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Function aggregation of new heavy load high voltage circuit breaker based on axiomatic design

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Abstract

To unify the design process of complex products to meet higher function and performance demands, a practical implementation for a new heavy load high voltage circuit breaker is presented. This paper analyzes the function and performance of a new heavy load high voltage circuit breaker, and addressed needs of being quick, accurate and stable. The superiority of the physical functional basis description method over the traditional functional basis model was demonstrated. The axiomatic design theory is described systematically and in detail using the function decomposition of the high voltage circuit breaker as an example. The concept of functional aggregation unit as the extension and expansion of axiomatic design theory is presented. This aggregation unit extracts essential characteristics of function and performance separately from their concrete structures, avoiding limits of the spring operating mechanism structure caused by reliance on a conventional structure. This function aggregation design method is presented for the design of a transmission unit. These results are of great theoretical significance to guide product innovation based on functional aggregation in axiomatic design theory.

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Keywords: Axiomatic design; High-voltage circuit breaker; Functional aggregation; Physical functional basis

1. Introduction

A high voltage circuit breaker (HVCB) is a breaker used in 3KV or higher power system. HVCB is an important control and protection equipment used in a power system to open and close the contact via a spring operation mechanism to effectively control and protect power transmission lines and electrical components [1,2]. To meet the needs of Chinese economic development and the increasing demands for electricity, the functional performance of HVCB must continuously improve. Once the power system fails or needs to change the mode of operation, the circuit breaker must respond accurately within tens of milliseconds[3,4]. Therefore, continued research on circuit breaker conceptual design method for with various functional requirements is of great importance.

Axiomatic design (AD) theory provides a guiding framework for product design and development that can guide the design process[5-7]. Gonçalves-Coelho[8] showed that AD stimulates group collaboration to determine the most cost-effective solution for the specified FRs. Mabrok[9] presented an extended design matrix that included the mapping of a complete set of requirements and the corresponding design parameters. Tan Zhang[10] developed a resilient robot based on AD theory. Thompson[11] introduced a model to integrate the traditional process requirements into AD theory and proposed a method to structure the requirements. Harutunian[12] provided a framework to describe design objects and a set of axioms to evaluate the relationships between specified functions (FRs) and the means to achieve these functions (DPs). AD theory[13,14] is one of the most frequently used methodologies in the design process. AD theory also plays an important role in software system design[15-17], product design[18,19] and solving engineering problems[20-23].

Functional analysis is part of the overall product design process[24]. Function is the basis of AD theory and an important attribute of product expression. Functional description plays a pivotal role in the whole product design process. Therefore, we propose the functional aggregation

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method to combine the function and the design process based on AD theory to guide HVCB design.

This paper is organized as follows. The comparison between the traditional functional basis and physical functional basis is presented and demonstrates the superiority of the physical functional basis description method in section 2. The major function decomposition of a new heavy load HVCB based on the physical functional basis was conducted. Section 3 presents the mapping process between FRs and DPs on the second layer, which extends AD theory by using the function decomposition of HVCB. In Section 4, we introduce the concept of the functional aggregation unit as the extension and expansion of AD theory. The functional aggregation design of the transmission unit is used to elaborate the function aggregation design method. Finally, our conclusions are summarized in section 5.

2. Function description and physical functional basis model of HVCB

2.1.Function description

A new type of heavy load HVCB can endure 550KV or higher voltage level, and the closing spring operating power of new HVCB is nearly 6KN, almost twice as much as the traditional circuit breaker. Additionally, the new type HVCB has more than 300 components and fast closing speed and requires endurance of a bigger closing impact. The structure of the HVCB is shown in Fig.1(a) and the physical model is shown in Fig.1(b).

