Modeling and simulation of a fuzzy heat distribution controlled high-voltage DC resistive divider

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Abstract
In order to improve quality in manufacturing, the measuring instruments used in production process should regularly be monitored and corrected according to international or national standards. Calibration of high-voltage equipment and precise measurements of DC high voltages are accomplished by standard voltage divider. Self-heating effect is the main error source of measurement in high-voltage DC resistive dividers. Therefore, precise control systems should be designed to keep stability of the ambient temperature and to regulate the heat distribution along the high-voltage DC resistive divider. For this purpose, a heat controlled resistive divider whose input voltage ($V_{in}$) is up to 5 kV was designed. This study is focused on heat convention and the dissipation model of the resistive divider and executes some control simulations under various conditions that aim to find the appropriate control method. Responses of the high-voltage DC resistive divider model are compared with and are validated by the responses of the designed actual system. The model provides us faster analyze and design solutions for novel methods. In this way, analyzing and controlling higher voltage dividers, such as 100 kV, will reduce just into a parameter change on the model. The fuzzy control method is suggested since the system dynamic has non-linear characteristics. Fuzzy temperature difference controller keeps temperature at a certain degree where fuzzy vertical temperature gradient controller keeps vertical temperature gradient around zero. Actual system and model responses for the fuzzy control are compared and interpreted.

Keywords
High-voltage DC resistive divider, self-heating, measurement uncertainty, heat control, fuzzy controller, heat and mass transfer model

Introduction
Resistive self-heating effects cause measurement uncertainties in high-voltage DC resistive divider (HVDC-ResDiv) systems.\textsuperscript{1,2} Calibration of equivalent measurement devices and precise measurements of DC HVs are realized by standard HVDC-ResDiv.\textsuperscript{3-5} HVDC-ResDiv designed for calibration of other reference systems should have a measurement uncertainty of less than 0.002%. Therefore, resistor modules’ thermal coefficients should be lowest, and temperature gradient caused by the self-heating should be reduced to reasonable levels.\textsuperscript{6} Power dissipation results in temperature difference (TD) in overall resistors and vertical temperature gradient (VTG) along the resistor block and significantly threatens precise measurements.\textsuperscript{7,8} Individual contribution of TD and VTG to the measurement uncertainties is emphasized in literature.\textsuperscript{1,3,7-10}

In this purpose, several TD control techniques are proposed in order to reduce TD errors.\textsuperscript{1,8,10} By means of a shielded structure of the resistors and TD control, a 2-ppm measurement uncertainty is achieved.\textsuperscript{10} Effects of noise rejection techniques and partial discharge measurements on HVDC cables should be investigated.\textsuperscript{11} Small-signal model of an HVDC system with angle control and an HVDC system with constant DC voltage control are proposed.\textsuperscript{12} Improvement in stability of HVDC systems by convenient control strategies is essential for providing standards.\textsuperscript{13,14}

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Mathematical modeling and simulation of heat and mass transfer offers definitely appropriate controller designs.\textsuperscript{15,16} Control method is getting important to maintain uncertainty arisen from heating around ppm levels.\textsuperscript{1,10} However, literature mention on neither TD nor VTG control methods. For this reason, an HVDC-ResDiv, which adjusts its TD and VTG by controllers and provides a consistent measurement, is realized.\textsuperscript{17}

Physical description and numerical calculation of a system’s heat and mass transfer characteristics under influence of temperature gradients allow us critical values of the temperature gradients and critical velocities of the convection. In the organization of complex systems, mathematical modeling and simulation are required.\textsuperscript{21} In this way, analyzing dissimilar operational modes could be possible, and statement of potential errors and their adjustment is achieved without additional costs of real conditions.\textsuperscript{22} Heat conduction model is commonly employed in analysis and designing of nano transistors. Simulations and improvements in the layer parameters could allow reducing self-heating effect and provide a considerable enhancement in the temperature performance of metal–oxide–semiconductor field-effect transistors (MOSFETs).\textsuperscript{23} Modeling HVDC systems provides more rapid and accurate designs that overcome the deficiencies, or combining and observing the advantages, of the previous systems.\textsuperscript{24–26}

Artificial intelligence is widely used as a method of self-heating control, feature extraction or classification of internal-corona-surface discharges in HVDC applications.\textsuperscript{27} Fuzzy-based systems provide effective controllers for uncertain non-linear systems.\textsuperscript{28} Application of fuzzy logic–based controllers on first- and second-order unknown non-linear systems is one of the state-of-art research studies on control theory.\textsuperscript{29,30}

In this study, heat conduction–convection and mass transfer model of the 5-kV HVDC-ResDiv is extracted: Heat conduction and energy equations are determined. General expression of system’s dynamic equations is given in terms of state-space equations and is converted to Simulink equivalent block model. A series of control simulations are realized under various conditions that aim to find the appropriate control method.

In the control of TD and VTG, fuzzy and proportional–integral–derivative (PID) methods are addressed. The study lies heavily on fuzzy inference systems (FISs) in order to satisfy non-linear relations\textsuperscript{31} of the HVDC-ResDiv control system. Fuzzy TD and fuzzy VTG controllers are developed, and the results for the actual system and the model are compared and interpreted.

Because of the non-linear system structure, proposed fuzzy control provides a contribution to accurate measurement of HVDCs. Each control experiment and returning of the system to initial conditions takes half of the hours of attendance. Modeling and simulation of the system accelerates design and parameter changes and allows rapid application of new control methods.

