Quantitative Selection Method of Product Conceptual Scheme Based On Bond Graph

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Title page

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ORIGINAL ARTICLE

Quantitative Selection Method of Product Conceptual Scheme Based On Bond Graph

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Abstract: The optimum conceptual scheme is mostly selected based on qualitative decision-making evaluation methods in conceptual design stage of engineering product, which lacks quantitative verification and evaluation. To solve this problem, quantitative selection method of product conceptual scheme based on bond graph is proposed. Through analyzing the correlation between function, effect and bond element, the bond graph model and corresponding AMESim simulation model of conceptual scheme are constructed to verify the feasibility of conceptual scheme, and the quantitative evaluation index of function-performance requirements is calculated. A conceptual scheme selection method considering quantitative evaluation index and qualitative evaluation by experts is proposed to obtain the optimum scheme. The conceptual scheme selection of transmission system of a shearer cutting unit is taken as an example to verify the effectiveness of the proposed method.

Keywords: Conceptual design • Bond graph • AMESim • Conceptual scheme verification • Quantitative selection

1 Introduction

With the increasingly fierce competition and the diversified development of demands on the market, the products' requirements on performance, function and quality have also been continuously improved [1]. Conceptual design is the most creative stage in the product design process [2]. Conceptual scheme selection which determines the optimum scheme among available alternatives is the most critical decision activity in the conceptual design phase. This process is very complicated, involving many factors such as functionality, technology, economy and so on. Therefore, using appropriate methods to select the optimum product conceptual scheme is the key to the success of product design.

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The premise of the conceptual scheme selection is to ensure the feasibility of the alternative scheme. Feasibility verification can be achieved through the modeling of the scheme and analysis of simulation results [3]. Most of the existing conceptual design modeling is simply to describe and express the knowledge of function, behavior and structure, which cannot help the subsequent quantitative verification work. This paper uses the advantages of bond graph in processing system modeling, simulation and analysis to solve this problem, helping designers determine the feasibility of the program. And at the same time, the quantitative data used in the subsequent selection process can be obtained through the bond graph simulation software AMESim.

In existing conceptual scheme selection, different numerical quantization methods is used to process the expert's qualitative judgment results, as far as possible to reduce the decision bias caused by the inaccuracy and subjectivity of qualitative evaluation data. Then, combine multiple ranking methods to analyze multiple evaluation indicators. And finally choose the best balanced plan for each target. However, the initial evaluation value is generally quantified through expert qualitative judgment. The result of the choice of the plan is affected by the expert's preference and subjectivity, and the result is not accurate enough [4]. This paper considers combining quantitative simulation data results with qualitative expert judgment, selecting the optimum scheme that satisfies both functional and performance requirements from multiple feasible schemes.

In summary, this paper proposes quantitative selection method of product conceptual scheme based on bond graph. The rest of this paper is structured as follows. Section 2 introduces the related works of conceptual scheme modeling, bond graph, and scheme evaluation method. Section 3 explains the construction of bond graph modeling and scheme verification based on AMESim simulation analysis. Section 4 presents the preferred approach, which combines quantitative simulations and qualitative judgments. In Section 5, the selection process of the transmission system of a shearer cutting unit is taken as an example to prove the effectiveness of the method. The conclusion is drawn in Section 6.

2 Related Works

2.1 Conceptual Scheme Modeling

Conceptual design modeling is an important part of implementation scheme verification. That is, describing product design information to show design intent [5]. It is one of the existing problems in the conceptual design phase of products. It mainly includes functions, behaviors, structures, and their relationship [6]. Function mainly describes the tasks that the product completes [7]. The purpose of functional expression is to provide semantic and grammatical support for the description of functions. There are mainly two ways of input / output conversion and language expression, including the following three types [8]: 1) Verb noun combinations, 2) Input and output streams Change, 3) input and output status changes. Behavior is a dynamic process which reflects the methods to realize functions, representing the specific way of input and output stream transfer and transformation [9]. It is a physical feature of the structure to realize functions. There are two main representation methods of behavior, state-based representation and action-based representation. Behavior bridges the map-ping relationship between function and structure, and plays a very important role in the model construction of conceptual design, ensuring the effectiveness and operability of function-to-structure mapping. Structure, as the carrier of behavior, describes the topological relationship between the various components of the product [10]. It is used to indicate how the function is implemented. In conceptual design, the main structural representation methods include vector representation, graph representation, and feature representation.

Of course, the modeling of conceptual design is not limited to the modeling of design knowledge objects in various domains of the product. At the same time, a lot of research on the design process model between domains has also been carried out. The design objects and processes are described hierarchically to help implement the innovation of product. Professor Gero of the University of Sydney proposed the FBS model [11]. He thought that the product design process is continuously transferred and advanced in the three domains of function, behavior, and structure, thereby establishing an eight-stage FBS model. On the basis of this, demand-function-structure [12], FBS Knowledge cell [13], Structure-behavior-function model [14], state-behavior-structure [15] and other process models have been proposed successively.

In general, most of the modeling of existing conceptual design simply describes the knowledge of functions, behaviors, and structures. And it is difficult to achieve the explicit expression of the coupling between various types of knowledge and the information of mathematical models contained. It cannot help the subsequent quantitative verification work.

2.2 Bond Graph

Bond graph is a dynamic analysis method for engineering systems that handles multiple energy categories by using a unified bond element model [16]. It can clearly and intuitively represent the power flow relationship between system components and subsystems [17]. Since the creation of bond graph, researchers at home and abroad have mainly conducted relevant exploration research in three directions [18]. In terms of theoretical research, bond graph mainly focuses on solving the problems of system equation derivation and causality analysis through the mathematical equation information contained in bond graph. Through research on Lagrange bond graph [19], rotating bond graph [20], vector bond graph [21], thermodynamic bond graph [22], and pseudo-bond graph [23] which derived from bond graphs, fault diagnosis and variable structure system analysis of existing products are carried out. In applied research, bond graph can be used to achieve system modeling and analysis of products, including mechanical, electronic, hydraulic, and thermodynamics. In the research of bond graph simulation software systems, researchers have also developed some related modeling and simulation software. With the help of these developed software such as ENPORT [24], BGGP [25], 20sim [36], etc., computer visualization of bond graph models can be realized. And the system can be simulated and analyzed.

At the same time, many scholars have introduced bond graph into the research of product systems for conceptual design. Wu [27] used bond graph to build conceptual dynamics diagrams and general models, and built component libraries suitable for the automatic modeling process of conceptual design mechatronic systems which used to store the dynamic models and design constraints information. Sampath [28] proposed bond graph based BG-UMF (unified meta-modeling framework) which as a general framework to bridge the concept-code gap rampant in design and development of complex, software intensive mechatronic systems called cyber-physical systems. Fu [29] addressed the virtual prototyping of electromechanical using the Bond-Graph formalism, realizing enable incremental modeling, thermal balance analysis, free-run or jamming fault response.

In summary, although bond graph has made some progress in the field of conceptual design of engineering systems, how to use bond graph theory combined with existing knowledge expression methods to extract design information in the conceptual design process, model the conceptual scheme as detailed as possible, and apply it to the practical application of existing products are still required in-depth research.

2.3 Scheme Evaluation

The evaluation of the conceptual scheme is the process of evaluating several reasonable schemes formed and selecting the optimum conceptual scheme. The scheme evaluation is a complex multi-criteria decision-making process, involving many factors (such as the complexity of the product, the relevance of the evaluation indicators, the incompleteness of the concept scheme information, and the uncertainty of expert evaluation, etc.) [30].

At present, the commonly used evaluation decision methods include fuzzy evaluation method, AHP (analytic hierarchy process), value engineering method, comprehensive evaluation method and so on. Zhu [4] proposed a systematic evaluation method integrated rough numbers which used rough numbers to deal with ambiguity and subjectivity in design concept evaluation, and combined AHP and VIKOR to evaluate alternatives and optimize. Tiwari [31] proposed MR-VIKOR (modified rough VIKOR) to reduce inaccurate content in the customer evaluation process improving the effectiveness and objectivity of product design. Zhang [32] used DEMATEL (decision making trial and evaluation laboratory) and fuzzy set to deal with qualitative evaluation of experts predicting the performance on alternatives and ranking them through PSO-SVM (Particle Swarm Optimization Based Support Vector Machine) and VIKOR. Ma [33] used fuzzy set theory and morphology matrix to deal with design preferences and failure risks in evaluation. Jiang [34] and Jing [35] considered the selection of feasible solutions under the morphological matrix by integrating design objective constraints, and used non-cooperative-cooperative game models and DEMATLE-cooperative game model respectively seeking “the equilibrium optimum” and “the most robust” design solutions, solving the problem that the evaluation data of principle scheme is qualitative and difficult to overlap under interactive targets. Finally, consider the performance to further optimize the principle scheme and get better one.

To sum up, the evaluation of the existing conceptual scheme is a process that uses different numerical quantification methods to process the qualitative judgment results of experts, then analyzes multiple evaluation indicators by different sorting methods, finally selects the balanced and optimum solution for each goal. However, the initial evaluation value is generally quantified by the qualitative judgment of the experts. The choice of the solution is affected by the preference and subjectivity of the experts. Therefore, it is critical to reduce the subjectivity of the evaluation process, so as to determine the best feasible solution needs further study.

3 Conceptual Scheme Verification Based on Bond Graph Model

3.1 Functional Expression and Effect Description

The functional represents the expected conversion from input stream into output stream, which can be described with the form of "operation + flow" (O+fl). The effect is expressed as the implementation principle of the function and describes the behavior of the product structure. When the structure acts as a functional carrier, there is its corresponding functional effect (FE). However, unintended behavior occurs during the actual behavior of a structure, resulting in a dependent effect (DE). The functional and effect models are shown in Figure 1.

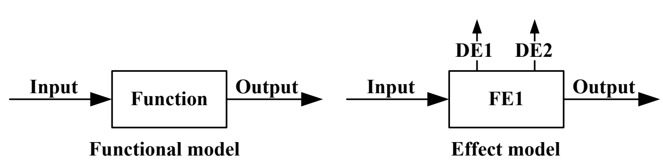


Figure 1 Functional expression and effect description model

According to the relationship between structure and function, the principle solution module (PS_i) and the sub-structure (S_{ij}) inside each principle solution module are separated. Then, the functional information of each structure is abstracted. The principle solution module corresponds to the sub-function (SF_i). The sub-structure corresponds to the meta-function (MF_{ij}). Thereby, the function tree of the scheme is constructed. Finally, the function chain is established according to the conversion and sequence of the input and output streams. The functional structure model is obtained, as shown in Figure 2.

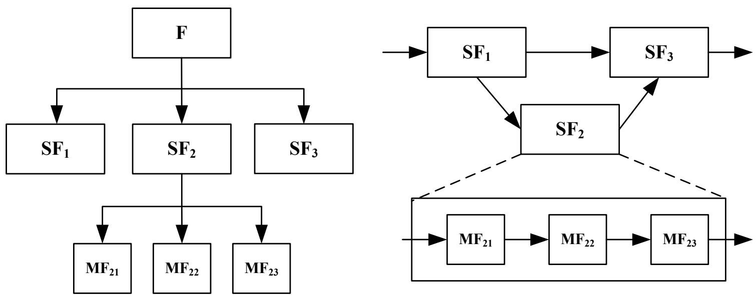


Figure 2 Functional decomposition tree and functional structure model

According to the relationship between structure, function, and physical effect, the construction process of the effect model is divided into the following steps. Firstly, the functional effects (FE_{ij}) are determined after analyzing the principle solution module. The main effect chain is established. Then, the substructure included in each principle solution is analyzed considering the dependent effect (DE_{ij}) existing in the actual behavior process. Finally, the dependent effect of each principle solution module is added to the corresponding functional effect, and the complete effect model is constructed.