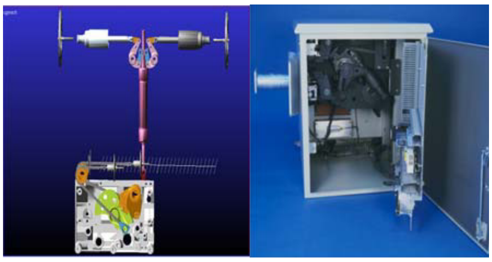

Fig. 1. (a) The structure of HVCB; (b) Physical model

The new type heavy load HVCB has special functional demands, requiring performance that is “quick, accurate, and stable”. The constraint of velocity and time during closing and opening process must be quick. Specifically, the opening time must be limited to 15 ~ 30ms, the opening speed must be limited to 7.8 ~ 9.2m/s, the closing time must be limited to 50 ~ 100ms, and the closing speed must be limited to 3 ~ 4m/s. "Accurate" describes the constraint of movement position and movement gait. The maximum allowable misalignment of the brake latch's movement position is 0.1mm. The beginning and end position of the brake latch require precise localization, so the mechanism should be able to be locked in a fixed position without the risk of tripping. "Stable" describes the need for stability of the movement process, as the maximum amplitude of the contact is 20mm. This requires small vibration to the contact and high reliability of reciprocating running to make sure the working life of all the components can work at least 50000 hours.

2.2.Physical functional basis

As shown in Fig.2, the traditional design process regards the product object as a whole and defines the interrelation between design object and external environment by inputs and outputs. This design process is like a "black box" in which the internal structure cannot be observed directly, but only by studying the object from the outside. Therefore, the design process is obscure and confused.

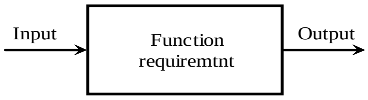

Fig. 2. Traditional functional basis model

The physical functional basis model expands the single input and output to the input and output of energy, substance, and information. This model can achieve the unified representation of functional knowledge in the product design cycle by establishing an ontology expression model of physical functional basis.

Function describes the relationship between energy, substance, and information. For product function, the terminologies used to reflect the essential characteristics of mechanism and the movement principle are the physical function basis PFB[25], design parameters DP, and functional goals FR. Together, these elements reflect the essential characteristics of function.

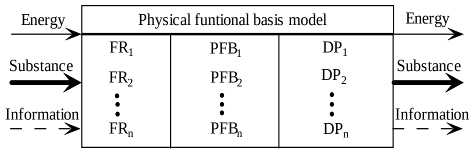

Fig. 3. Physical functional basis model

However, the functional basis only signifies the function category, but does not include the quantized requirements that play an integral role for the functional object in the design process. Each functional object of the product is associated with corresponding physical functional basis. Meanwhile, the source and design objective of each functional object are associated with a certain function carrier. Each function corresponds to one or more design parameters and there is a coupling relationship between the function and design parameters. As shown in Fig.3, by establishing a physical functional basis to unify the design standard, the function can be achieved by the combination of several functional components in a certain relationship. In this way, the designer can decouple the design of a certain product to facilitate the design process.

Tab.1 shows the major function decomposition of HVCB based on the physical functional basis. To describe the functional characteristics FR_1, we used "Electric power dQ → Mechanical power dW" to produce mechanical energy. For functional characteristics FR_2, we used "Electric power dQ → Mechanical power dW" to transfer mechanical energy. Physical functional basis decomposition is used to obtain a group of possible solutions for the major function of HVCB spring operating mechanism. The use of a spring energy storage mechanism to provide and store the original energy for the whole operation mechanism was selected, because a compression spring can bear a heavy load, store large mechanical power, for lower cost. Additionally, under the same conditions, the stiffness and reliability of the spring steel are much higher than other materials. We used compressed air contact to transfer the mechanical energy and interrupt the arc because compressed air is harmless to humans and inexpensive.

Table. 1. Major functional decomposition of HVCB based on the physical functional basis

FRx	Physical functional basis decomposition		Potential solution	Final solution
FR_1	Natural language expression	Provide and store the original energy for whole operation mechanism	Mechanism: Hydraulic energy storage, Spring energy storage, Motor energy storage, Electromagnetic energy storage	Spring energy storage
	Physical expression	Produce mechanical energy		
	PFB expression	Electric power dQ→Mechanical power dW		
FR_2	Natural language expression	Transfer mechanical energy to the operating mechanism contact	Arc interrupter： SF6 gas contact, Compressed air contact, Magnetic blow-out contact	Compressed air contact
	Physical expression	Transfer mechanical energy		
	PFB expression	Force F→ Displacement s		

