physical rules exist in the Universe. The most popular algorithms are Simulated Annealing (SA), Gravitational Local Search Algorithm (GLSA), Big-Bang Big-Crunch (BBBC), Gravitational Search Algorithm (GSA), Charged System Search (CSS) [24–29], etc. The third group is nature-inspired social behaviours of living creatures. Few examples are PSO, ACO, Monkey Search and Cuckoo Search, etc. [30–33].

This paper utilizes three optimization algorithms, two of them are nature-inspired meta-heuristic optimization algorithm called GWO, Whale Optimization Algorithm (WOA) and other one is the physics based method called Sine-Cosine Algorithm (SCA) for optimal selection of component values of state variable filter. The selection of component values should make compatible with the manufacturers' preferred three different types E series such as E12, E24 and E96. In order to make compatible with E series the code is developed. Gain on pass band is made constrained for determination of component values. By adapting the gain constrained concept, any required gain can be achieved. The state variable filter is briefly reviewed in Section 2. The coding schemes and formation of cost function with gain constrained concept is presented in Section 3. The brief review of GWO, WOA and SCA are discussed in Section 4. In Section 5, the obtained results are discussed and the concluding remark is included in the last section.

2. State variable filter

Analog active filters are realized by op-amps, with resistors and capacitors in their feedback loops, to synthesize the desired filter types such as low pass, high pass and band pass. They are widely used in separation of signals according to frequency bands, frequency selection decoding and estimation of a signal from noise, demodulation of signals, and amplifying elements [34]. Realization of op-amp creates high input impedance, low output impedance and virtually any arbitrary gain without inductors reducing the problems associated with them. A state variable filter (SVF) is realized through state-space model and can capable of producing low pass, high-pass, and band pass outputs simultaneously from a single input. A second order SVF is shown in Fig. 1 and was well explained in [34,35]. However, different aspects considered for designing the filters are presented in various existing literatures [13,37–45]. Their performance parameters are specified by the pass band gain(G_S), the cut-off frequency(ω_S) and quality factor (Q_S). The mathematical expressions are as follows:

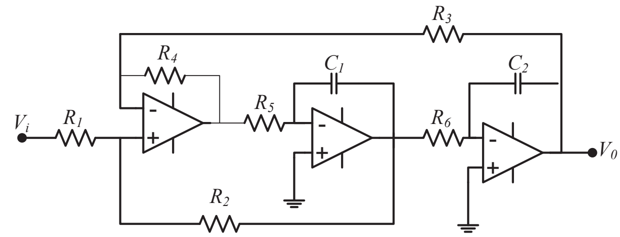

Fig. 1. Second order state variable low pass filter [34].

$$G_S = \frac{R_2(R_3 + R_4)}{R_3(R_1 + R_2)} \tag{1}$$

$$\omega_S = \sqrt{\frac{R_4}{R_3 R_5 R_6 C_1 C_2}} \tag{2}$$

$$Q_S = \frac{R_3(R_1 + R_2)}{R_1(R_3 + R_4)}\sqrt{\frac{R_4 R_5 C_1}{C_2 R_3 R_6}} \tag{3}$$

The specification chosen for optimization are $\omega_S = 10\,\text{k rad/s}$ and $Q_S = 0.707$. The pass band gain (G_S) is not so much important in most applications since it can be compensated by other cascaded analog circuits and hence for optimization it is chosen as unconstrained [34]. In conventional approach $R_1$to R_6 except R_2 are chosen as 4 kΩ each. The value of R_2 is determined using Eq. (6) and found to be 1.656 kΩ for the gain of 0.585. The capacitor values are determined using Eqs. (7) and (8). The value of C_1 and C_2 is 25 nF each. The transfer function of low pass second order state variable filter is expressed as:

$$\frac{V_0(s)}{V_i(s)} = \frac{G_s \times Q_s \times \omega_s^2}{Q_s S^2 + \omega_S S + Q_s \omega_s^2} \tag{4}$$

To make the gain constrained, the Eq. (1) can be modified in terms of R_2 as:

$$R_2 = \frac{R_1 R_3 G_S}{R_3 + R_4 - R_3 G_s} \tag{5}$$

Now, R_2 can be determined using Eq. (5) for any value of G_s. Here, all component values except R_2 are made compatible with the E series by forming the coding scheme. Since G_s is not bounded by E series, the value of R_2 is not compatible with this series. But for unity gain, all parameters are compatible with E series which is evident from the Eq. (6). The expression of R_2 for unity gain of state variable filter is obtained as,

$$R_2 = \frac{R_1 R_3}{R_4} \tag{6}$$

The gain may be compensated by cascading other op-amp with extra passive parameters if the gain constrained is not adopted. This type of combination increases noise caused by the built-in semiconductors and resistors; and also affects the stability. In addition, the numbers of variables in the cost function are 16 in comparison to 14 for gain