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A smart current control for superconducting cable test

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Abstract- A smart current control system for enhancing performance of a superconducting cable test station is proposed. According to the Fuzzy Gain Scheduling logic, the controller parameters are modulated by the working conditions. An improved flexibility for the definition of the set point is achieved. The system effectiveness has been proved through several simulations and demonstrated experimentally on the Facility for Research on Superconducting Cables at European Organization for Nuclear Research (CERN).

I. Introduction

The superconductivity is widely exploited in many applications from applied physics to engineering. In all the applications, the characterization of the superconducting cables is a key point and has to be carried out thoroughly by means of ad hoc testing. In test facilities, often cables are tested by a superconducting transformer in order to cut operation cost [1]-[2]. In the Facility for Research on Superconducting Cables (FReSCa) at CERN, the current driven in the sample is controlled by a digital Proportional Integral (PI) control. However, bandwidth constraints require the definition of slow start and stop for current ramping. Furthermore, available control strategy limits the acceleration at 800 As^{-2}. Finally, the system to be controlled, namely the chain current source and superconducting transformer, exhibits significant non-linear behaviour.

Control performance can be improved by taking into account the system variations in the design of the control strategy. Adjusting control parameters according to the system behaviour is the main feature of the Adaptive Control (AC) strategies [3]. Assuming a deep knowledge on the system dynamic, the Gain Scheduling (GS) control strategy is the most suitable to perform this task [3], with a particular focus on the Fuzzy PI Gain Scheduler (FGS) [4]. The GS strategy divides the operating domain in several subspaces, according to the homogeneity of the system behaviour.

In this paper, a smart current control system, for improving metrological performance of a superconducting cable measurement station, is proposed. The controller is based on an ad-hoc adaptive GS strategy, customized by means of a Takagi-Sugeno-Kan (TSK) Fuzzy inference [5], exploiting the representation capability of Fuzzy system to realize a suitable PI controller for each working condition. In particular, in Section II, state-of-the-art controllers of superconducting transformers are reviewed, and in Section III, a background on Fuzzy Gain Scheduling is reported. In Section IV, the proposed adaptive control system is outlined, and in Section V, the experimental validation results at FReSCa of CERN are illustrated.

II. Digital control for superconducting transformer: a review

In measurement stations based on superconducting transformers (Fig. 1), the cable is linked to the transformer secondary and the current I_s flowing into the sample is sent through the feedback loop to the control system.

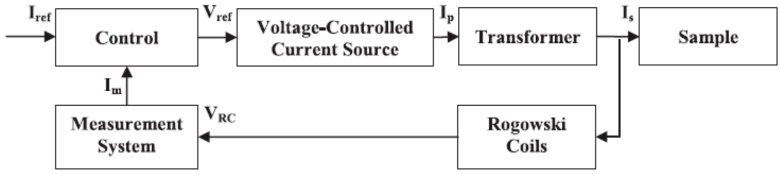

Figure 1 Architecture of a cable test station based on superconducting transformer.

The measurement system integrates the voltage read from the Rogowski coils, by measuring the current on the sample; this value, subtracted from the current reference I_{Ref}, gives the error to the PI controller to adjust the voltage reference value to be sent to the current source.
In the measurement station of FReSCa at CERN, the control system does not take into account the potential non-linearity of the current source; indeed it is not included in the system dynamic to be controlled.

III. Background

In the following, (A) the Gain Scheduling and (B) the Takagi Sugeno inference are outlined.

A. Gain Scheduling

When the working conditions require enhanced frequency bandwidth and low complexity in the control logic, the GS strategy is a suitable solution [3]. GS divides the operating spaces (e.g. the range of I_s) in several homogenous subspaces. By linearizing each subspace, GS computes an optimal digital controller for each of the domain parts (Fig. 2). GS schedules each PI control for the corresponding operating range of optimization.