### Heat distribution controlled HVDC-ResDiv platform

Heat distribution control of the system is ensured by keeping TD at a constant degree and by reducing VTG around zero. In this purpose, a system composed of two chambers filled with transformer oil, a motor pump, Peltier effect heat pump (PHT) and their control software is designed (Figure 1). Transfer of the heat through the HVDC-ResDiv is carried out with both forced convection and conduction.\textsuperscript{32} Total resistors (TRs) are kept in heat producer cylinder tank (HPCyT) on the left, where \( Q_P \) (W), origin of TD, \( C \), and VTG, \( C \), is removed from cooling tank (CoT) on the right: circulation pump (CP) forces heated oil and convects \( Q_P \) to CoT and PHTs and cooling fans on the CoT transfer it to the outer ambiance.

Tupper and Tlower sensors of the HPCyT determine TD and VTG values (Figure 2), (equation (2)).

#### Features of the mentioned HVDC-ResDiv system are listed:\textsuperscript{17}
- \( V_{in} \) is up to 5 kV
- TR is \( 10 \, \text{M} \Omega \): \( 9 \times 1 \, \text{M} \Omega \) + \( 9 \times 100 \, \text{k} \Omega \) + \( 10 \times 10 \, \text{k} \Omega \)
- HV arm resistors: 9990 kΩ
- Low-voltage (LV) arm (output) resistor: \( R_{low} \): 10 kΩ
- Voltage division ratio (VDR): 1000:1
- Max \( V_o \): 5 V.

One of the most critical assisting tools in the analysis and design of measurement systems and measuring instrumentation is the mathematical modeling.\textsuperscript{33}
Heat conduction and convention model of the 5-kV HVDC-ResDiv

Extraction of mathematical model and its simulation, which allows analysis and evolution of various operating modes and behaviors of systems, is essential in the design of complex installations.34,35

Heat conduction and energy equations

$Q_P$ is about 2.5 W, and a trivial amount is stored in the resistors, and the rest is transferred to the liquid (Figure 1). When the temperature of the outer ambiance is cooler than the inner ambiance of the HPCyT, a certain part of the heat is transferred to the outer ambiance through the lateral surface of the tank. Another part of the heat is stored on the cylinder tank (CyT) and on the liquid. The rest is brought to the CoT by means of the CP. Similarly, the heat which arrived is stored in the liquid of the CoT and on its aluminum body. The rest is transferred from the system by means of PHTs. Heat is thrown from the heated surface of the PHT by forced convection which uses cooling fans. Related temperatures are given in the nomenclature.

The temperatures and heat conduction in the temperature controlled 5-kV HVDC-ResDiv system are illustrated in Figure 2.

General heat equation describes energy exchanges as follows (equation (1))

$$E_s = E_i - E_o + E_p$$  (1)

Assumptions:

1. In the experiments, $T_{OCyT}$ is accepted as average of $T_{Upper}$ and $T_{Lower}$ sensorial results (Figure 1). Thus

$$T_{Upper} + T_{Lower} = 2 \times T_{OCyT}$$  (2)

2. Referring to the experimental observations of the system (Figure 3), relation between difference of $T_{Upper}$ and $T_{Lower}$ and $V_m$ and $V_p$ is as follows (Figure 3).

According to observations given in Figure 3, a linear empiric approximation of $T_{Upper}/T_{Lower}$ as a function of $V_m$ and $V_p$ which provides the behavior of the $T_{Upper} - T_{Lower}$ dynamic is as follows

$$T_{Upper} - T_{Lower} \approx f(V_m, V_p)$$

$$= \left[(-0.15 \times V_m + 1) + (0.08 \times V_p - 0.56)\right] / 2$$  (3)

Solution of equations 2 and 3 yields

$$T_{Upper} = T_{OCyT} + \frac{f(V_m, V_p)}{2}$$  (4)

$$T_{Lower} = T_{OCyT} - \frac{f(V_m, V_p)}{2}$$  (5)

Heat distribution in the HPCyT. All heat expressions in this section refer to the quantity of heat in a unit time (W)

$$Q_P \approx 2.5$$  (6)

$$Q_{C1} = \frac{T_{S1} - T_{OCyT}}{R_1}$$  (7)

Referring to the direction of the motor pump, HPCyT will remove the heat $Q_{OCyT}$ and receives a heat of colder oil mass, $Q_{NOyT}$ (Figure 2). Let us define the net heat as
Heat distribution in the CyT

\[ Q_{net} = Q_{EOCyT} - Q_{ICyT} \]  

\[ Q_{C2} = \frac{T_{OCyT} - T_{S2}}{R_2} \]  

\[ Q_{EOCyT} = mc(T_{Lower} - T_{OCyT}) \]  

\[ Q_{ICyT} = mc(T_{OCyT} - T_{Upper}) \]  

\[ Q_{ICyT} = mc\left(\frac{f(V_m, V_p)}{2} - T_{OCyT}\right) \]  

\[ Q_{net} = mc\left(\frac{f(V_m, V_p)}{2} - T_{OCyT}\right) \]  

\[ -mc\left(T_{OCyT} - T_{OCyT} - \frac{f(V_m, V_p)}{2}\right) \]  

\[ Q_{net} = 2mc\left(T_{OCyT} - T_{OCyT}\right) \]  

\[ Q_{C3} = \frac{T_{S3} - T_{m}}{R_3} \]  

\[ Q_{t4} = \frac{T_{OCyT} - T_{S4}}{R_4} \]  

\[ Q_{t5} = \frac{T_k - T_{m}}{R_k} \]  

\[ Q_{t, c} = \frac{T_{S5} - T_C}{R_{2t, c}} \]  

\[ Q_{c} = P_{in} + Q_{C} \]  

\[ Q_{c} = Q_{max}\left(1 - \frac{T_h - T_c}{\Delta T_{max}}\right) \]  