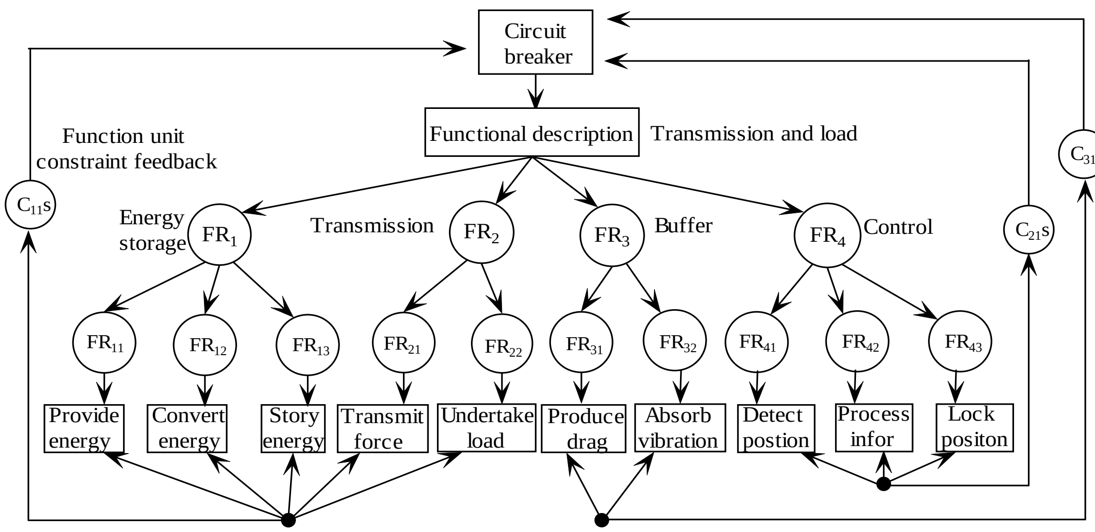

Fig. 4. Functional decomposition model of circuit breaker

3. Functional decomposition of HVCB based on AD theory

Based on AD theory, we described the overall functional requirements of the new heavy load HVCB's spring operating mechanism. By functional analysis, kinematics analysis, and dynamic analysis, we mapped the high level functional requirements and design parameters.

By continuous refinement and decomposition of FR and DP, we established a layer upon layer mapping framework from the functional domain to the structural domain of HVCB. The coupled design and layer upon layer mapping relationship is the research focus in the design process and serves as the main research target of the conceptual design of new heavy load HVCBs.

As shown in Fig.4, the primary function of new heavy load HVCB is to complete the transmission and load. This can be divided into four components that provide energy storage, transmission, buffering, and the control system.

As shown in Tab.2, $C11s$ mainly limits the functional units FR_1 and FR_2. To meet the requirements of speed and time, the energy storage system must provide sufficient power for the execution unit to allow faster response and higher sensitivity. $C21s$ limits the functional unit FR_4. To ensure the maximum allowable misalignment of location accuracy is 0.1mm, the locking mechanism must be appropriately locked in a fixed position without the risk of tripping. $C31s$ limit the functional unit FR_3. To limit the maximum amplitude within 20mm, the buffer mechanism must provide sufficient buffer resistance to reduce the vibration from the spring operating mechanism.

Table. 2. Functional constraints of new HVCB

Property	Constraint Index	Constraint description	Influence FRx 1	2	3	4
Speed and time	C11s	Opening time 15 ~ 30ms, opening speed 7.8 ~ 9.2m/s.	—	—		
Location accuracy	C21s	The maximum allowable misalignment is 0.1mm.				—
Amplitude	C31s	The maximum amplitude is 20mm.			—	

Using FRs and DPs to construct hierarchical mapping of HVCB, the first layer design equation of FRs functional decomposition and DPs mapping is as follows:

$$\begin{pmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \end{pmatrix} = \begin{pmatrix} X & 0 & 0 & 0 \\ X & X & 0 & 0 \\ X & X & X & 0 \\ 0 & 0 & 0 & X \end{pmatrix} \begin{pmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \end{pmatrix} \qquad (1)$$

The design matrix shows the relationships between the FRs and DPs at the first layer can be decoupled, indicating the feasibility and correctness of this design. In the specific design equation of AD, 0 indicates that there is no coupling relationship between the functional requirements domain and the design parameters domain and X indicates that there is interaction between FRs and DPs. When the design matrix is a diagonal matrix, the design process is a non-coupling design. In contrast, a triangular matrix indicates that the design process is a decoupling design.