3.2 Construction of Bond Graph Model

Using bond graph, every effect can be converted into a corresponding bond element using the specific steps in Figure 3, and the corresponding bond graph model for conceptual scheme is constructed.

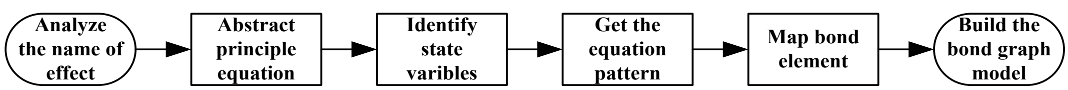


Figure 3 Process of bond graph model construction

1) Abstract principle equation. The effect is the basic principle followed in the product functional design process, including the principle equation, analysis of the product effect model, and abstraction of the principle equation corresponding to each effect name.

2) Determine state variables. The state variables are set of variables that completely describe the motion of the system. It can determine the future evolution behavior of the system. Bond graph generalizes various physical parameters into four states: potential variable e, flow variable f, generalized momentum variable p, and generalized displacement variable q. The state variables in different fields are presented in Table 1. The principle equation is generally composed of a combination of multiple physical parameters. The state variables in the physical parameters can be determined by analyzing the principle equation. The parameters unrelated to the state variables are uniformly represented as constant variables k.

3) Obtain the equation pattern. Based on the determination of the principle equation, the state variables and constant variables in the equation, the principle equation is transformed to the corresponding equation pattern.

4) Map the bond element. The corresponding bond element is obtained according to the identified equation pattern.

5) Construct a bond graph model. First, each bond element is connected by the input and output relationship of the flow. Then, a causal line is marked on each power bond by the rule of determining causality. Finally, the complete bonding graph model is established.

Table 1 Bond element and its equation of state

Bond element	State equation	Bond element	State equation
C	$e = k \cdot q$ or $e = k \cdot \int f dt$	I	$f = k \cdot p$ or $f = k \cdot \int e\, dt$
TF	$e_1 = k \cdot e_2$ and $f_2 = k \cdot f_1$	GY	$e_1 = k \cdot f_2$ and $f_1 = k \cdot e_2$
Se	$e = e_1$	Sf	$f = f_1$
0	$e = e_i\,(i = 1, \cdots, n)$ and $\sum_{i=1}^{n} \alpha_i f_i = 0$	1	$f = f_i\,(i = 1, \cdots, n)$ and $\sum_{i=1}^{n} \alpha_i e_i = 0$
R	$e = k \cdot f$		

3.3 Conceptual Scheme Verification Based on AMESim

Based on the mathematical model basis of each bond element in bond graph, the conceptual scheme and state equation are derived, and their AMESim simulation model is established. Through comparing simulation results, the conceptual scheme is verified to meet the functional requirements. The conceptual scheme verification based on AMESim is mainly divided into the following steps:

1) Derive the state equation. Through analyzing the power flow of bond graph model and interrelationship between bond elements, the state equations of bond elements and the overall system of conceptual scheme are obtained.

2) Search for AMESim components. Through analyzing the correspondence between the state equation of bond graph model and the mathematical equations contained in AMESim component library, the appropriate AMESim components are selected for the corresponding modeling expression.

3) Connect the components. Based on the power flow relationship of the bond graph model, each AMESim component is connected in turn to construct a complete AMESim simulation model.

4) Set the variable parameters. The system variables and parameter information are obtained by the state equation. The corresponding variables are found in the AMESim component model. Then, the related system parameters are set.

5) Simulate for verification. After determining the correctness of the model and setting parameters, the simulation analysis is implemented. The process of AMESim modeling based on bond graph is shown in Figure 4.

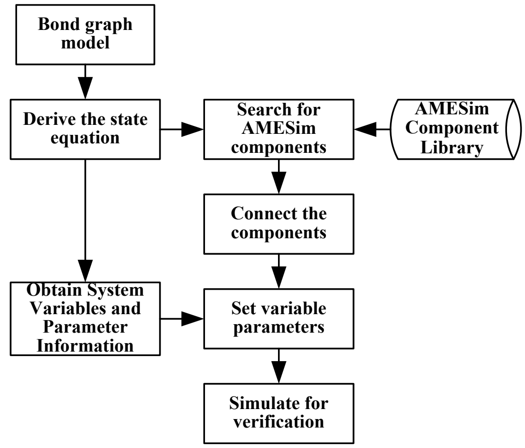


Figure 4 Process of AMESim modeling based on bond graph model

6) Verify the function and performance. The feasibility judgment aims to judge the feasibility of the scheme from the perspective of function realization, determining whether the scheme meets the functional requirements. The performance analysis evaluates the scheme from the aspect of performance, obtaining the performance of the design scheme. The specific process is shown in Figure 5. The unreasonable schemes can be eliminated from a large number of initial design schemes, and feasible schemes that meet the functional requirements can be selected.

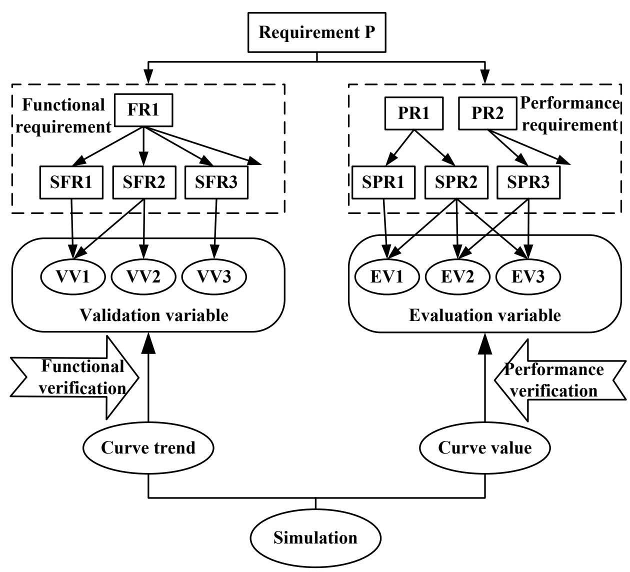


Figure 5 Functional and performance verification process of schemes based on requirements

4 Conceptual Scheme Selection for Integrating Qualitative Judgment and Quantitative Simulation

4.1 Construction of Quantitative Indicator

The quantitative evaluation index indicates the performance expectation values of the conceptual scheme, which can be realized by the AMESim software, such as the vibration of the transmission system, fuel consumption of the vehicle system, and comfort of the passenger. The interval value of the evaluation index SD_{iq} is obtained by analyzing AMESim simulation results in Eq. (1), where SD_{iq}^{L} indicates the lower limit of the simulation data and SD_{iq}^{U} indicates the upper limit.

$$SD_{iq} = \left[SD_{iq}{}^{L}, SD_{iq}{}^{U} \right], \tag{1}$$

An initial feasible decision matrix $\mathbf{S}_v$ is constructed in Eq. (2) to verify the evaluation index.

$$\mathbf{S}_v = \begin{pmatrix} SD_{11} & SD_{12} & \cdots & SD_{1s} \\ SD_{21} & SD_{22} & \cdots & SD_{2s} \\ \vdots & \vdots & \vdots & \vdots \\ SD_{m1} & SD_{m2} & \cdots & SD_{ms} \end{pmatrix}, \tag{2}$$

SD_{iq} ($1 \le i \le m$, $1 \le q \le s$) represents the simulation evaluation data of the q-th verification evaluation target of the i-th scheme, m is total number of feasible schemes, s is the sum of verification evaluation targets.

4.2 Quantitative Representation of Qualitative Indicators

Some non-validation evaluation indices, such as economic, technical aspects and reliability of the specific data, cannot be represented based on the constructed bond graph model and AMESim simulation model. Therefore, the scoring of such evaluation indicator is achieved using rough set theory based on expert semantic judgment.

1) Obtain the initial decision evaluation value for non-verified evaluation index

The experts ($1 \le k \le D$) make an original judgment on each non-verified evaluation indicator of the feasible scheme set. According to the expert's preference, the linguistic variables of the judging standard are inconsistent, and this leads to an increase in the complexity of the problem. To simplify the processing of the judgment expression, the qualitative judgment is expressed by quantitative fuzzy number, as shown in Table 2.

Table 2 Quantitative fuzzy number of qualitative judgment

Linguistic variables	Fuzzy numbers
Very good	5
Good	4
Medium	3
Poor	2
Very poor	1

Therefore, $P_{nv\text{-}ip}{}^{k}$ ($1 \le k \le D$, $1 \le i \le m$, $1 \le p \le t$) represents the judgment of the k-th expert on the p-th non-validation performance evaluation objective of the i-th conceptual scheme. All experts' evaluation semantic judgments of non-verified indicators are aggregated, obtaining the non-verified index initial evaluation integrated decision evaluation values, as expressed in Eq. (3).

$$\tilde{P}_{nv-ip} = \left\{ P^{1}_{nv-ip}, P^{2}_{nv-ip}, \cdots, P^{D}_{nv-ip} \right\}, \tag{3}$$

$\tilde{P}_{nv-ip}$ ($1 \le k \le D$, $1 \le i \le m$, $s+1 \le p \le n$) indicates the integrated judgment of all experts on the p-th non-validation performance evaluation target of the i-th conceptual scheme.

2) Convert the non-verified evaluation values to rough decision values

Based on the definition of the rough number, the evaluation scheme index's fuzzy number P^{k}_{nv-ip} of the expert is converted into a fuzzy rough number. P^{kL}_{iq} represents the minimum limit of the rough number and P^{kU}_{iq} represents the maximum limit of the rough number.

$$RN\left(P^{k}_{ip}\right) = \left[P_{ip}{}^{kL}, P_{ip}{}^{kU} \right], \tag{4}$$

Therefore, the expert's integrated judgment value $\tilde{RN}(P_{ip})$ for the non-verified indicators can be expressed as

$$\tilde{RN}\left(P_{ip}\right) = \left\{ \left[P_{ip}{}^{1L}, P_{ip}{}^{1U}\right], \left[P_{ip}{}^{2L}, P_{ip}{}^{2U}\right], \ldots, \left[P_{ip}{}^{DL}, P_{ip}{}^{DU}\right] \right\}, \tag{5}$$

Base on the rough set algorithm, the average rough number $RN(P_{ip})$ is calculated in Eq. (6) to represent the expert's consistency judgment on non-verified indicators.

$$RN\left(P_{ip}\right) = \left[\sum_{k=1}^{D} P^{kL}_{ip} \Big/ D, \sum_{k=1}^{D} P^{kU}_{ip} \Big/ D \right], \tag{6}$$

Therefore, the non-verified initial coarse decision matrix can be expressed as

$$\mathbf{R}_{nv}=\begin{pmatrix}\left[P_{11}^{L},P_{11}^{U}\right] & \left[P_{12}^{L},P_{12}^{U}\right] & \cdots & \left[P_{1t}^{L},P_{1t}^{U}\right]\\ \left[P_{21}^{L},P_{21}^{U}\right] & \left[P_{22}^{L},P_{22}^{U}\right] & \cdots & \left[P_{2t}^{L},P_{2t}^{U}\right]\\ \vdots & \vdots & \vdots & \vdots\\ \left[P_{m1}^{L},P_{m1}^{U}\right] & \left[P_{m2}^{L},P_{m2}^{U}\right] & \cdots & \left[P_{mt}^{L},P_{mt}^{U}\right]\end{pmatrix}, \quad (7)$$

4.3 Construction and Analysis of Integrated Decision Matrix

1) Integrate the verification indicator decision value and non-verification index decision value to determine the comprehensive decision matrix **M**.

$$P_{ij}=\begin{cases}SD\left(P_{iq}\right) & 1\le i\le m,1\le q\le s\\ RN\left(P_{ip}\right) & 1\le i\le m,s+1\le p\le n\end{cases}, \quad (8)$$

$$\mathbf{M}=\left(\mathbf{S}_{v}\quad \mathbf{R}_{nv}\right)=\begin{pmatrix}P_{11} & \cdots & P_{1j} & \cdots & P_{1n}\\ \vdots & \ddots & \vdots & \vdots & \vdots\\ P_{ij} & \cdots & P_{ij} & \cdots & P_{in}\\ \vdots & \vdots & \vdots & \ddots & \vdots\\ P_{m1} & \cdots & P_{mj} & \cdots & P_{mn}\end{pmatrix}, \quad (9)$$

P_{ij} represents the judgment score of the j-th evaluation index of the i-th scheme in the comprehensive decision matrix.