Therefore

\[ C_{CyT} \frac{dT_{CyT}}{dt} = \frac{T_{OCyT} - T_{S2}}{R_2} = \frac{T_{S3} - T_{m}}{R_3} \]  

Heat distribution in the CyT. The net heat entering CoT will be equal to heat stored in the CyT and the heat removed from the HPCyT by forced convection. Stored heat of the fluid inside the CyT is described by the equation (28)

\[ C_{OCyT} \frac{dT_{OCyT}}{dt} = Q_{net} - Q_{t4} \]  

\[ C_{OCyT} \frac{dT_{OCyT}}{dt} = 2mc(T_{OCyT} - T_{OCyT}) - \frac{T_{OCyT} - T_{S4}}{R_4} \]  

- Heat stored in the body of the CyT is expressed by equation (30)

\[ C_{CyT} \frac{dT_{CyT}}{dt} = Q_{t4} - Q_{t, c} \]  

where

\[ C_{CyT} \frac{dT_{CyT}}{dt} = \frac{T_{OCyT} - T_{S4}}{R_4} - \frac{T_{S5} - T_C}{R_{2t, c}} \]  

Because \( R_{t, c} \) is too low, \( T_{S5} \cong T_C \) assumption could be acceptable. All the heat in the outer surface of CyT is completely transferred from \( T_c \) to \( T_k \). For this reason, \( Q_{c} \) can be used directly instead of the thermal load \( Q_{t, c} \) drawn by the Peltier from the system. \( Q_{t, c} \) is found in the catalog details of the Peltier (W).  

Thus, the modified form of equation (30) is as follows

\[ C_{CyT} \frac{dT_{CyT}}{dt} = Q_{t4} - Q_{C} \]  

\[ C_{CyT} \frac{dT_{CyT}}{dt} = \frac{T_{OCyT} - T_{S4}}{R_4} - \frac{T_{S5} - T_C}{R_{2t, c}} \]  

- Heat stored in the cooling fins

\[ C_{k} \frac{dT_k}{dt} = Q_{k} - Q_{t5} \]  

\[ C_{k} \frac{dT_k}{dt} = P_{in} + Q_{max}\left(1 - \frac{T_h - T_c}{\Delta T_{max}}\right) - \frac{T_k - T_{m}}{R_k} \]  

Expression of heat transitions in terms of state equations for the system is as follows.  

Assumptions

\[ x_1 = \frac{T_{TR} \cong T_{S1}}{R_1} \]  

\[ x_2 = T_{OCyT} \]
\[ x_3 = T_{CTY} \cong T_{S2} \cong T_{S3} \]  
(38) 
\[ x_4 = T_{OCaT} \]  
(39) 
\[ x_5 = T_{COT} \cong T_{S4} \cong T_{S5} \cong T_c \]  
(40) 
\[ x_6 = T_h \cong T_k \]  
(41) 

and the empiric equation for the temperature gradient is

\[ x_7 = T_{upper} - T_{lower} \]  
\[ = \left[ (-0.15 \ast V_m + 1) + (0.08 \ast V_p - 0.56) \right] / 2 \]  
(42)

HPCyT and CoT equations are expressed in terms of state variables, respectively

\[ \dot{x}_1 = \frac{Q_p}{C_{TR}} - \frac{x_1}{R_1 C_{TR}} + \frac{x_2}{R_1 C_{TR}} \]  
(43) 
\[ \dot{x}_2 = \frac{x_1}{R_1 C_{OCT}} - \frac{x_2}{C_{OCT}} \left( \frac{1}{R_1} + \frac{1}{R_2} + 2m_{CO} \right) x_2 + \frac{x_3}{R_2 C_{OCT}} \frac{2m_{CO} x_4}{C_{OCT}} \]  
(44) 
\[ \dot{x}_3 = -\frac{x_2}{R_3 C_{CTY}} - \frac{1}{R_3} \left( \frac{1}{R_2} + \frac{1}{R_3} \right) \frac{x_3}{C_{CTY}} + \frac{T_\infty}{R_3 C_{CTY}} \]  
(45)

And CoT equations become

\[ \dot{x}_4 = \frac{x_3}{R_3 C_{CTY}} - x_4 \frac{Q_{max}}{C_{OCT}} \]  
(46) 
\[ \dot{x}_5 = \frac{x_4}{R_4 C_{CTY}} - \frac{x_5}{R_4 C_{CTY}} \frac{Q_{max}}{C_{OCT}} \left( 1 - \frac{x_6 - x_5}{\Delta T_{max}} \right) \]  
(47) 
\[ \dot{x}_6 = \frac{P_m}{C_k} + \frac{Q_{max}}{C_k} \left( 1 - \frac{x_6 - x_5}{\Delta T_{max}} \right) \]  
(48)