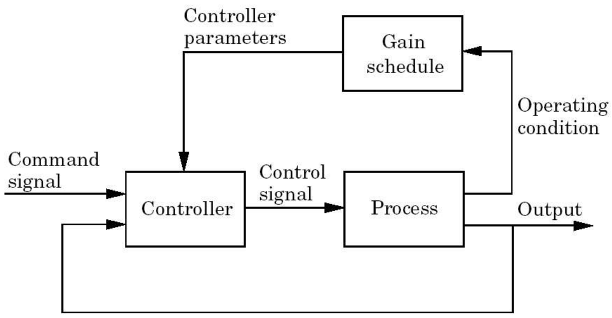

Figure 2 Gain Scheduling logic perspective.

GS is a popular method for handling parameter variations in flight control and other systems. Another attractive approach for wide-range control of nonlinear processes is the Multimode Control [6]. This strategy switches among several controllers, each one designed for a partition of the operating space according to the operating conditions (Fig. 3).

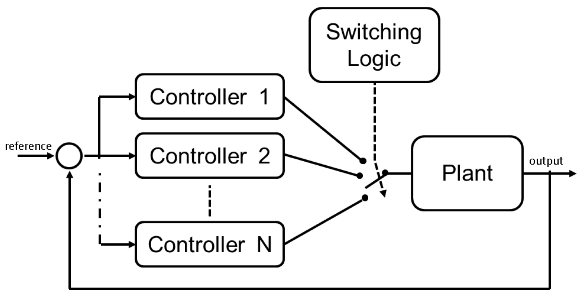

Figure 3 Multimode control scheme.

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This approach is equivalent to the GS method, provided that the local controllers have all the same structure.

B. Takagi-Sugeno-Kan inference

Fuzzy systems exploit the possibility offered by fuzzy sets and logic to represent actual models in symbolic terms by providing a close link between them. In this way, models can be easily understood and represented. The basic idea of fuzzy systems is to define a set of rules in the "*if ... then ... else*" form, the *rule-base*, in order to establish a relationship between input conditions and desired output.
In control systems, the TSK inference approach is widely used [7]. In this model, the rules are in the form:

$$R_j\text{: IF } (x_1 \text{ is } \underline{A_{j1}}) \wedge (x_2 \text{ is } A_{j2}) \wedge \ldots \wedge (x_l \text{ is } A_{jl}) \text{ THEN } y = z_j. \quad (1)$$

where $x_1, x_2, \ldots x_l$ are the system input variables, and A_{ji} the possible fuzzy set whose elements are values of the corresponding input variable with a certain degree of membership. The antecedent of each rule is a conjunction ("AND" operator) of propositional clauses ("x is A"). The y is the output variable and can assume only crisp values z_j (i.e., numerical). A system including such rules can be represented by means of a non-linear function of the input variables: $y = f(x_1, x_2, \ldots x_l)$.

IV. Proposal

In the proposed FGS, the present operating state and the corresponding digital control are identified by means of a Fuzzy Inference System (FIS), typically a first-order TSK system [5]. In the first part of the FIS, the input variables are fuzzified and the present operating conditions are evaluated. The FGS takes two inputs and returns one output. The first input enters the scheduling variable α, namely the reference current signal I_{ref}. The other input is the measured signal required by the PI controller to calculate the reference voltage V_{ref} for the current source (Fig. 4).

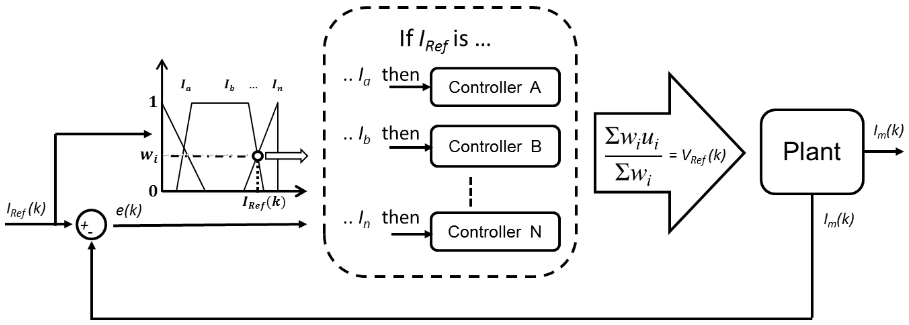

Figure 4 PI-FGS system with input divided into 3 subspaces.