2) Use the vector normalization method to achieve the standardization processing of the comprehensive decision matrix, obtaining the vector normalization matrix $\mathbf{M}_{st}=(Y_{ij})_{m\times n}$.

$$Y_{ij}=P_{ij}\Big/\sqrt{\sum_{i=1}^{m}P_{ij}^{2}}, \quad (10)$$

After normalization, the index values are all satisfied with $0\le Y_{ij}\le 1$. The directions of the positive and negative indicators do not change. After the normalization of the positive indicators, it is still a positive indicator. After the normalization of the reverse index, it is still a reversed indicator. Through the standardization process, the obtained simulation data and qualitative evaluation data are dimensionless, determining the standard comprehensive decision matrix.

After obtaining the weight value of the evaluation index and the comprehensive decision matrix of the integrated expert judgment and numerical simulation, the VIKOR is used to sort the feasible schemes. First, determine the value of positive ideal solution (PIS) and negative ideal solution (NIS). Then, calculate the group benefits $\left[S_i^L,S_i^U\right]$, individual regrets $\left[R_i^L,R_i^U\right]$ and the comprehensive indicator of aggregate function intervals $\left[Q_i^L,Q_i^U\right]$. Q_i is a trade-off between the group benefits and maximum individual regrets. Finally, the schemes are organized according to S_i, Q_i and R_i. The schemes are sorted by the rough mean $\bar{Q}_i$. The $\bar{Q}_i$ is smaller, the scheme is better. The optimum scheme is selected by comparing the size of $\bar{Q}_i$.

5 Case Analysis

The coal mining machinery is the most important mechanical equipment in modern industry. The cutting variable speed drive (CVSD) is an important part of the shearer cutting unit. Its main function is to transfer the motor power to the drum to meet the drum speed and torque requirements. The main functional requirement of the shearer is to make the cutting speed variable. A number of schemes can be obtained by analyzing this requirement, as listed in Table 3

Table 3 Three principle solutions of the CVSD

Scheme	Principle Solution									
	PS_1	PS_2	PS_3	PS_4	PS_5	PS_6	PS_7	PS_8	PS_9	PS_{10}
A1	Cutting motor	gear drive	Planetary gear train	Cutting drum	gear transmission	Clutch handle	—	—	—	—
A2	Cutting motor	gear drive	Planetary gear train	Cutting drum	Variable frequency motor	gear drive	Differential gear train	—	—	—
A3	Cutting motor	gear drive	Planetary gear train	Cutting drum	motor	Variables plunger pump	Solenoid valve	Relief valve	Hydraulic motor	Differential gear train

In scheme A1, a pair of gears is replaced by a shifting gear in the cutting transmission system. The shifting gear is shifted on the shaft by the clutch handle to complete the meshing of three different gear pairs, thus realizing the cutting speed shift of the shearer drum. In scheme A2, the differential gear train is added to the cutting transmission system. The rotation speed of the shearer drum is changed by the variable-frequency motor and the input speed of one component in the reduction gear adjustment differential gear train, realizing the shift in cutting speed of the shearer drum. In scheme A3, the differential gear train is added to the cutting transmission system. However, the change in output speed of the drum is realized by adjusting the output speed of the hydraulic motor, that is, the variation in the output speed of the drum is determined by the participation of the hydraulic system in the work. The change in the output speed of the hydraulic motor is completed by changing the flow in the hydraulic system, realizing the shift in cutting speed of the shearer drum.

Take the cutting motor in scheme A2 as an example for detailed description. The sub-function of the cutting motor PS_1 is to generate rotation, which is composed of three sub-structures: the power source S_{11}, the rotating body S_{12}, and the motor output shaft S_{13}. The corresponding sub-function of each substructure is as follows: MF_{11}, supplying the voltage; MF_{12}, converting the voltage into torque; and MF_{13}, transmitting the torque. The functional structure model of PS_1 is shown in Figure 6.

According to the structure and functional structure model of the cutting motor, the functional effects are the voltage source effect (FE_1) and electrokinetic effect (FE_2), which contain four dependent effects: inductance effect (DE_{21}), resistance effect (DE_{22}), rotational inertia effect (DE_{23}), and viscous friction effect (DE_{24}). The resulting effect model is as shown in Figure 7.

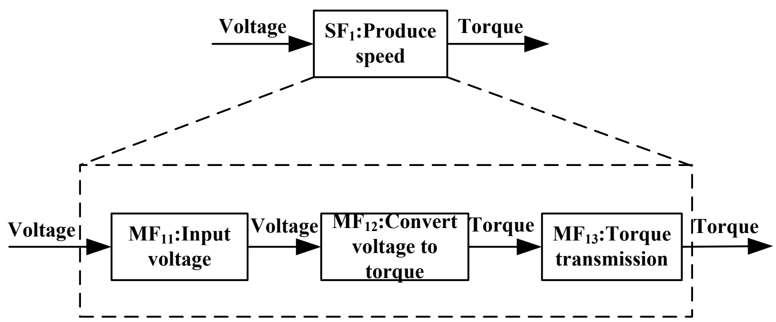


Figure 6 Functional structure model of the cutting motor

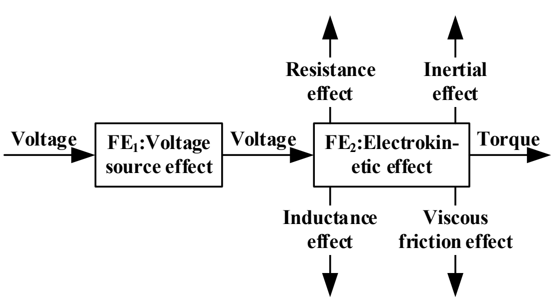


Figure 7 Effect model of the cutting motor

Based on the effect model of the cutting motor, the bond graph model is constructed by the suitable bond element, which is obtained by the matching of the effect and the bond element. The process is shown in Figure 8.

According to the matching process, the voltage source effect can be matched to the potential source component *Se*. The motor effect is represented by a converter *GY* with a certain conversion ratio. The inductance and inertia effects are represented by the inertial component *I*. The resistance and friction effects are represented by the resistive component *R*. The torque coupling effect is represented by a 1-junction. The speed coupling effect is represented by a 0-junction. The bond elements are sequentially connected in accordance with the connection order of the effects, thereby obtaining the bond graph model of the cutting motor, as shown in Figure 9. According to the construction process of the bond graph model of the cutting motor, the bond graph model of the whole scheme A1 can also be obtained, as shown in Figure 10.