Here, general expression of system’s dynamic equations is

\[ \dot{x}(t) = Ax(t) + Bu(t) \]  
\[ y(t) = Cx(t) + Du(t) \]  
(49)

For convenience in representation of the Matlab Simulink blocks, state-space equations of the heat model are modified as follows

\[ \dot{x}_1 = \frac{1}{C_{TR}} \left[ Q_p - \frac{1}{R_1} (x_1 - x_2) \right] \]  
(50) 
\[ \dot{x}_2 = \frac{1}{C_{OCT}} \left[ \frac{1}{R_1} (x_1 - x_2) - \frac{1}{R_2} (x_2 - x_3) - 2m_{CO} (x_2 - x_4) \right] \]  
(51) 
\[ \dot{x}_3 = \frac{1}{C_{CTY}} \left[ \frac{1}{R_2} (x_2 - x_3) + \frac{1}{R_3} (T_\infty - x_3) \right] \]  
(52) 
\[ \dot{x}_4 = \frac{1}{C_{COaT}} \left[ 2m_{CO} (x_2 - x_4) - \frac{1}{R_4} (x_4 - x_5) \right] \]  
(53) 
\[ \dot{x}_5 = \frac{1}{C_{COaT}} \left[ \frac{1}{R_4} (x_4 - x_5) + Q_{max} \left( 1 - \frac{x_6 - x_5}{\Delta T_{max}} \right) \right] \]  
(54) 
\[ \dot{x}_6 = \frac{1}{C_k} \left[ -\frac{Q_{max}}{\Delta T_{max}} (x_6 - x_5) - \frac{1}{R_6} (x_6 - T_\infty) + P_m + Q_{max} \right] \]  
(55)

The \( P_m \) power is applied to the Peltiers. Resistors of the Peltiers are about 5.57Ω. \( V_p \) varies between 0 and 14V. Thus, \( P_m \) is between 0 and 78W. The motor’s mass flow rate \( m \) is taken as the input variables, and the outer ambiance temperature \( T_\infty \) and the heat generated in the resistances \( Q_p \) are constants. In addition, \( T_{upper} - T_{lower} \) is defined by the empiric equation (equation (3)).

1. \( V_m \) range is between 0 and 12V and the corresponding \( m \) is between 0 and 0.228 kg/s. The transformation coefficient is as follows:

\[ K18 = 0.228/12 = 0.019. \]  
Thus, \( m = 0.019 \) \( V_m \)  
(56)

2. \( P_m = 7.84V_p \)  
(57)

\[ Q_{max} = 0.52P_m = 4.0768V_p \]  
(58)

Thus, equations are reinterpreted as

\[ \dot{x}_1 = \frac{1}{C_{TR}} \left[ Q_p - \frac{1}{R_1} (x_1 - x_2) \right] \]  
(59) 
\[ \dot{x}_2 = \frac{1}{C_{OCT}} \left[ \frac{1}{R_1} (x_1 - x_2) - \frac{1}{R_2} (x_2 - x_3) - 0.038C_O V_m (x_2 - x_4) \right] \]  
(60) 
\[ \dot{x}_3 = \frac{1}{C_{CTY}} \left[ \frac{1}{R_2} (x_2 - x_3) + \frac{1}{R_3} (T_\infty - x_3) \right] \]  
(61) 
\[ \dot{x}_4 = \frac{1}{C_{COaT}} \left[ 0.038C_O V_m (x_2 - x_4) - \frac{1}{R_4} (x_4 - x_5) \right] \]  
(62) 
\[ \dot{x}_5 = \frac{1}{C_{COaT}} \left[ \frac{1}{R_4} (x_4 - x_5) + 4.0768V_p \left( 1 - \frac{x_6 - x_5}{\Delta T_{max}} \right) \right] \]  
(63) 
\[ \dot{x}_6 = \frac{1}{C_k} \left[ -4.0768V_p (x_6 - x_2) - \frac{1}{R_6} (x_6 - T_\infty) + 7.84V_p + 4.0768V_p \right] \]  
(64)
As output, the temperature of the oil in HPCyT where the resistances are found is taken as $T_2$, and the TD along the resistances is taken as $T_{upper} - T_{lower}$. The Simulink model based on the equations provides viability of the model in terms of prescription blocks that illustrate the physical relations between the variables. The Simulink equivalent block model is shown in Figure 4.

The coefficient values of the equivalent block diagram are given in Table 1.

### Control methods

PID and fuzzy methods carry out the process to determine the suitable control for the system.
**PID (three terms) control method**

The PID control algorithm is composed of three parameters: Proportional (P) + Integral (I) + Derivative (D) terms. The P parameter defines return to mentioned error where the I defines the response to the sum of recent errors and the D defines the reaction to the error rate. Total reaction of the PID adjusts the output of the system to the desired value.

**Fuzzy control method**

Fuzzy control generally deals with control of complex non-linear systems, which are hard to express by accurate mathematical models. FIS is a linguistic instruction-orientated system which is composed of fuzzification, fuzzy decision-making (conjunction of the antecedent propositions refers to their supporting degrees and implication of consequent results), aggregation of the results in a output set and defuzzification of the output fuzzy set (Figure 5). Outputs of the FIS systems command both the $V_p$ and the $V_m$.