The FRs on the second layer must satisfy the DPs on the first layer. In a design of an energy storage system, an appropriate power source is needed to provide and convert energy and an appropriate power storage device is required to provide energy conversion and storage. The transmission system requires an appropriate mechanism to transmit force and appropriate surface to undertake the load, described as an energy transmission function. The buffer system requires an appropriate device to generate resistance and constructed of appropriate material to absorb the vibration, providing an energy consumption function. The control system acts as the cerebral center of HVCB, and requires an appropriate sensor to detect movement position and an appropriate device to lock the system. Additionally, it needs appropriate control units to control the whole system, described as an energy control function.

The mapping process between the FRs and DPs on the second layer is shown in Tab.3.

Table. 3. The mapping process between FRs and DPs on the second layer

FRs	Function Description	DPs	Parameter Description
FR11	Provide Energy	DP11	Power Source
FR12	Convert Energy	DP12	Electrical Motor
FR13	Store Energy	DP13	Spring
FR21	Transmit Force	DP21	Chain
FR22	Undertake Load	DP22	Cam Contact Surface
FR31	Produce Drag	DP31	Buffer
FR32	Absorb Vibration	DP32	Hydraulic Oil
FR41	Detect Position	DP41	Displacement Sensor
FR42	Process Information	DP42	PLC
FR43	Lock Position	DP43	Brake Latch

The second layer design equations are as follows:

$$\begin{cases} \begin{pmatrix} FR_{11} \\ FR_{12} \\ FR_{13} \end{pmatrix} = \begin{pmatrix} X & 0 & 0 \\ X & X & 0 \\ X & X & X \end{pmatrix} \begin{pmatrix} DP_{11} \\ DP_{12} \\ DP_{13} \end{pmatrix} \\ \begin{pmatrix} FR_{21} \\ FR_{21} \end{pmatrix} = \begin{pmatrix} X & 0 \\ 0 & X \end{pmatrix} \begin{pmatrix} DP_{21} \\ DP_{22} \end{pmatrix} \\ \begin{pmatrix} FR_{31} \\ FR_{31} \end{pmatrix} = \begin{pmatrix} X & 0 \\ X & X \end{pmatrix} \begin{pmatrix} DP_{31} \\ DP_{32} \end{pmatrix} \\ \begin{pmatrix} FR_{41} \\ FR_{42} \\ FR_{43} \end{pmatrix} = \begin{pmatrix} X & 0 & 0 \\ X & X & 0 \\ X & 0 & X \end{pmatrix} \begin{pmatrix} DP_{41} \\ DP_{42} \\ DP_{43} \end{pmatrix} \end{cases} \qquad (2)$$

All design matrices of the second layer are a triangular matrix, so the design scheme of this layer as a decoupled design satisfies the independence axiom.

4. Functional aggregation unit model of transmission mechanism

During the conceptual design stage, designers mainly focus on the realization of function. To establish an effective correlation between function and structure, the essential structural characteristics are extracted from different parts that provide the same function. This information is used to produce a geometric model of functions and structures and consists of a group of units. We then define the structure collection that can independently transmit function as a strongly connected structure to establish functional structure aggregation units.

The aggregation unit extracts essential characteristics of HVCB functional performance separately from their concrete structure. This process avoids limitations of the spring operating mechanism structure by using conventional structure.

Fig.5 shows the transmission part aggregation unit model. The transmission part should include input, output, positioning, and braking functions. To achieve this, the aggregation unit model is comprised of separate functional units capable of various functions: the output unit used to output power to the executive part, the input unit which is used to accept the power input, and the transmission unit which is used to transmit the energy. These individual units together provide all necessary functions in the aggregation unit model.