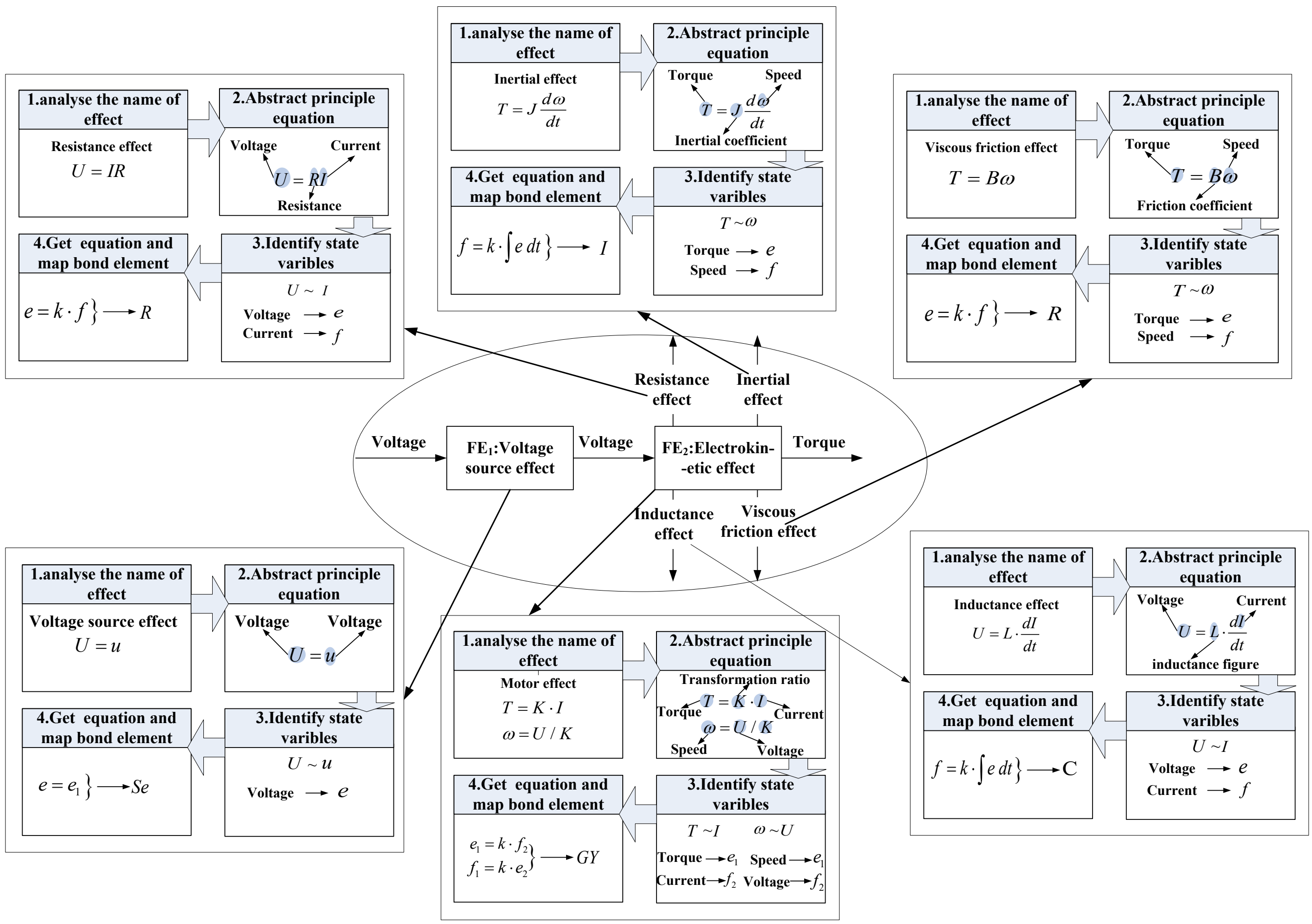


Figure 8 Bond element matching process for cutting motor

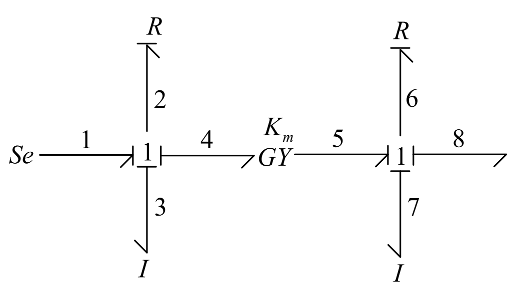


Figure 9 Bond graph model of the cutting motor

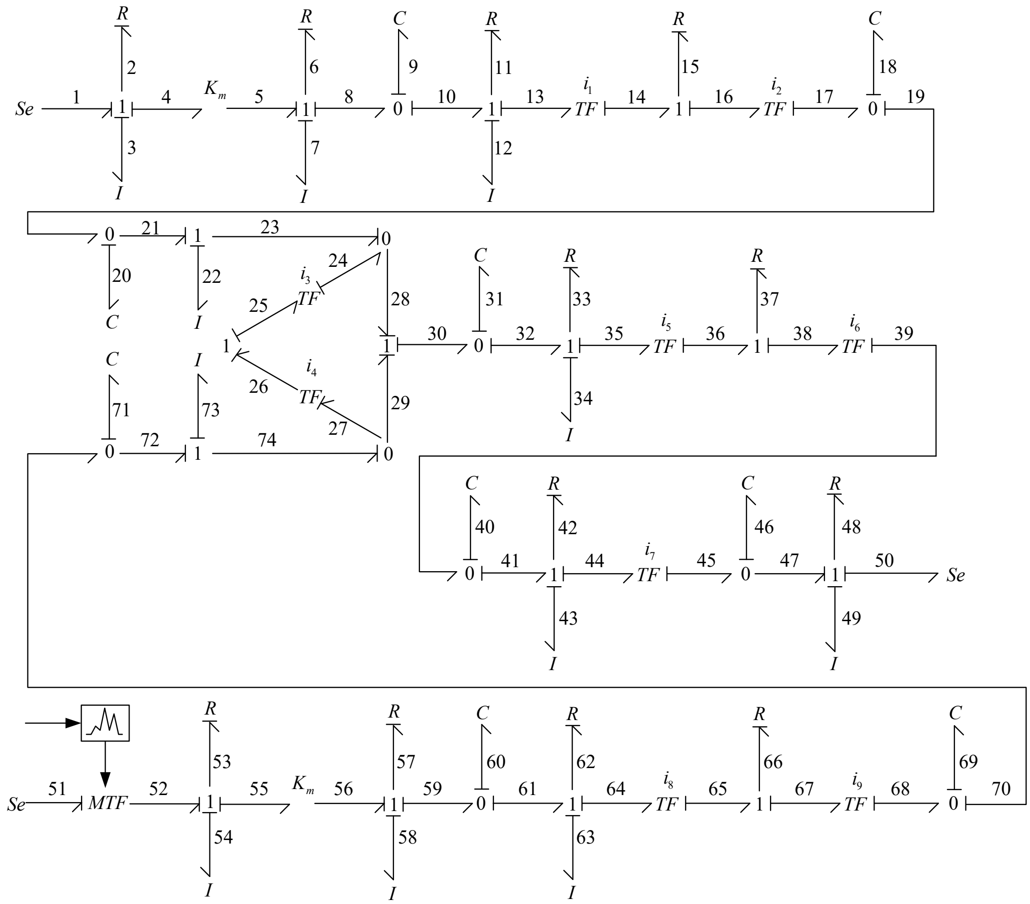


Figure 10 Bond graph model of CVSD-A1

According to the bond graph model of CVSD-A1, the simulation analysis model is established by AMESim, as shown in Figure 11.

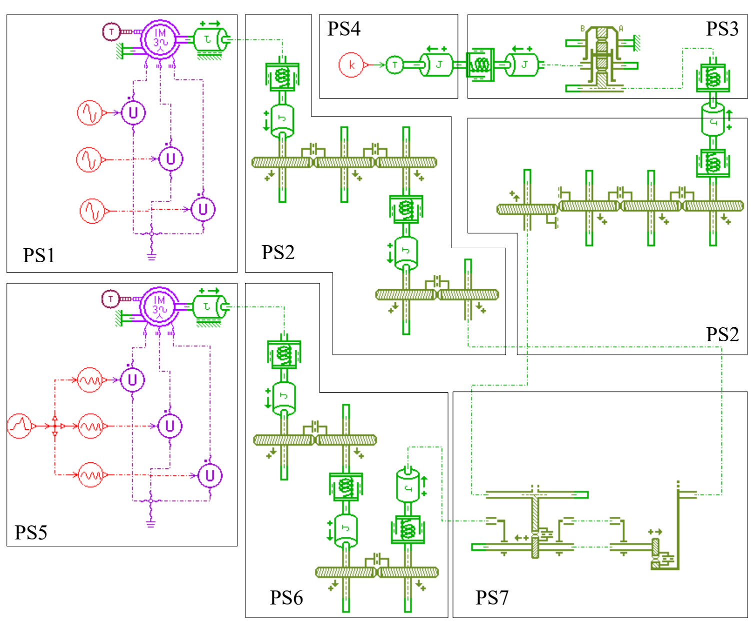
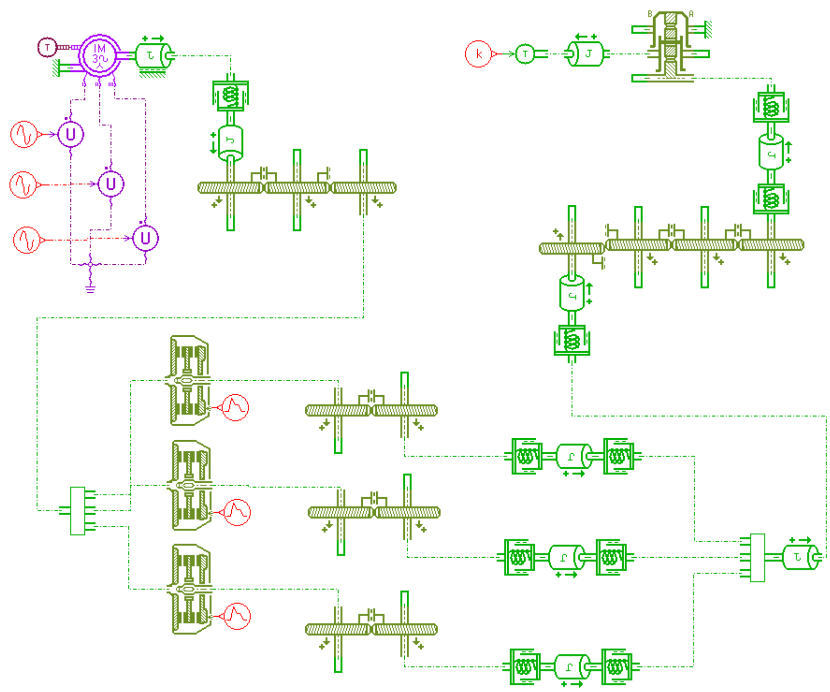
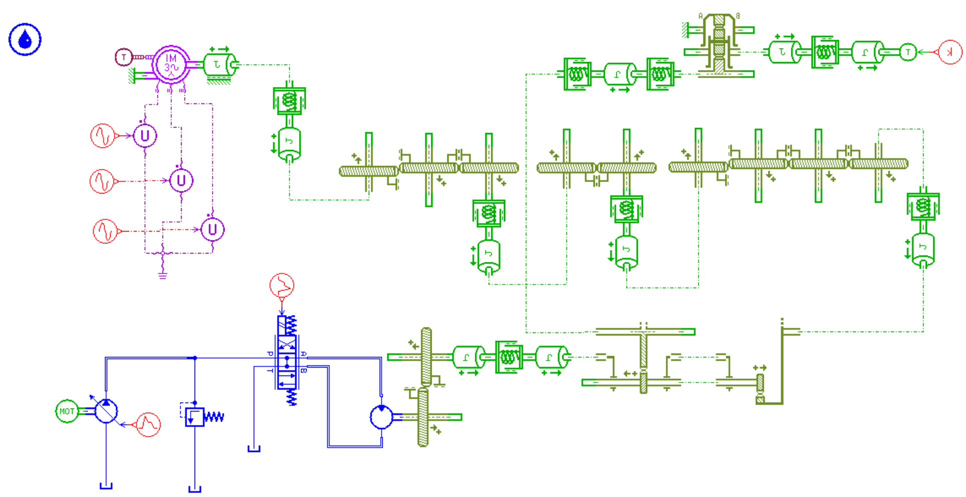


Figure 11 AMESim simulation model of CVSD-A1

Further, according to bond graph model and the modeling process of the AMESim simulation model, the constructed AMESim simulation models of schemes A2 and A3 are shown in Figure 12.



AMESim simulation model for scheme A2



AMESim simulation model for scheme A3

Figure 12 AMESim model implementation of schemes A2 and A3

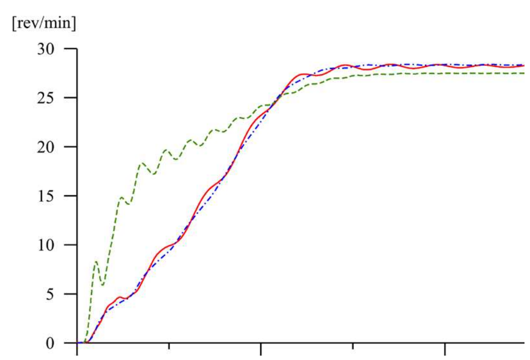
The output speed of the three schemes is calculated in AMESim, which are shown in Figure 12. The three schemes can realize the function of “cutting and shifting”. Thus, they are all feasible schemes. After ensuring that the selected schemes are feasible, the three feasible schemes are evaluated and selected by the scheme selection method of fusion of quantitative simulation and qualitative judgment.

1) Acquisition and classification of evaluation indicators. Analyzing the basic requirements of the cutting transmission, the device should meet the performance requirements of high cutting stability, high reliability, and high economy. Based on the analysis of the simulation results of the scheme, the stability can be evaluated by using the two verification indexes of the drum in AMESim, speed fluctuation (C_{va1}) and drum rotation

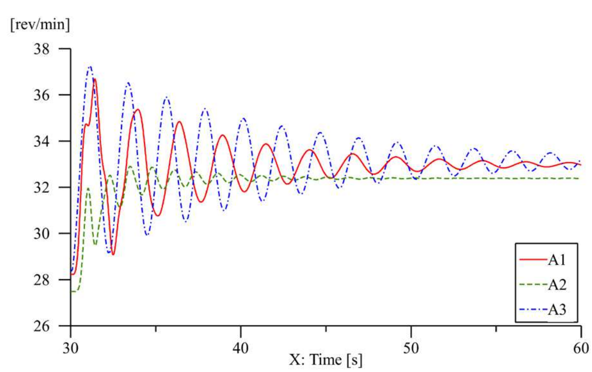
speed (C_{va2}). The reliability (C_{nv1}) and economy (C_{nv2}) cannot obtain evaluation values from the system simulation results. Used as two non-validation indicators, they generate qualitative evaluation decisions by means of four qualitative judgments from experts in different subject areas.

2) Determination of the weight of each indicator. This is achieved through expert analysis of the four evaluation indicators, speed fluctuation (C_{va1}), speed stability time (C_{va2}), reliability (C_{nv1}), and economy (C_{nv2}). According to the AHP method, the weight value of each indicator can be obtained by comparison of its importance among the indicators: 0.402, 0.302, 0.113, and 0.183.

