An Intelligent Control-Based Vacuum Circuit Breaker with Permanent Magnet and Dynamic Characteristic Analysis

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In the transmission and distribution of energy, circuit breaker plays a very important role. In order to fulfill the current market/user demands, they must be capable of promptly identifying the problem and isolating the problematic areas. According to the extinguishing medium used, circuit breakers are divided into the following categories: air blast, SF6, vacuum, and oil. Among others, permanent magnet (PM) based vacuum circuit breaker is also gaining popularity with each passing day and has become a crucial control and protection equipment in the modern power systems. This study proposes the pulse width modulation (PWM) intelligent control strategy for PM vacuum circuit breaker closing/opening capacitance, group charging, and movement process. For the practical implementation of this idea, dual CPUs are utilized for PM vacuum circuit breaker intelligent control components, by taking STM32F103RBT6 as the core and combining peripheral hardware circuit. PWM pulse output drives IGBT to fulfill the closing/opening capacitance group intelligent charging. On the other hand, PM circuit breaker closing/opening motion displacement signals and coil current feedback achieve closed-loop for PWM intelligent control. The experimental results show that the proposed intelligent control component and PWM intelligent control strategy effectively improve the PM circuit breaker intelligent charging and motion dynamic characteristics.

1. Introduction

With the growth of contemporary technology, particularly electronics, people’s reliance on energy is growing continuously [1]. As a result, the current power systems are facing serious challenges like dealing with huge currents and ensuring proper safety. In order to address these challenges, a smart and intelligent control system based on modern technology like a circuit breaker is needed. Circuit breakers play a crucial role in the transmission and distribution of electricity nowadays. These circuit breakers need to have enough intelligence, in order to identify the fault and isolate the defective sections quickly and clearly. Every circuit breaker should be built in a way that fulfills some basic criteria including interrupt at zero natural current, enduring dielectric stresses generated by interruption, and thermal interruption requirement. Circuit breakers are categorized as air blast, SF6, vacuum, and oil according to the utilization of the extinguishing medium [2].

Compared with spring devices, the vacuum circuit breaker is popular in the power industry due to its high efficiency, interruption rate, and approximately 150-1000A/μs current rate-of-change (di/dt) [3]. PM vacuum circuit breakers get popularity in the recent past due to its role in the electrical industries. Because of its simpler structure, more concise driver components, less opening/closing time dispersity, better insulation and arc extinction, less weight, and a lower failure rate, its use is increasing with each passing day [4–9]. With the fast development in power electronic technology, intelligent control theory, and a microprocessor, the trend of intelligent control is directed toward PM vacuum circuit breakers.

Different researchers have worked on this topic and attained good results at both domestic and abroad levels. Huang et al. [10] have worked on the advancement of vacuum circuit breaker with a permanent magnet by addressing the difficulties of the traditional vacuum circuit breaker such as large current peak and long start-up time.
In synchronization operation and high-voltage switchgear, the utilization of vacuum circuit breakers is limited due to these flaws [11]. In order to overcome these problems, a novel drive circuit was developed that utilizes an auxiliary capacitor to drastically lower the flux of the holding force [12]. When the PM actuator is ready to turn on or off, a negative current is cycled in the relevant coil in the circuit. Another similar work on the self-actuating vacuum interrupter (SAVI) was proposed by Falkingham et al. [13]. According to the author’s claim, the proposed SAVI provides several advantages over the traditional designs that include the drive insulator, elimination of the bellows, and the creation of a switching device with no exterior moving components. These major gains are expected to result in a new generation of switchgear that is not limited by the traditional problems of an external mechanism.

The literature includes a lot of related work on the domain of PM vacuum circuit breakers; however, there are still some challenges that need to be addressed. Thus, it is important to study PM vacuum circuit breaker intelligent control technology to improve breaker dynamic characteristics, reliability, and service life [9, 10, 13, 14–18].

The basic contribution of this study is to design a dual CPU modular hardware and software architecture. The implementation of the PWM intelligent control for PM vacuum circuit breaker closing/opening capacitance charging and motion process. Finally, the design of a PM vacuum breaker intelligent control prototype and perform the experimental analysis. The experimental results show that PMW intelligent control algorithm effectively controls closing/opening capacitance charging current and coil current dynamic adjustment.

The rest of the paper is organized as follows: Section 2 of the paper gives an overview of the intelligent control components architecture. Section 3 is about the designing of different hardware components for an intelligent control system such as power supply and microprocessor. The required software that operates the designed hardware is discussed in Section 4 of the paper. Section 5 highlights the experimental setup and analysis of the result. Finally, Section 6 recaps the overall theme and findings of the paper.