The fuzzified inputs are then used in the *rule-base,* where a rule includes in its consequent the implemented digital control for the corresponding working condition. The final output of the FGS is a weighted average of the rules output, where the weights are the operating conditions previously computed.

A. Implementation

The first step in the development process was a detailed system identification. A measurement campaign was carried out to obtain a dense input-output representation (V_{ref} vs I_s) of the system under control. An inferential approach was adopted to define a model of the system under control. Among the inferential identification methods, the autoregressive neural networks approach [8] was initially considered, but without sufficient generalization of the system dynamics for all operating conditions. More satisfactory results were achieved by using a fuzzy identification [5]. From the resulting model, an ideal control strategy able to provide a control reference for each of the identified operating regions was synthetized. Such a controller was designed according

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to the PI-FGS strategy, where an ideal PI controller was computed for each operating region. The controller including its parameters derived from simulations was implemented in C++. This language choice was chosen for compatibility with the existing system where the new control logic is hosted. The inputs are fuzzified through functions mapping the trapezoidal membership functions for the I_{Ref} input, while the system error, calculated as the difference between the desired current level I_{Ref} and the measured value I_m, is forwarded without being fuzzified. Regarding the rules implementation, the complexity is limited by the presence of just one rule for each domain partition. No T-Norm operator is computed, because just a single condition is present in the antecedent (i.e. the "IF" part) of each rule, thus the implementation is reduced to the calculation of the linear combination of the local PI controller parameters and the inputs. The network output is the sum of the output of each individual branch multiplied by the truth value obtained from the membership function computed at the input fuzzification step. The control logic following this implementation is placed inside the remote monitoring system of the measurement station. Finally, a tuning phase was carried out to understand the preliminary performance and eventually correct the parameters.

Preliminary experimental results highlighted the simulation trend of an excessive sensitivity of the PI-FGS controller. This problem was faced by imposing a transition time of 0.5 s between a ramp and a plateau (or conversely between a plateau and a ramp). This turns out to be negligible in a regular test, but conversely very useful to help the controller in avoiding excessive overshooting. Thus, a new reference signal is built by calculating the acceleration *a* and deceleration *d* of the ramp-plateau transition according to the ramp rate *rr*:

$$a\ (d) = (-)\ rr/\Delta t. \qquad (2)$$

where Δt is 0.5 s.

V. Experimental results

The proposed system based on PI-FGS strategy was validated in two steps: first, experiments on the test chain as a whole, i.e., measurement and control loop, were performed. In this session, the reference tracking of current waveforms was studied in a configuration where the transformer insert is closed on a short circuit. Then, a final validation by testing an LHC outer layer dipole cable (LHC cable of type 2) [10] was carried out. The test generally consists in determining the voltage-current characteristic (i.e. the V-I curve), and defining the cable critical current at a criterion of resistivity of 10^{-14} Ω m. This type of measurement has an expected repeatability of ±0.5 % and reproducibility of ±2 % [10]. A measurement campaign, with background field from 3.0 to 9.0 T, and current ramp rates from 50 to 800 As^{-1}, was carried out by using both the PI control strategy and the FGS one.

In Fig. 5, the system responses in a short-circuit configuration obtained by using the available PI and the proposed PI-FGS control strategy are compared. The results show a common trend, regardless the considered ramp rate and maximum current. Under the same conditions, the error of the proposed PI-FGS is considerably less, sometimes more than 50 %, with respect to the previous PI strategy. Such an error is accumulated mainly in the ramp phases; under these circumstances, the proposed controller shows satisfactory promptness in following the ramp and negligible oscillations during transitions between ramp and plateau.