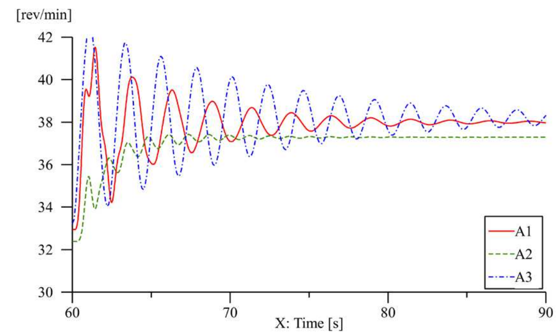
3) Determination of the verification index decision matrix $\mathbf{S}_v$ of each scheme through the simulation results. The AMESim software verification results are output in the form of graphs. The analysis data of the quantitative simulation can be obtained by analyzing Figure 13, as presented in Table 4.



(a) 0-30 s



(b) 30-60 s



(c) 60-90 s

Figure 13 Drum speed-time relationship of the three conceptual schemes

Table 4 Values of the verification indicator SD_{iq}

Scheme	C_{nv1} Speed fluctuation (r/min)	C_{nv2} Speed stability time (s)
A_1	[12,16]	[0,13]
A_2	[18,20]	[0,1]
A_3	[27,30]	[0.4,8]

Based on the value of the verification indicator, $\mathbf{S}_v$ is obtained.

$$\mathbf{S}_v = \begin{pmatrix} [0,13] & [12,16] \\ [0,1] & [18,20] \\ [0.4,8] & [27,30] \end{pmatrix}, \tag{11}$$

4) Acquisition of the non-verified initial coarse decision matrix $\mathbf{R}_{nv}$.

The evaluation values of each indicator of the four experts in the scheme are integrated. Based on the rough number theory, the evaluation values of each scheme are converted into rough number evaluation values, the non-verified initial coarse decision matrix $\mathbf{R}_{nv}$ is obtained.

$$\mathbf{R}_{nv} = \begin{pmatrix} [2.1\ ,3.35] & [2.25,2.75] \\ [1.65,2.9\ ] & [1.71,3.38] \\ [1.59,2.42] & [1.59,2.42] \end{pmatrix}, \tag{12}$$

5) Construction of the standard comprehensive decision matrix $\mathbf{M}_{st}$.

$$\mathbf{M}_{st} = \begin{pmatrix} [0,0.616] & [0.759,0.968] & [0.952,0.986] & [0.130,0.182] \\ [0,0.049] & [0.975\ ,0.991] & [0.091,0.141] & [0.094,0.165] \\ [0.015,0.254] & [0.952,0.986] & [0.091,0.141] & [0.151,0.155] \end{pmatrix}, \tag{13}$$

6) Determination of the positive ideal solution (PIS) and the negative ideal solution (NIS). The group benefits $\left[S_i^L, S_i^U\right]$, the individual regrets $\left[R_i^L, R_i^U\right]$, the aggregated function interval $\left[Q_i^L, Q_i^U\right]$, and the values of the rough mean $\bar{Q}_i$ are calculated, and the results are listed in Table 5. Comparing the size of the values, the optimum scheme is selected.

Table 5 Values of $\left[S_i^L, S_i^U\right]$, $\left[R_i^L, R_i^U\right]$ and $\left[Q_i^L, Q_i^U\right]$

Scheme	$\left[S_i^L, S_i^U\right]$	$\left[R_i^L, R_i^U\right]$	$\left[Q_i^L, Q_i^U\right]$	$\bar{Q}_i$	Sequence
A_1	[0.296,852]	[0.183,0.410]	[0.067,1]	0.534	3
A_2	[0.183,0.424]	[0.280,0.302]	[0.298,0.458]	0.378	2
A_3	[0.407,0.580]	[0.250,0.295]	[0.312,0.362]	0.337	1

Based on the analysis results, the scheme is ranked as A3 > A2 > A1. A3 is the optimum scheme, thereby forming a schematic diagram of the conceptual scheme A3. The detailed design structure corresponding to the scheme A3 realizes the speed coupling of the mechanical and hydraulic transmission through the differential gear train. It also uses the variable pump to adjust the displacement of the hydraulic system realizing the change in the rotational speed. The oil quantity of the hydraulic system is output from the height adjusting pump, solving the problem that the space is excessive in schemes A1 and A2, which use gear shifting and a variable frequency motor. In scheme A3, when the hydraulic circuit connecting the hydraulic motor fails, the gear transmission of the cutting section can still work normally. However, in schemes A1 and A2, when the shifting part fails, the drum will be shut down. There is a relief valve avoiding the overload damage of the cutting motor in scheme A3, but schemes A1 and A2 cannot guarantee the safety of the cutting because of the lack of an overload safety device.

6 Conclusions

In this study, quantitative selection method of product conceptual scheme based on bond graph is introduced. The bond graph model and its corresponding AMESim model for conceptual scheme are constructed by the mapping analysis among effects, bond elements and AMESim element. The simulation result of AMESim verifies function feasibility judgment and performance analysis of the scheme, which helps to eliminate infeasible schemes that do not meet functional requirements. Finally, VIKOR is used to sort the schemes selecting the optimum feasible scheme. The quantitative simulation data and qualitative expert evaluation are integrated into the selection process. The scheme A3 is selected to be the optimum conceptual scheme of transmission system, which verifies the effectiveness of the proposed method.

7 Declaration

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Not applicable

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Availability of data and materials

The datasets supporting the conclusions of this article are included within the article.

Authors' contributions

The author' contributions are as follows: SJ was in charge of the whole trial; QX wrote the manuscript; JL gave advice on the structure of the paper; JW studied the software used in the paper; LJ researched to obtain raw data; TS assisted with simulation analyses; XP substantively revised it.

Competing interests

The authors declare no competing financial interests.