2. Overview of the Intelligent Control Component Architecture

PM vacuum circuit breaker utilizes the STM32F103RBT6 as the core with dual CPU. One CPU monitors real-time voltage and current metrics for closing/opening capacitance and fulfills capacitance PMW intelligent charging control. While the other CPU monitors real-time motion displacement metrics for the PM operating device and performs the closing and opening process closed-loop control of the PM vacuum circuit breaker. The dual CPU architecture assigns distinct responsibilities to each core, therefore, increasing the control system’s speed and reliability. Figure 1 depicts the architecture of the intelligent control components system.

3. Intelligent Control System Hardware Design

3.1. Power Supply Circuit Design. The quality of the power supply directly impacts measurement precision and affects the general functionality and reliability of a system [19]. The proposed design of the power supply uses an integrated power module with high precision, low ripple wave, and strong short circuit protection capability. The power board and buck chopper are fed by alternating current (AC) from the voltage regulator output. The power board takes AC voltage in the range of 85–264 VAC as input and produces multiple level DC voltages as output. Buck chopper performs rectifier filter for alternating voltage from the voltage regulator and implements closing/opening capacitance intelligent charging via PWM control. The complete diagram of the power supply architecture is illustrated in Figure 2.

3.2. Microprocessor Control Circuit Design. STM32 is a 32-bit single-chip microcomputer (SCM) based on an advanced RISC machine (ARM) cortex with high performance, low power consumption, and cost. The proposed design uses STM32F103RBT6 with 128 K FLASH, 20 K RAM, 72 MHz highest clock frequency, high-speed PWM timer, and 4.5 Mbits/s USART serial port. STM32F103RBT6 hardware resources can support the functions of PM-based vacuum circuit breaker intelligent control module. Figure 3 shows the main diagram of the microprocessor control circuit architecture.

3.3. Closing/Opening Capacitance Voltage/Current Detection Circuit. For the detection of closing/opening capacity voltage, the linear optocoupler isolation technique is utilized with high precision of 0.1% and resistance of 1 MΩ and 10 KΩ to split voltage. High capacitance voltage is converted to low voltage signals and sent to STM32 for detection via isolation. Real-time capacitance-voltage metrics are obtained via calculation in STM32. Closing/opening capacitance-voltage detection shares the same isolation detection module, and time division detection is achieved via a relay switch. The closing/opening capacitor voltage detection circuit is shown in Figure 4.

When current \(I_f\) flows through light-emitting diode \(D_1\), its emitting light produces current \(I_1\) and \(I_2\), which are directly proportional to emitting light intensity. \(I_1\), \(I_2\), and \(I_3\) satisfy the following relation.

\[
I_1 = K_1 I_f, \quad (1)
\]

\[
I_2 = K_2 I_f, \quad (2)
\]

\[
K_3 = \frac{I_1}{I_2}, \quad (3)
\]

where \(K_1\) and \(K_2\) are the input and output current transmission ratios, with a typical value of \(\sim 0.5\%,\) and \(K_3\) represents a transmission gain.
Voltage detection circuit transmission gain is fixed via adjusting $R_9$ and $R_4$ ratio per virtual short circuit and virtual opening circuit characteristics infer the following relation.

\[ I_1 = \frac{V_{in}}{R_9}, \]  
\[ V_{out} = I_2R_4, \]  
\[ \frac{V_{out}}{V_{in}} = K_3 \left( \frac{R_9}{R_4} \right), \]  
\[ I_f = \frac{(VCC5 - V_{D1} - V_{O1})}{R_{10}}, \]

where $V_{D1}$ is the voltage across $D_1$, $V_{in}$ is the input voltage, $V_{O1}$ is the output LM1A output voltage, and $V_{out}$ is the output voltage of LM2A.

A CSM005A Hall current sensor is used for the detection of current. This sensor uses a double voltage power supply with a $\pm 12\,V \sim \pm 15\,V$ voltage range and $\pm 5\%$ voltage variance. The internal coil turn ratio is $N_1 : N_2 = 5 : 1000$, and Figure 5 depicts the current detection diagram. When current flows from $I^+$ to $I^-$, the current of the primary coil is detected by the secondary coil and generates output voltage via port M. It converts $R_{13}$ detected current to voltage and feeds it to STM32 for processing. A maximum precision value of 0.1% resistance is selected for $R_{43}$ to ensure detection precision. Voltage-regulator tube $D_{20}$ is used for voltage limiters to prevent high input current from the microprocessor damage. $R_{42}$ and $C_{41}$ fulfill passive low-pass filter and filters out high-frequency signal interference. If the input current is $I$ and the output voltage is $V_{out1}$, then, the following equation shows the process of output voltage generation.

\[ V_{out1} = I \times \frac{N_1}{N_2} \times R_{43}, \]

3.4. Motion and Displacement Detection Circuit Design. To implement touchless remote measuring, an MTI product LTS-120-40 standalone laser displacement sensor is selected.
Figure 3: Microprocessor control circuit architecture diagram.