**Design of the controllers**

TD controller adjusts $V_p$ between 0 and 14.5 V and yields an amount of $Q_c$ between 0 and 136 W. VTG controller regulates $V_m$ between 0 and 12 V and convects oil within a rate of $v$ between 0 and 0.228 kg/s. Reduced VTG and TD allows appropriate conditions for precise measurements.

**Design of TD controller**

In the first stage, $\eta_c$ should be determined: $\eta_c$ (equation (2)) could vary within $0-0.65$ rates, and together with TD, they determine $V_p$.

$$\eta_c = \frac{Q_c}{P_{Peltiers}}$$  \hspace{1cm} (65)
Table 2. Rule base that determines relation between \( \eta_{\text{Total}} \) and its factors.

| Rule | Condition | Output |
|------|-----------|--------|
| 1 | If \( V_m \) is L AND \( T_h - T_c \) is ZG THEN \( \eta_c \) is H | |  
| 2 | If \( V_m \) is L AND \( T_h - T_c \) is L THEN \( \eta_c \) is H | |  
| 3 | If \( V_m \) is L AND \( T_h - T_c \) is M THEN \( \eta_c \) is M | |  
| 4 | If \( V_m \) is L AND \( T_h - T_c \) is B THEN \( \eta_c \) is L | |  
| 5 | If \( V_m \) is H AND \( T_h - T_c \) is ZG THEN \( \eta_c \) is ZG | |  
| 6 | If \( V_m \) is H AND \( T_h - T_c \) is L THEN \( \eta_c \) is H | |  
| 7 | If \( V_m \) is H AND \( T_h - T_c \) is M THEN \( \eta_c \) is M | |  
| 8 | If \( V_m \) is H AND \( T_h - T_c \) is B THEN \( \eta_c \) is L | |  

L: low; H: high; M: medium; B: big; ZG: zero grade.

Since \( R_{\text{Peltiers}} \approx 1087 \, \text{\Omega} \) then

\[
P_{\text{Peltiers}} \approx V_p^2
\]

In order to reduce TD around zero, necessary voltage will be about

\[
V_p = \sqrt{\frac{(mc_0 TD)}{\eta_c}}
\]

\( \eta_c \) is a function of the Peltiers \( T_h - T_c \) and \( \Delta T_{\text{max}} \) is 67 °C\(^{-3}\).

\[
\eta_c = 0.65 \left(1 - \frac{T_h - T_c}{\Delta T_{\text{max}}} \right)
\]

PID TD controller design for the system is proposed in detail.\(^{17}\)

Fuzzy TD controller design. The empirical interpretations of the experiments point out that \( \eta_c \) is a non-linear characterization of \( v \) and \( T_h - T_c \), where \( T_m = 24 \, ^\circ\text{C} \) and \( Q_m = 2.5 \, \text{W}. \)\(^{17}\) Processing regions of \( V_m \) and its corresponding \( v \) are 4–8 V and 0.076–0.152 kg/s, respectively. Higher speed results in rising of heat caused by increasing friction. \( \eta_c \) should be revised as \( \eta_{\text{Total}} \) after taking \( Q_h \) and \( Q_m \) effects into account (Figure 6).

Instead of the linear relation given in equation (26), the empirical relation can be realized by means of fuzzy rules.

Therefore, a fuzzy rule base, which describes the non-linear relation, could be derived based on Figure 6 as shown in Table 2. The relation between controller output \( V_p \), and inputs \( \eta_{\text{Total}} \) and TD is given in Table 3.

When we interpret the first rule, “If TD is Zero Grade AND \( \eta_{\text{Total}} \) is High (This means \( V_m \) is Low AND \( T_h - T_c \) is Zero Grade) THEN \( \eta_c \)”

Table 5 is derived by means of locating Table 2 in Table 3. Input variables concerned with the TD controller are given in Figure 7. Corner membership functions (MFs) are represented by means of trapezoidal functions, where interiors are represented by means of triangles. Input variables TD, \( V_m \) and \( T_h - T_c \) are composed of four, two and four MFs, respectively.

Operating band, B, for the controller is optional but generally selected as 1 °C out of where it operates in on-off mode.

Shape of the output MFs plays fewer roles on the output than input MFs, rules and defuzzification methods.\(^{22}\) Therefore, output variable is composed of four singleton MFs which make our program\(^{33}\) simpler.

Rules agreed in Table 5 given in “Appendix 2” are set by means of experimental try-and-faults to

Verbal

| Rule | Condition | Output |
|------|-----------|--------|
| 1 | If VTG is NG AND \( \Delta \text{VTG} \) is NG THEN \( V_m \) is L | |  
| 2 | If VTG is NG AND \( \Delta \text{VTG} \) is ZG THEN \( V_m \) is L | |  
| 3 | If VTG is NG AND \( \Delta \text{VTG} \) is P THEN \( V_m \) is L | |  
| 4 | If VTG is ZG AND \( \Delta \text{VTG} \) is NG THEN \( V_m \) is L | |  
| 5 | If VTG is ZG AND \( \Delta \text{VTG} \) is ZG THEN \( V_m \) is L | |  
| 6 | If VTG is ZG AND \( \Delta \text{VTG} \) is P THEN \( V_m \) is L | |  
| 7 | If VTG is PM AND \( \Delta \text{VTG} \) is NG THEN \( V_m \) is L | |  
| 8 | If VTG is PM AND \( \Delta \text{VTG} \) is ZG THEN \( V_m \) is L | |  
| 9 | If VTG is PM AND \( \Delta \text{VTG} \) is P THEN \( V_m \) is L | |  
| 10 | If VTG is PB AND \( \Delta \text{VTG} \) is NG THEN \( V_m \) is M | |  
| 11 | If VTG is PB AND \( \Delta \text{VTG} \) is ZG THEN \( V_m \) is M | |  
| 12 | If VTG is PB AND \( \Delta \text{VTG} \) is P THEN \( V_m \) is M | |  

M: medium; L: low; P: positive; PM = positive medium; PB = positive big; VTG: vertical temperature gradient; NG: negative; ZG: zero grade.
accomplish the results of the non-linear behavior. In this way, the fuzzy TD controller determines a convenient control $V_p$ (Figure 7).