Consent for publication

Not applicable

Ethics approval and consent to participate

Not applicable

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Figures

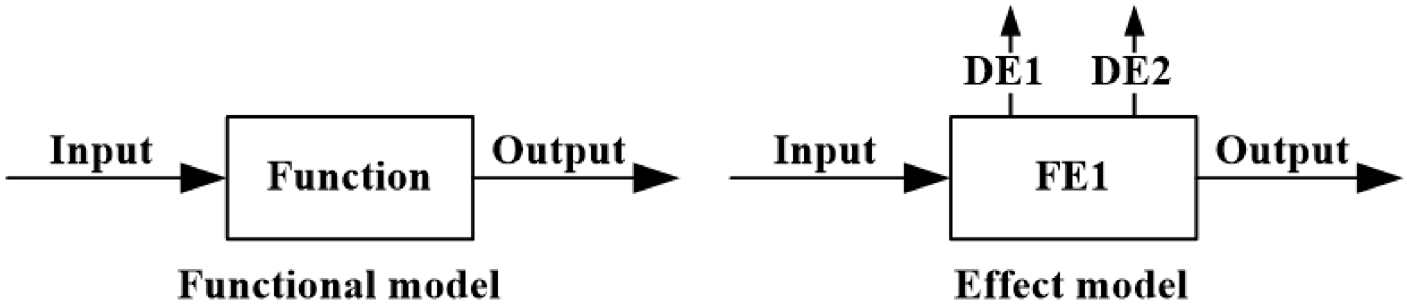

Figure 1

Functional expression and effect description model

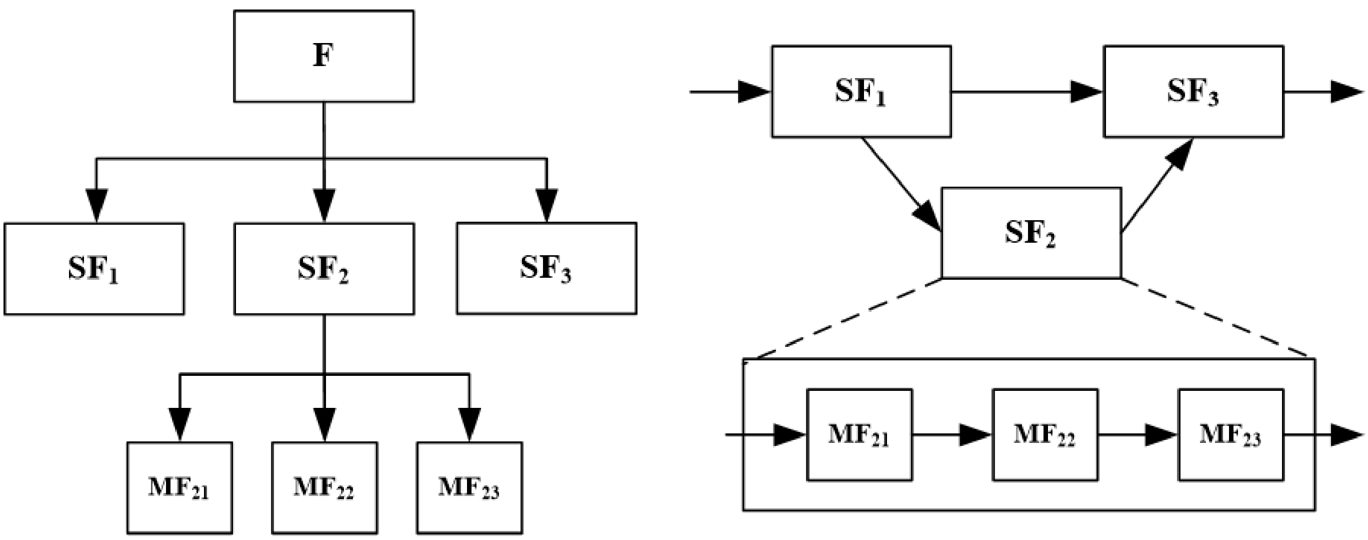

Figure 2

Functional decomposition tree and functional structure model

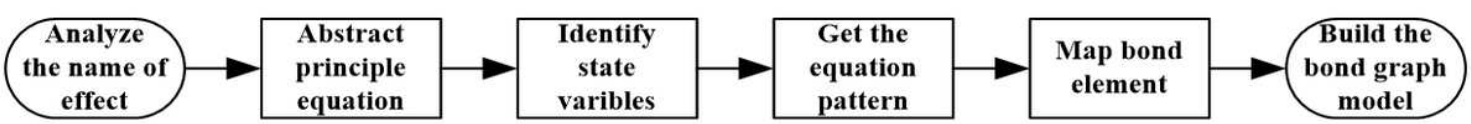

Figure 3

Process of bond graph model construction