Figure 4: Closing/opening capacitance-voltage detection circuit.
Because, it has high precision, high measuring speed, high measuring range, and strong anti-interference capability. Further, it takes a DC voltage of 24 v as an input. The measurement range is based on a distance of 120 mm from the sensor head, with a variability of 20 mm, thus, it provides a 40 mm measurement range. Its sampling rate is 40 kHz and its resolution is ±20 μm which can fulfill real-time detection requirements. The laser displacement sensor outputs the detected real-time displacement signal via the RS485 serial port. RS485 uses coil voltage differential signal negative logic, with logic 1 as +(2~6)V and logic 0 as -(2~6)V. As STM32 uses the TTL level, conversion is needed for the communication between RS485 and STM32. P2 is connected to the laser displacement sensor RS485 output port. 485_RX, 485_EN, and 485_TX are also connected to STM32 corresponding ports. The detected real-time displacement signal is fed into STM32 via its USART2 port. The RS485-TTL conversion module circuit diagram is shown in Figure 6.

3.5. IGBT Drive Circuit Design. This design uses an optoisolator drive circuit as shown in Figure 7. The drive circuit uses a dual power supply with port E as a shared ground for the supply of both voltage and R11 as an internal LED current restrictor. DZ3 and DZ2 are bidirectional voltage regulator tubes for the prevention of overvoltage damage to IGBT.

(i) When STM32 PA7 port has a high input level, the drive circuit outputs around - 8.7 V voltage to close IGBT

(ii) When a low input level feeds STM32 PA7 port, the drive circuit outputs around +15 V voltage to open IGBT

3.6. Filter Capacitor and Closing/Opening Capacitor Self-Discharge Circuit Design. The filter capacitor and closing/opening capacitance group have high residual voltage to cause a potential safety hazard when the system is down. The proposed design takes the residual voltage hazard into account and makes a large capacitance self-discharge circuit. Figure 8 shows this phenomenon in more detail. Figure 8(a) shows the filter and closing capacitor self-discharge circuit. When this circuit works, the TLP520 optocoupler opens and keeps triode T3 in saturation to close the switch. The relay U4 motion switch moves from closed contact to open contact in order to prevent the discharge of the circuit. Once the system is down, the relay resets to closing contact and triggers the discharge procedure via C2 and R37 which are parallel connections. C1 discharges via R37 until discharge fully completes. In the meantime, C1 does ground discharge until the store power of the capacitor is fully released via R18, D18, and R37. The C2 voltage is always higher than C1, but the series connection of diode D18 prevents charging from C2 to C1. Figure 8(b) shows the opening capacitor self-discharge circuit. During the working of the circuit, replay opening contact closes and closing contact opens. Port FZ- has no connection to GND_main. When the system becomes down, the relay closing contact is closed. IGBT ports G and E have short circuits, and the closing capacitance residual voltage discharges via an opening coil.

3.7. Closing/Opening Coil Drive Circuit Design. The PM vacum breaker closing/opening coil drive circuit is shown in Figure 9. Here, CF+ is a positive opening capacitor, GND_main is a ground circuit as well as a negative opening capacitor, and PD is a breaker opening coil. The diode D18 is an opening coil freewheel channel. Resistor R19 and voltage-regulator diode D9 splits the 24 V chip voltage into 15 V and 9 V, respectively. D3 is a 1N4739 voltage-regulator diode with a voltage of 9.1 V. Capacitors C6 and C64 are used for power storage and filtering. To prevent gate pole circuit failure or gate pole nonworking state (gate pole opening state) from destroying IGBT via the main circuit applied voltage, a 10 K resistance R22 is connected between the IGBT gate pole and emitter. STM32 PA6 port outputs low level and IGBT conducts. The opening capacitor discharges via the opening coil and the breaker opens.

4. Intelligent Control Module Software Design

4.1. Closing/Opening Capacitor PWM Intelligent Charging Software Design. PM vacuum circuit breaker intelligent control module uses the dual CPU control. One CPU monitors real-time closing/opening capacitor voltage and current. It runs a PWM control algorithm to fulfill closing/opening capacitance group PWM intelligent charging. The other CPU monitors real-time breaker motion device displacement.
Figure 7: IGBT drive circuit diagram.

(a) Filter and closing capacitor self-discharge circuit

(b) Opening capacitor self-discharge circuit

Figure 8: Filter and closing/opening capacitor self-discharge circuit.

Figure 9: Closing/opening coil drive circuit.
It implements closing/opening process closed-loop control via emitting PWM to control closing/opening device movement velocity. Figure 10 shows the flowchart of the closing/opening capacitor PWM intelligent charging control software. The microprocessor STM32 handles the current and voltage data via the real-time monitoring current/voltage metrics. Then, it uses a PWM control algorithm to output a rapidly changing duty cycle and controls the IGBT isolation drive circuit. Thus, it controls buck chopper to output variant current for the intelligent charging system.