**Fuzzy VTG controller design**

Length of the TR block and amount of the self-heating effect determines the VTG. In this study, VTG is reduced by controlling the $V_m$ which provides a forced convection against natural convection of the $O_{CyT}$ caused by the $Q_R$. Lesser $v$ below 0.076 kg/s, natural convection dominates the forced convection and rises $T_{upper}$ (Figure 8). Contrariwise, $v$ over 0.152 kg/s reverses the convection and $O_{CyT}$ cooled by the Peltiers dominates on $T_{upper}$ and brings VTG about negative values.

The $v$ should operate within the mentioned values, and their corresponding voltages are within 4–8 V. Variation curves for VTG versus $V_m$ and $V_p$ are depicted in Figure 3 which commented and guided to fuzzy rules. For example, for lower $V_p$s around 2–4 V, $V_m$ is reduced to maintain VTG around zero. On the other hand, for increased $V_p$ within 6–14 V range, just medium $V_m$ could minimize the VTG. Proposed input and output fuzzy variables for the VTG controller are shown in Figures 9–11.

Fuzzy rules are established due to status of the variables: VTG and its derivative ($\Delta VTG$). VTG input has four and $\Delta VTG$ input has three MFs. Output variable is composed of two singletons (Figure 17). Rules are given in Table 4.

**Programs developed for the system**

Fuzzy and PID control program is developed in Delphi 5.0. Programs and their flowcharts are explained in previous studies in detail. Simulation programs are developed in Matlab Simulink. In the fuzzy program, min functions are used for AND and IMPLICATION operators. Sum function is preferred for simplicity in AGGREGATION operations and center of gravity is used as DEFUZZIFICATION method.

**Simulation model of the control process**

The experimental results of the control processes are thoroughly discussed. Scope of the study is heat and mass transfer modeling of the system and comparison of its performance with that of the real-time results: Both PID and fuzzy control methods are applied to the system and to the model. Simulink block diagram (Figure 4) is embedded as a subsystem to the control system model given in Figure 12. The model allows switching between PID and fuzzy control methods. However, the study is focused on fuzzy control results of the actual system and the simulation results of the
model. Fuzzy control blocks are essentially attached to Matlab Simulink models and allow design process being shorter.47

**Results and discussion**

Fuzzy control software prepared uses the sum-min method as a fuzzy inference method (OR and AND methods, respectively) and the center of gravity method for defuzzification processes. Minimum and maximum functions are utilized for implication and aggregation methods, respectively.46 The same methods and parameters are used both in experimental and simulation applications.

In the fuzzy TD controller, eight rules are inherently active at the same time, and their defuzzification results determines and drives $V_p$. Similarly, four rules are simultaneously active for the VTG controller and drives $V_m$. The set value of the TD is 19.5°C, and set value of the VTG is 0°C.

Actual and simulation of fuzzy control results of the TOCyT is shown in Figure 13. Actual system and the model reach to the set value in 60 and 35 min, respectively. Around 0.2°C of steady-state error occurred in the model response.

Actual system yields an undershoot around 82nd minute, which is arisen from unpredictable turbulences in the circulation of the oil against natural convection. However, model follows general trend of the actual system. Actual TOCyT is obtained by average of measured data from $T_{upper}$ (Figure 18) and $T_{lower}$ (Figure 19) sensors (equation (2)) where the simulation model yields TOCyT in reference to its differential estimation, $x_2$ (integration of equation (60) in Figure 4).

Since TOCyT should follow an average trend similar to as that of $T_{upper}$ and $T_{lower}$, their graphics are given

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**Figure 8.** Illustration of convection loop of heat and its corresponding VTG refer to $v$.

**Figure 9.** Membership functions of the input variable VTG.

**Figure 10.** Membership functions of the input variable $\Delta$VTG.

**Figure 11.** Membership functions of the output variable $V_m$. 
in the Appendix 2: Information acquired from $T_{upper}$ and $T_{lower}$ sensors is monitored in Figures 18 and 19, respectively. It is clear that the turbulence is originated around the $T_{upper}$ sensor, which forced convected OCoT from the CoT, faced of heated OCyT risen by natural convection in the CyT.

Simulation results of $T_{upper}$ and $T_{lower}$ are shown in Figures 18 and 19. $T_{upper}$ and $T_{lower}$ values are important for determination of VTG and for adjusting the $V_p$. The results, which indicate the heat and mass transfer behavior, are approximately imitated by the proposed model.

In the controller section, $V_p$ determines $T_{OCoT}$. In this purpose, efficiency, $\eta$, of the Peltiers as a function of $T_h - T_c$ is required. $T_h$ of the actual system is
acquired by sensors mounted between the hot surface of the Peltiers and the fins (Figure 14).