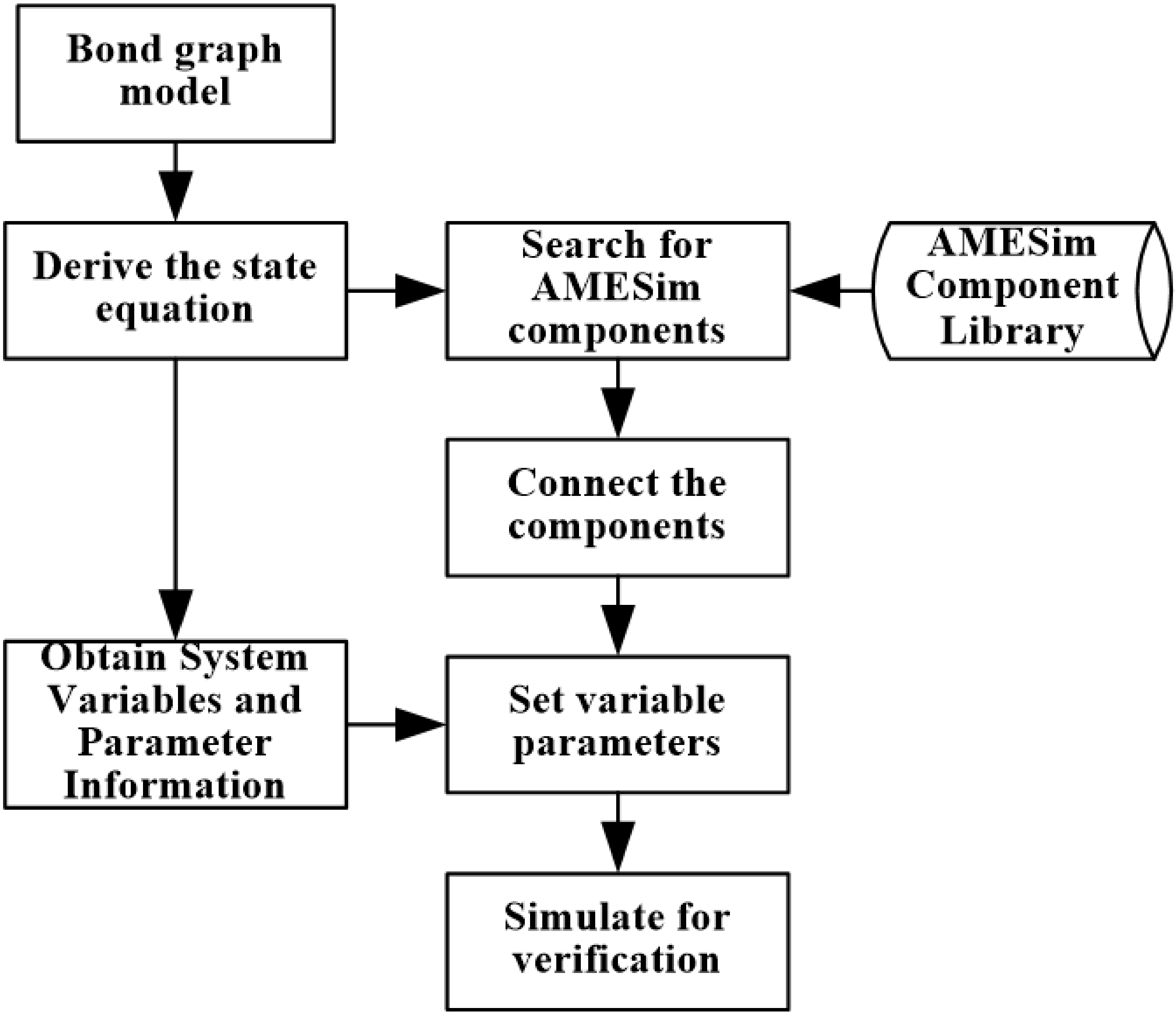

Figure 4

Process of AMESim modeling based on bond graph model

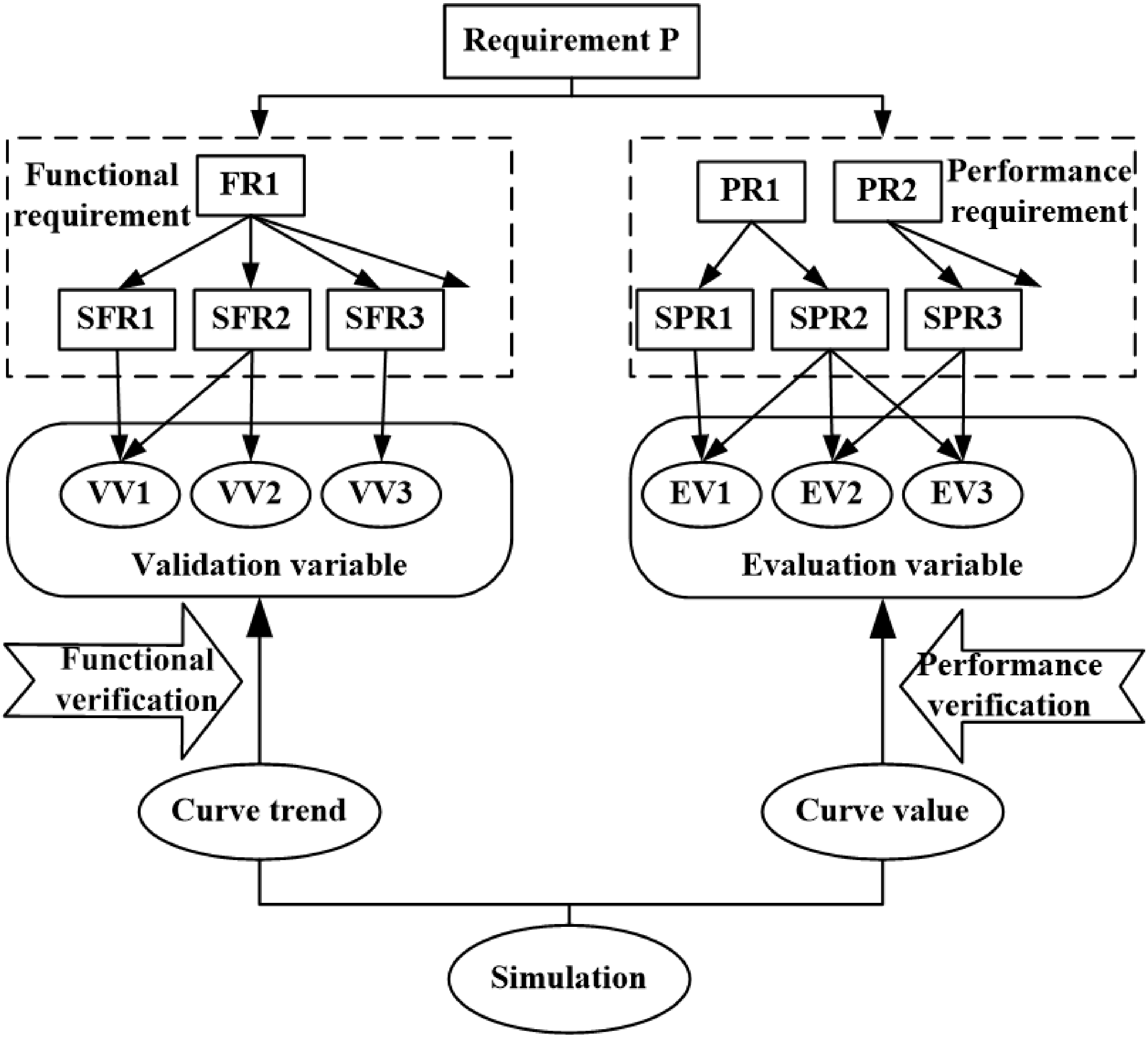

Figure 5

Functional and performance verification process of schemes based on requirements

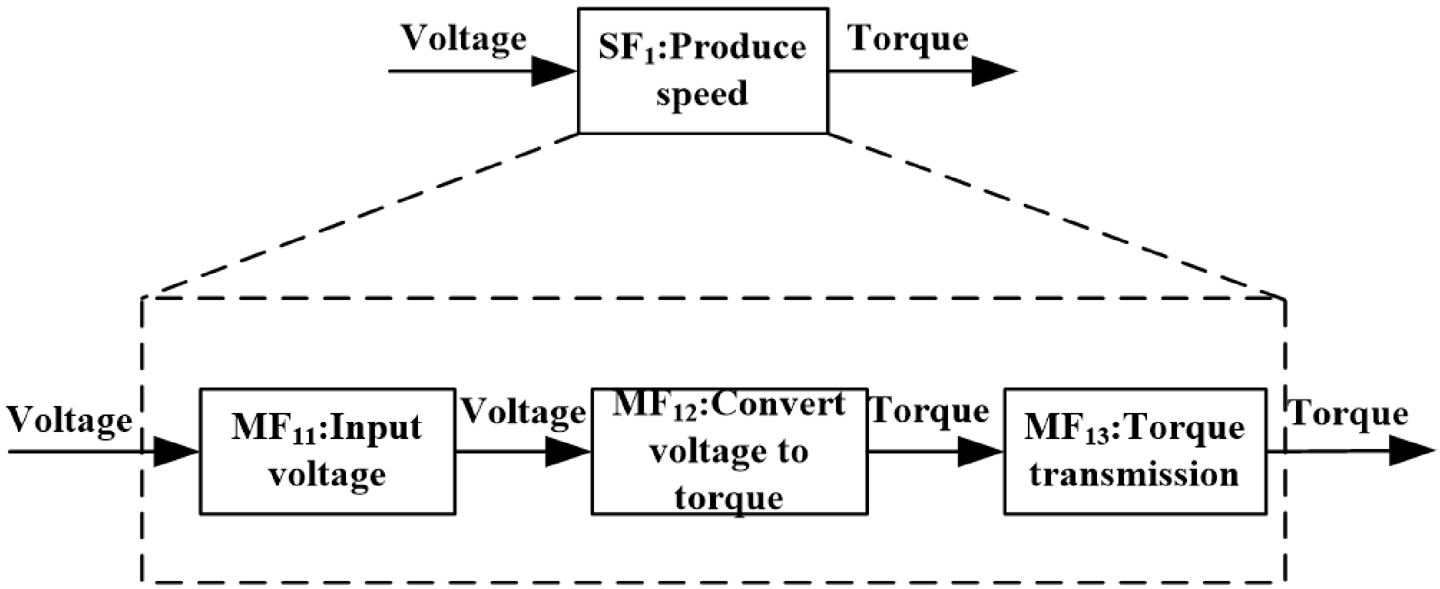

Figure 6

Functional structure model of the cutting motor

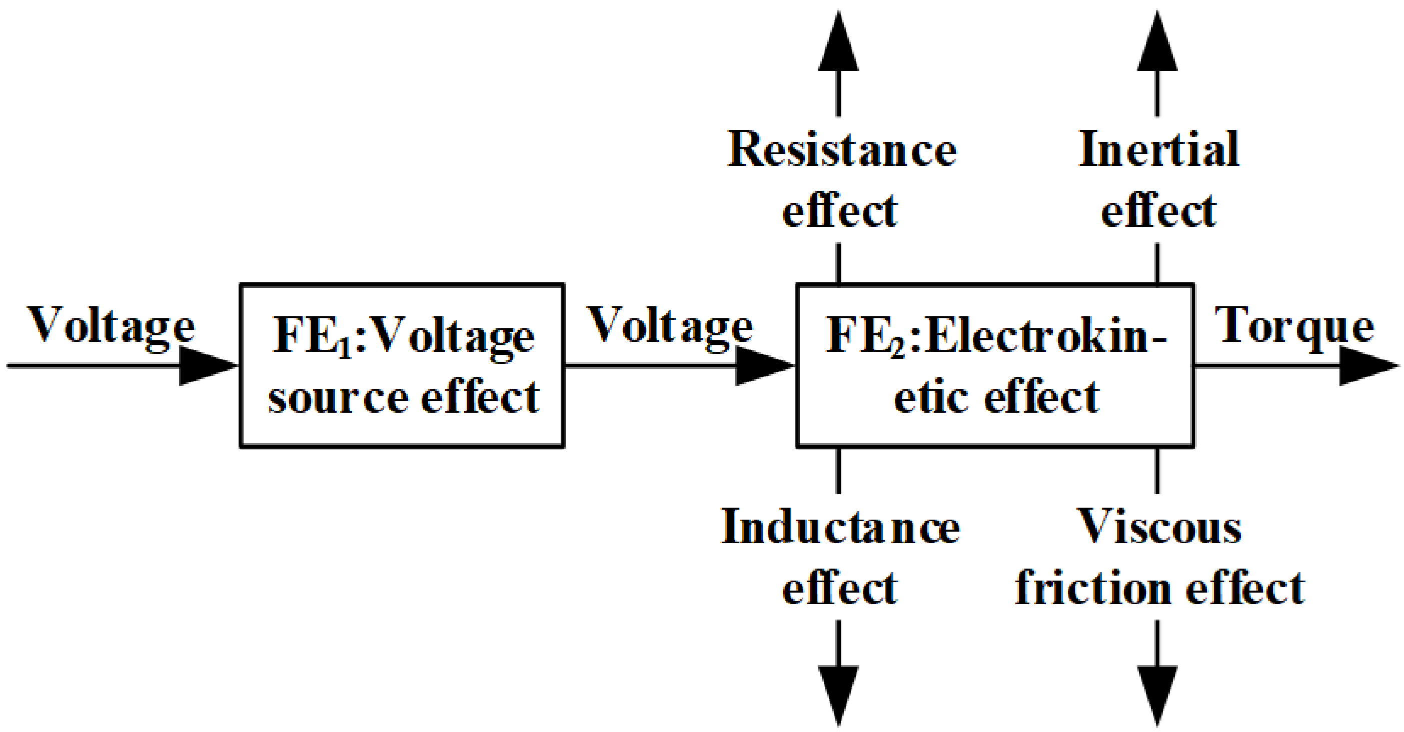

Figure 7

Effect model of the cutting motor

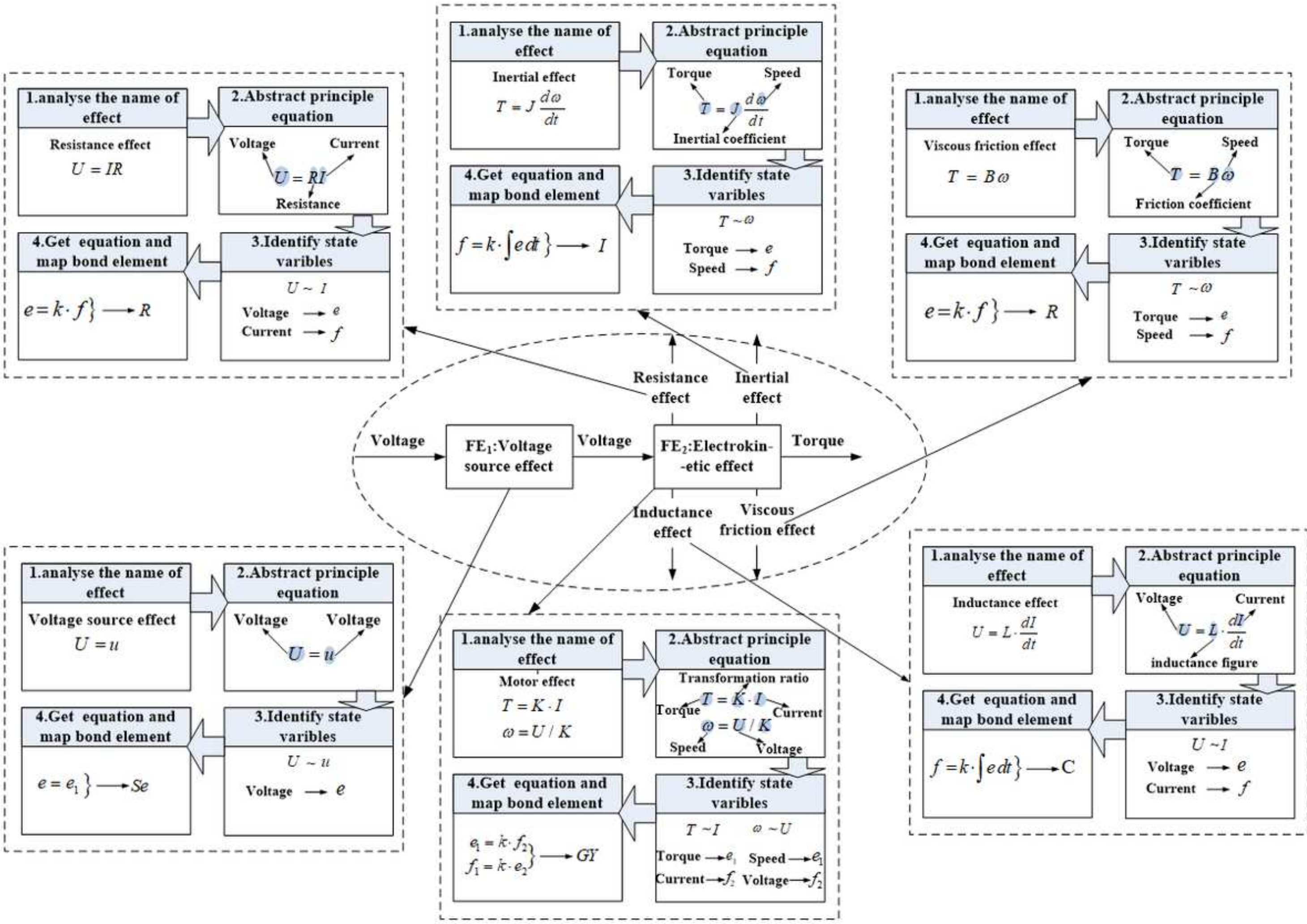

Figure 8

Bond element matching process for cutting motor