**4.2. Closing/Opening Procedure Control Software Design.** The flowchart of the closing/opening procedure control software is shown in Figure 10. When the intelligent control module bootstraps, it reads the displacement data for baseline. Then, it subtracts the baseline from the next displacement data to get the displacement delta. The PM vacuum circuit breaker closing or opening state can also be obtained via the displacement signal. This is due to the fact that the displacement is relative to the iron core, and the closing/opening state can be inferred from displacement. The proposed design uses a laser displacement sensor to perform real-time sampling for PM vacuum circuit breaker motion device displacement during the closing/opening process. The displacement signal detected by the displacement sensor is handled via RS485-TTL conversion module and transmitted to STM32 in 57.6 bps baud. Once the receiving closing/opening signal is in process, the STM32 handles the displacement calculation and queries, the corresponding PWM control signal maps to each displacement in real-time. Later, the PWM control signal drives the IGBT switch via the TLP250-based IGBT drive circuit. It controls the flowed current volume via the IGBT closing/opening control circuit and further controls the electromagnetic force magnitude generated from closing/opening coils. Thus, it achieves the goal to control the velocity of PM vacuum circuit breaker motion device. The closing/opening process control software flow chart is shown in Figure 11.
5. Intelligent Control Module Experiments and Analysis

The PM vacuum circuit breaker prototype and intelligent control module is an important part of this study and is shown in Figure 12. The intelligent control module consists of a microprocessor, power circuit, 485-TTL conversion circuit, IGBT, IGBT drive circuit, and closing/opening capacitor PWM charging circuit. The voltage is closing/opening capacitance group charging voltage, and the oscilloscope shows closing/opening capacitance group PWM intelligent charging current wave.

Two control strategies (no control vs. PWM intelligent control) are used to test closing/opening capacitance group charging. The closing/opening capacitance group charging current wave is shown in Figure 13 (with the current value of 0.3A). Figure (a) shows the closing capacitance group charging current wave without control, while figure (b) shows the opening capacitance group charging current wave without control. On the other hand, figure (c) shows the closing capacitance group charging wave with PWM intelligent control while figure (d) shows the opening capacitance group charging wave with PWM intelligent control. The closing/opening capacitor group without control shows that...
the instant charging current value was high at ~1.45A, with a short duration and then dropped rapidly. In the PWM intelligent control-based closing/opening charging, the current value was stable at ~0.36A from the charging initial state to the final complete state.

The control tests for PM vacuum circuit breaker closing/opening procedure were performed in two strategies (no control vs. PWM intelligent control). Figure 14 shows the closing/opening coil current wave. Figure (a) is the closing coil current wave without control while figure (b) is the opening coil current wave without control. On the other hand, figure (c) is the closing coil current wave with PWM intelligent control while figure (d) is the opening coil current wave with PWM intelligent control. For the no control strategy, the closing and opening current peak value reaches ~40A and ~30A separately, with large current for a long duration. For PWM intelligent control, the closing and opening coil current peak values were ~37.5A and ~25.8A in movement process. The current control was remarkable, and the closing and opening motion velocity was also well controlled. Thus, it reduces breaker contact wear and greatly extends its service life.

6. Conclusion

In recent past, PM vacuum circuit breakers have gained popularity due to their simpler structure, less opening/closing time dispersity, and lower failure rate. Based on its PM operating device technology and intelligent control technology, this study proposes PM based vacuum circuit breaker intelligent control module. This study focuses on both the designing of hardware and software for the PM-based vacuum circuit breaker. The hardware parts include a dual CPU control module and modularity design pattern. To fulfill the software requirements, a self-charging PWM control algorithm is implemented for the breaker closing/opening capacitance group and closing/opening process closed-loop control. Besides this, the intelligent control module has built-in large bulk capacitor to support self-discharge functionality, and it also improves the circuit safety in filter capacitors and closing/opening capacitance group when the system goes down. In the software part, a modular structure and loop scanning mechanism are used to utilize the PMW intelligent control algorithm for breaker closing/opening capacitance charging and motion process. Finally, the prototype of the PM vacuum circuit breaker and intelligent control module was designed, and some experiments were performed to verify the performance of the proposed system. The experimental results show that the PWM intelligent control algorithm provides better control for closing/opening capacitance group charging current and also closing/opening coil current peak value during its motion process. Further, it also provides well-controlled mechanism for the velocity of the PM vacuum circuit breaker closing/opening motion, improves the closing/opening capacitance group service life, and enhances the performance of the circuit breaker.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflict of interest.

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