\( T_h \) in the simulation model is derived from equation (60) (Figure 14(b)). Following an equilibrium situation, \( T_h \) follows a trend corresponding the TD fuzzy logic controller (FLC) voltage, \( V_p \), which is acquired from DAC card of the computer (Figure 15(a)) and drives the Peltiers. When TD exceeds 0–1 °C band, the controller behaves as on-off.

TD FLC of the model behaves similar to the actual system. Second FLC controller feeds back \( T_{upper} - T_{lower} \) VTG (Figure 16(a)). Referring to the acquired VTG and its derivative, \( V_{vtg} \) is controlled (Figure 17(a)). By means of the FLC VTG controller, VTG does not exceed ±0.5 °C.

Similarly, simulation model keeps VTG around zero (Figure 16(b)). Actual and simulation outputs of \( V_{vtg} \) are given in Figures 17(a) and (b), respectively.

The comparison of experimental results and modeling outputs is shown in the figures above. When these mappings are examined carefully, their results signify that the system is modeled considerably realistic.

**Conclusion**

Heat and mass transfer model interprets high voltages in terms of heat, which means higher voltages correspond to higher heats. Once the model is validated, it could be directly applied to higher voltages such as 100 and 200 kW. Since the backbone of the system is extracted, changes or annexes on the hardware could easily be adapted to the model as a mathematical expression.

Uncertainties arisen from both TD and VTG could be determined by a certain function. Minimization of TD and VTG directly results in decreasing uncertainty and allows accurate HVDC measurements.

Experimental tests for HVDC systems with temperature control last for hours. Cooling of the oil and then returning of the system to initial conditions takes
almost 4–5 h. Hence, modeling and simulation of such systems are unavoidable.

In this study, fuzzy control method is applied to the model. However, the proposed model could be used in performance comparison of new control methods. Application of new control methods and parameter changes will take considerably short time in the simulations compared to actual control applications.

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Appendix I

Notation

| Notation | Description |
|----------|-------------|
| $K_d$ | derivative coefficient |
| $K_i$ | integral coefficient |
| $m$ | mass flow rate (kg/s) between 0 and 0.228 kg/s. |
| $MO$ | maximum overshoot |
| $OCoT$ | oil in the cooling tank |
| $P_{iu}$ | power applied to the Peltiers |
| $P_{Peltiers}$ | power of Peltiers |
| ppm | parts per million |
| $Q_{Cooling}$ | power applied to Peltiers |
| $t_d$ | delay time |
| $t_r$ | rise time |
| $t_s$ | settling time |
| $V_{in}$ | input voltage of the HVDC-ResDiv |
| $V_{m}$ | motor voltage |
| $V_{o}$ | output voltage of the HVDC-ResDiv |
| $V_{p}$ | voltage applied to the Peltiers |
| $\eta_c$ | rate of cooling amount |
| $v$ | mass flow rate (kg/s) |
| $v_{max}$ | maximum flow rate |
| $v_{min}$ | minimum flow rate |

Temperatures

| Temperature | Description |
|-------------|-------------|
| $T_{CT}$ | temperature of the polyamide body of the HPCyT (°C), |
| $T_e$ | temperature of the Peltier’s cold surface (°C) |
| $T_{CoT}$ | temperature of the CoT (°C), |
| $T_F$ | temperature of the cooler fins (°C) |
| $T_h$ | temperature of the Peltier’s hot surface (°C) |
Specific heats:

- $C_{\text{o}}$: Specific heat of the oil (J/kg K)
- $C_{\text{TR}}$: Thermal capacity that is stored on the total resistors.
- $C_{\text{CyT}}$: Thermal capacity of the polyamide side walls of HPCyT

Energy and heat definitions:

- $E_i$: Heat energy entered to the system
- $E_o$: Heat energy exited from the system
- $E_p$: Heat energy produced in the system
- $E_s$: Heat energy stored in the system
- $Q_C$: Heat transferred from the Peltiers (deg C)
- $Q_{C1}$: Heat transferred from the resistors to the fluid by means of conduction (W)
- $Q_{C2}$: Heat transferred from the fluid from the side wall (W)
- $Q_{C3}$: Exit heat of HPCyT from side wall (deg C)
- $Q_{\text{EOCyT}}$: Exit heat of the HPCyT (deg C)
- $Q_h$: Total heat passed to the hot side of the Peltier (W)
- $Q_{\text{ICyT}}$: Inlet heat to the HPCyT from the neighbor tank (deg C)
- $Q_{\text{max}}$: Maximum heat transfer capacity of the Peltier under ideal conditions.
- $Q_{\text{net}}$: Heat removed by forced convection from HPCyT (W)
- $Q_p$: Heat produced by the resistor.
- $Q_{L,c}$: Heat transferred to cold surface contacting the Peltier from the outer surface of CoT.
- $Q_{S1}$: Heat transferred to CoT from the fluid inside by convection (W)
- $Q_{S2}$: Total heat transferred from the fin to the outer ambience (W)

Temperature resistances:

- $R_{\text{thermal}}$: Thermal resistance between fins and the outer ambience (K/W)
- $R_{C}$: Thermal resistance between total resistance and the fluid (OCyT) (K/W)
- $R_{c,e}$: Thermal resistance between the outer surface of the CoT and the outer side of the Peltier (K/W)
- $R_{3}$: Thermal resistance between outer surface of the HPCyT and the outer ambience (K/W)