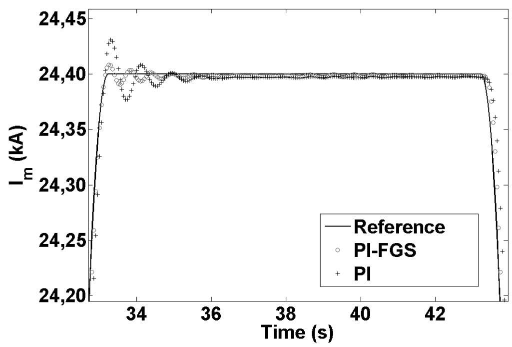

Figure 5 System reference tracking in short-circuit configuration tested using PI and FGS.

A view of the tracking error, expressed as RMSE, for the PI and the PI-FGS strategy, in the short-circuit configuration, is given in Tab 1. In this configuration, the overshooting phenomenon is still more evident at higher ramp rate than at lower current. The absolute overshooting value is almost constant for the same ramp rate, thus the percentage value decrease drastically according to the current.

Ramp Rate (As^{-1}) / I Max (A)	**800 FGS / PI**	**500 FGS / PI**	**300 FGS / PI**	**100 FGS / PI**
5000	25.52 / 48.36	18.24 / 34.28	14.15 / 22.99	4.74 / 8.85
10000	30.31 / 58.69	20.77 / 40.10	13.41 / 25.92	4.98 / 9.52
15000	33.08 / 64.03	22.24 / 42.96	14.13 / 27.29	5.14 / 9.86
20000	34.93 / 67.38	23.20 / 44.72	14.62 / 28.15	5.28 / 10.11
24500	36.60 / 69.52	24.15 / 45.83	15.15 / 28.72	5.43 / 10.29

Table 1 Aggregated RMSE mean values from the FGS / PI comparison measurements.

In Fig. 6, the measured V-I curves on a length of 610 mm of the cable are compared at 7.0 T and 5 T with current ramp rate of 50 As^{-1} and 250 As^{-1} respectively. The delay introduced by the FGS is significantly lower than the one due to the PI controller. The resulting curves are extremely close and the critical currents measured are the same. Indeed, the quality of the V-I curves measured by the proposed FGS system is better than the one obtained using the available PI controller.

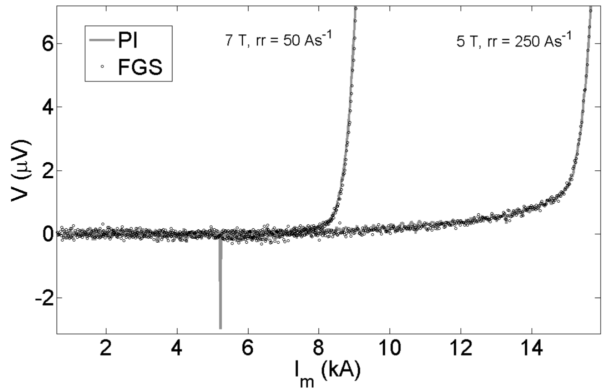

Figure 6 Comparisons of U-I curves on a LHC cable of type 2 measured using the PI and FGS control strategies.

VI. Conclusions

An adaptive current control strategy to provide performance improvements in the sample current control was designed. The current control strategy was developed by following the Gain Scheduling strategy by varying the controller parameters according to the working conditions. The variable chosen for driving the changes in the controller was the reference current I_{Ref} whose domain has been divided in subspaces according to the system behaviour.

The controller implementation was performed in C++ and included in the superconducting transformer measurement station at the Facility for Research on Superconducting Cables (FReSCa) of CERN. The response for the most critical current and ramp rates showed a short overshoot keeping the same capability to follow the reference ramp. In terms of error both absolute and RMS in the compared results showed a reduction up to 52% with respect to the state-of-the-art-control strategy previously adopted at CERN. The significant improvement achieved in the ramp phase together with the ability to settle within the given transition time are the main reasons for the strong error decreasing. This improvement turned into the possibility to run cycle with acceleration up to 1600 As^{-2} for an 800 As^{-1} ramp rate.

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