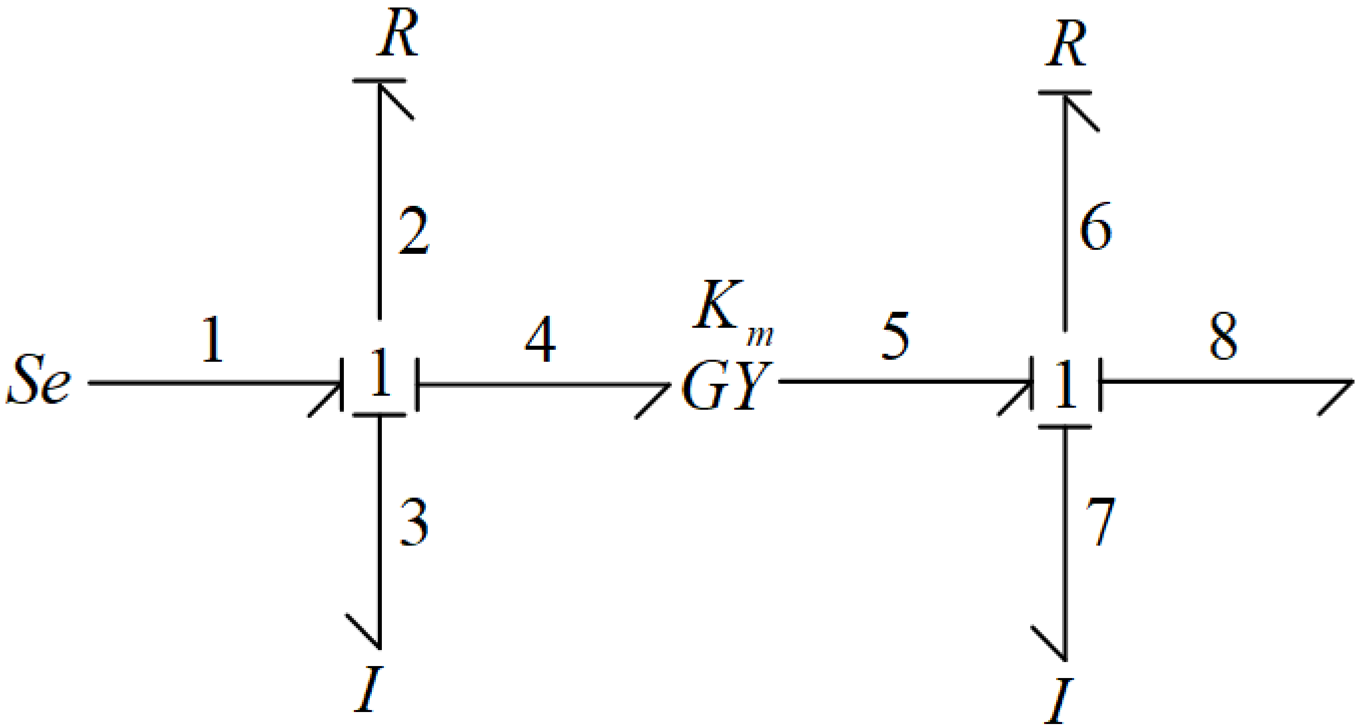

Figure 9

Bond graph model of the cutting motor

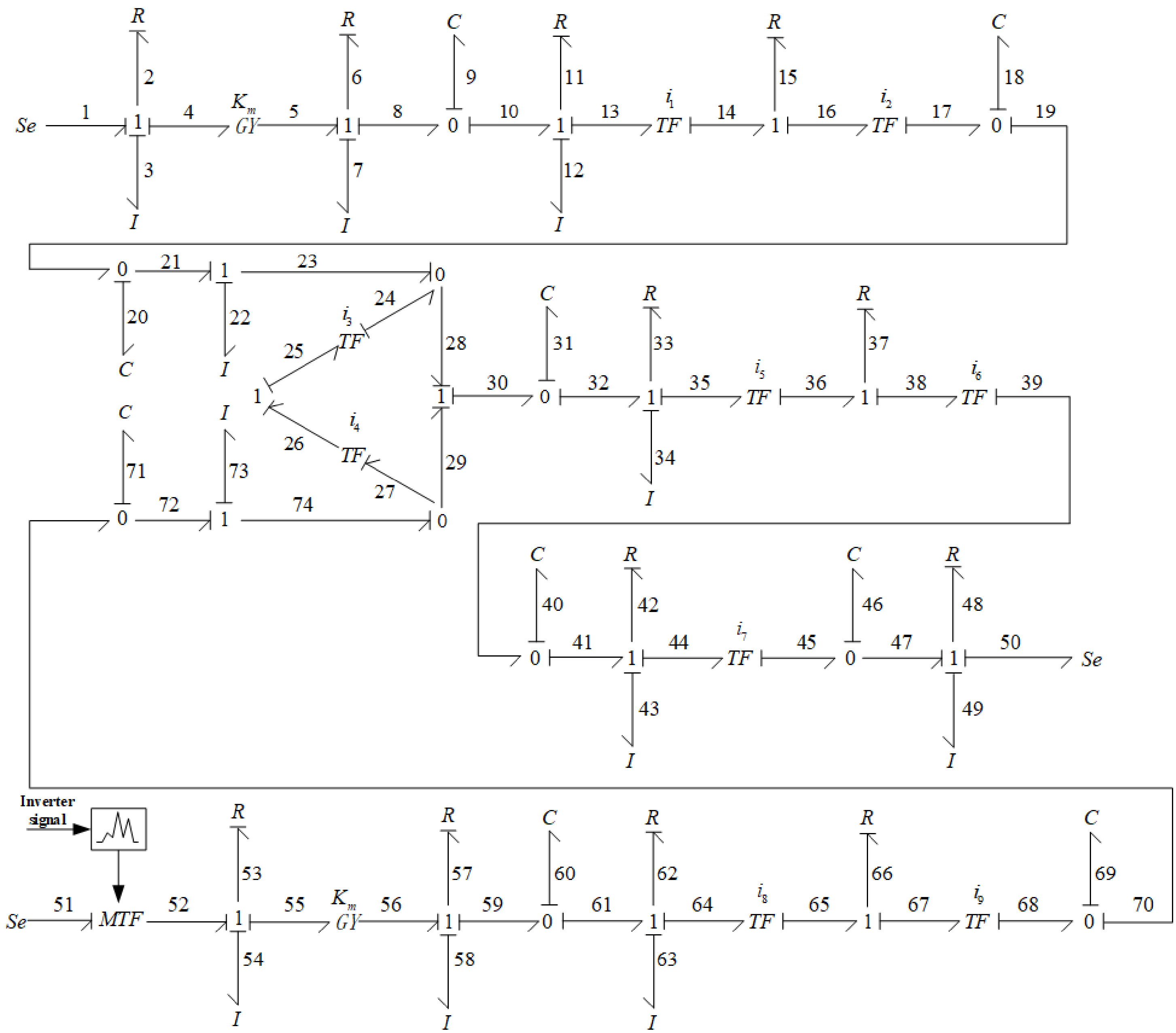

Figure 10

Bond graph model of CVSD-A1

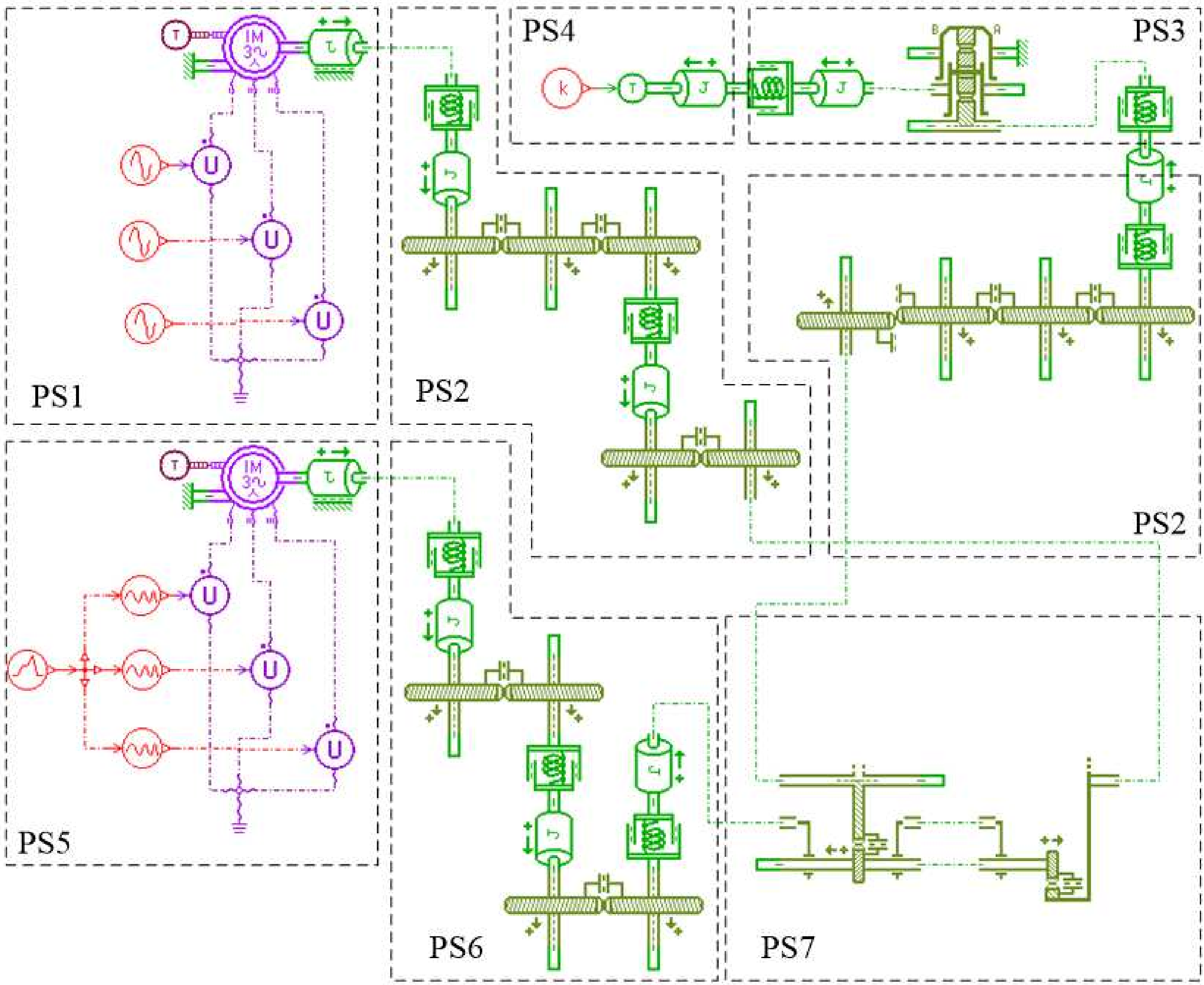

Figure 11

AMESim simulation model of CVSD-A1

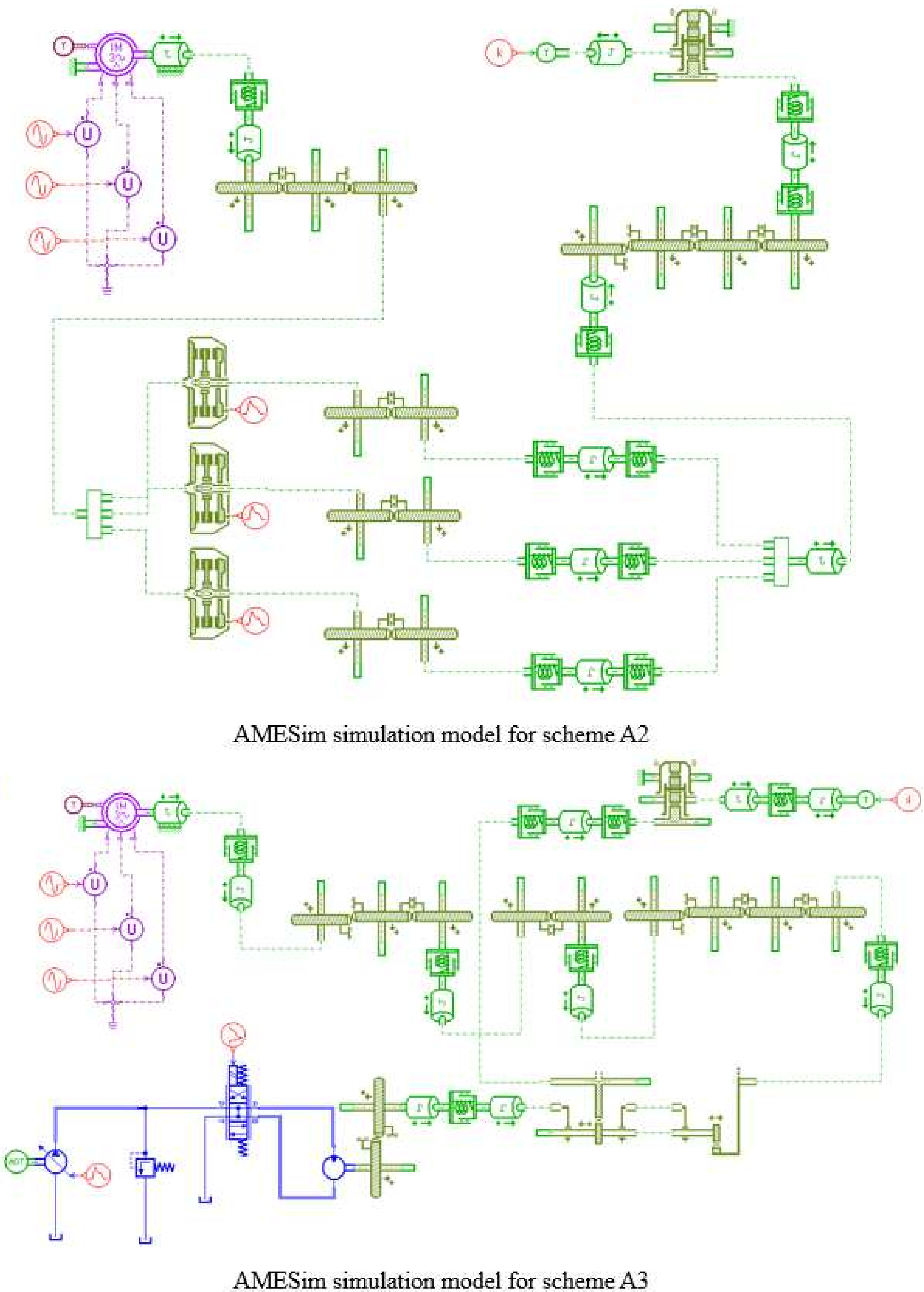

Figure 12

AMESim model implementation of schemes A2 and A3

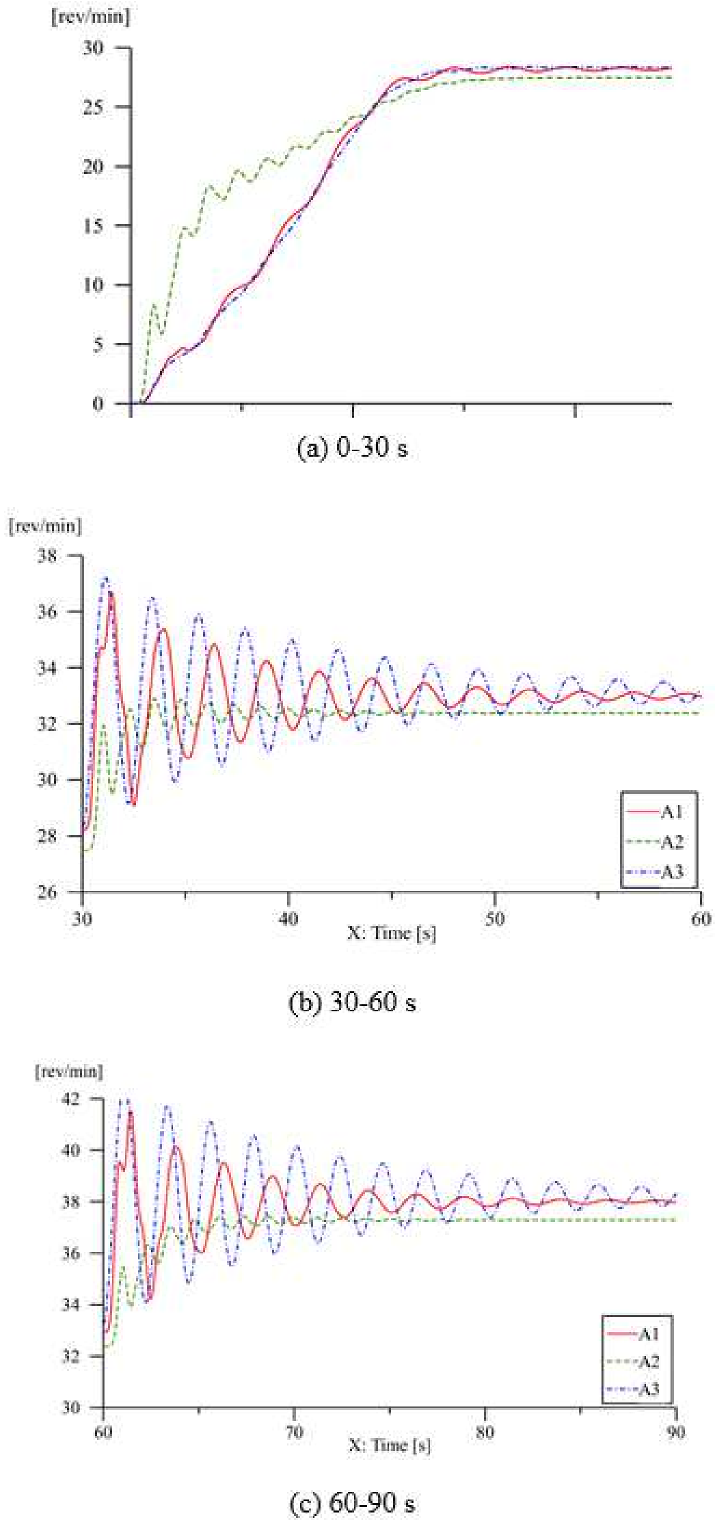

Figure 13

Drum speed-time relationship of the three conceptual schemes