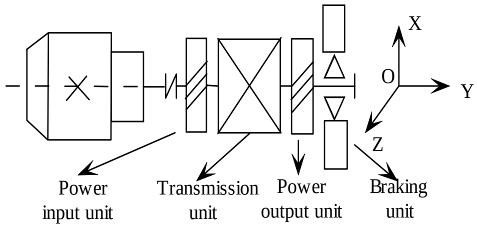

Fig. 5. Transmission part aggregation unit model

The aggregation unit model has expandability in structure. As shown in Fig.6, by extending the input unit, output unit and transmission unit, this model can associate each unit with a designed part to establish a one-to-one, one-to-many, many-to-one, or many-to-many relationship. For example, in the complex process of designing HVCB, the transmission unit can be mapped to a combination of connecting rod and chain mechanisms.

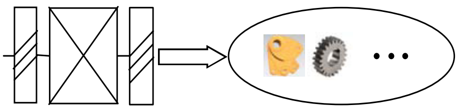

Fig. 6. Correspondence between transmission unit and part

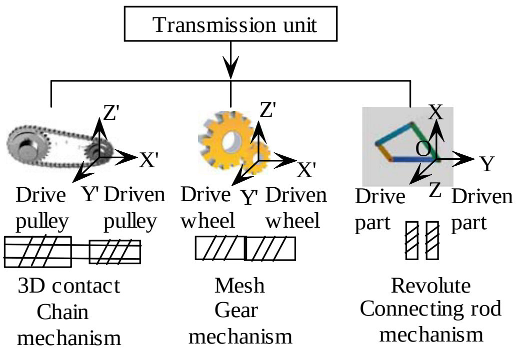

Fig. 7. Functional aggregation design of transmission unit

The functional aggregation design of the transmission unit is shown in Fig.7. The transmission unit can be subdivided into the chain transmission mechanism, gear transmission mechanism, and connecting rod transmission mechanism. The input and output unit of the chain transmission mechanism can be mapped to the drive and driven pulleys and the transmission unit can be mapped to the 3D contact. The gear mechanism is similar. The input and output unit of the connecting rod transmission mechanism can be mapped to an active part and a passive part and the transmission unit can be mapped to revolute. In this way, a designer can obtain the final design by the extension of layers in the functional unit.

Because the aggregation unit is a collection of functional units, it is more easily extended and is more specific than a traditional functional decomposition method that relies on functional description and structural expression. This method can solve the problem of multiple solutions between function and structure mapping to facilitate the conceptual design of HVCB.

5. Conclusions and Future Works

The paper analyzes the applications of HVCB and suggests the importance of focusing on the design method for new type HVCB. We next analyzed the functional and performance demands of HVCB to be “quick, accurate and stable”, and proposes a standard expression of functions, constraints, and characteristics. The physical functional basis model of the spring-operating mechanism is described as well as its ontology representation strategy. Next, we analyzed the differences between description on a traditional functional basis and description based on physical functionality. The major function decomposition of HVCB based on a physical functional basis model serves to illustrate and advance this functionality-based description method.

By using the first and second layer function decomposition of the high voltage circuit breaker as an example, AD theory is described in detail in this paper. We introduced the concept of a functional aggregation unit as the extension and expansion of AD theory. This aggregation unit extracts the essential functional and performance characteristics independently from their concrete structures, thus avoiding limitations from the use of conventional structure. The fundamental theory of functional aggregation design was illustrated using the design of a transmission unit.

To unify and standardize the design process of complex products in order to meet higher functional and performance demands, we proposed a good practical implementation for the designed new heavy load HVCB. The study results are of great theoretical significance to guide product innovation based on functional aggregation under the axiomatic design theory and method.

The future directions of this study will continue theoretical research to strengthen the foundation of the new approach to further promote the functional aggregation design method. Meanwhile, we will continue to modify the functional aggregation frame structure to improve the generality and adaptability of the aggregation unit. Additional experiments studying HVCB are also needed to demonstrate the validity of the function aggregation theoretical design method.

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