Appendix 2:

Table 5. Rule base of the TD controller.

| Rule | Condition | Action |
|------|-----------|--------|
| 1 | IF TD is ZG AND $V_{in}$ is L AND $T_{c}$ - $T_{r}$ is ZG THEN $V_{p}$ is ZG | |
| 2 | IF TD is ZG AND $V_{in}$ is L AND $T_{c}$ - $T_{r}$ is L THEN $V_{p}$ is ZG | |
| 3 | IF TD is ZG AND $V_{in}$ is L AND $T_{c}$ - $T_{r}$ is M THEN $V_{p}$ is ZG | |
| 4 | IF TD is ZG AND $V_{in}$ is M AND $T_{c}$ - $T_{r}$ is ZG THEN $V_{p}$ is S | |
| 5 | IF TD is ZG AND $V_{in}$ is M AND $T_{c}$ - $T_{r}$ is L THEN $V_{p}$ is ZG | |
| 6 | IF TD is ZG AND $V_{in}$ is M AND $T_{c}$ - $T_{r}$ is M THEN $V_{p}$ is ZG | |
| 7 | IF TD is ZG AND $V_{in}$ is M AND $T_{c}$ - $T_{r}$ is B THEN $V_{p}$ is ZG | |
| 8 | IF TD is ZG AND $V_{in}$ is M AND $T_{c}$ - $T_{r}$ is B THEN $V_{p}$ is ZG | |
| 9 | IF TD is S AND $V_{in}$ is L AND $T_{c}$ - $T_{r}$ is ZG THEN $V_{p}$ is S | |
| 10 | IF TD is S AND $V_{in}$ is L AND $T_{c}$ - $T_{r}$ is L THEN $V_{p}$ is S | |
| 11 | IF TD is S AND $V_{in}$ is L AND $T_{c}$ - $T_{r}$ is M THEN $V_{p}$ is S | |
| 12 | IF TD is S AND $V_{in}$ is L AND $T_{c}$ - $T_{r}$ is B THEN $V_{p}$ is S | |
| 13 | IF TD is S AND $V_{in}$ is M AND $T_{c}$ - $T_{r}$ is ZG THEN $V_{p}$ is M | |
| 14 | IF TD is S AND $V_{in}$ is M AND $T_{c}$ - $T_{r}$ is L THEN $V_{p}$ is S | |
| 15 | IF TD is S AND $V_{in}$ is M AND $T_{c}$ - $T_{r}$ is M THEN $V_{p}$ is S | |
| 16 | IF TD is S AND $V_{in}$ is M AND $T_{c}$ - $T_{r}$ is B THEN $V_{p}$ is S | |
| 17 | IF TD is M AND $V_{in}$ is L AND $T_{c}$ - $T_{r}$ is ZG THEN $V_{p}$ is M | |
| 18 | IF TD is M AND $V_{in}$ is L AND $T_{c}$ - $T_{r}$ is L THEN $V_{p}$ is M | |
| 19 | IF TD is M AND $V_{in}$ is L AND $T_{c}$ - $T_{r}$ is M THEN $V_{p}$ is M | |
| 20 | IF TD is M AND $V_{in}$ is L AND $T_{c}$ - $T_{r}$ is B THEN $V_{p}$ is M | |
| 21 | IF TD is M AND $V_{in}$ is M AND $T_{c}$ - $T_{r}$ is ZG THEN $V_{p}$ is B | |
| 22 | IF TD is M AND $V_{in}$ is M AND $T_{c}$ - $T_{r}$ is L THEN $V_{p}$ is M | |
| 23 | IF TD is M AND $V_{in}$ is M AND $T_{c}$ - $T_{r}$ is M THEN $V_{p}$ is M | |
| 24 | IF TD is M AND $V_{in}$ is M AND $T_{c}$ - $T_{r}$ is B THEN $V_{p}$ is M | |
| 25 | IF TD is B AND $V_{in}$ is M AND $T_{c}$ - $T_{r}$ is ZG THEN $V_{p}$ is B | |
| 26 | IF TD is B AND $V_{in}$ is M AND $T_{c}$ - $T_{r}$ is L THEN $V_{p}$ is B | |
| 27 | IF TD is B AND $V_{in}$ is M AND $T_{c}$ - $T_{r}$ is M THEN $V_{p}$ is B | |
| 28 | IF TD is B AND $V_{in}$ is M AND $T_{c}$ - $T_{r}$ is B THEN $V_{p}$ is B | |
| 29 | IF TD is M AND $V_{in}$ is L AND $T_{c}$ - $T_{r}$ is ZG THEN $V_{p}$ is B | |
| 30 | IF TD is M AND $V_{in}$ is L AND $T_{c}$ - $T_{r}$ is L THEN $V_{p}$ is B | |
| 31 | IF TD is M AND $V_{in}$ is L AND $T_{c}$ - $T_{r}$ is M THEN $V_{p}$ is B | |
| 32 | IF TD is M AND $V_{in}$ is L AND $T_{c}$ - $T_{r}$ is B THEN $V_{p}$ is B | |

B: Big; M: Medium; S: Small; L: Low; TD: Temperature difference; ZG: Zero grade.
Figure 18. $T_{\text{upper}}$ time response for actual and simulation of the system control.

Figure 19. $T_{\text{lower}}$ time response for actual and simulation of the system control.