

ABSTRACT

dissertation submitted for the degree of Doctor of Philosophy (PhD)
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" Development and research of controlled transformer type shunt reactors with
direct current magnetization"

Ensuring normal operating modes of electric power systems and compliance with power quality standards is impossible without controlled means of reactive power and voltage regulation. Maintaining optimal voltage levels at substation buses minimizes active power losses in power grids and improves grid efficiency. FACTS devices are integral elements of next-generation power transmission systems.

One of the FACTS devices performing reactive power regulation is the shunt reactor (SR). The issue of limiting excess reactive power is acute both in long inter-system transmission lines and in urban high-voltage power grids. The charging power of cable lines significantly exceeds that of overhead lines: for a 110 kV cable line it is 8.4–18.0 MVar per 100 km against 3.4–4.0 MVar for an overhead line of the same voltage class.

A representative example is the power grid of Alatau Zharyk Kompaniyasy JSC (AZhK) — the largest regional distribution company of Almaty and Almaty region. Its infrastructure includes 47.45 km of 220 kV cable lines and 206.36 km of 110 kV cable lines forming the city ring grid. The total charging power of the 220 kV cable lines alone amounts to approximately 50–240 MVar depending on cable type — a magnitude requiring continuous controlled compensation to prevent overvoltages during low-load periods.

Despite significant demand in the 35–500 kV grids of the Republic of Kazakhstan, domestic production of magnetically controlled shunt reactors has not been established. Supply is sourced from Russia, Spain, Italy, Ukraine and other countries at inflated prices including transportation. In accordance with the "Program for the Development of Domestic Value and Export-Oriented Industries", establishing domestic production of controlled shunt reactors is a strategically important objective.

The concept of a three-limb transformer-type reactor with DC control is not fundamentally new. In the 1980s, two such reactors were put into service at the Taksimo substation of the BAM railway in Russia — manufactured from 6.3 MVA, 35 kV transformers produced by the Chirchik Transformer Plant and reconstructed at the Yuzhkazenergopemont facility in Alma-Ata. However, their fundamental drawback was a high level of harmonic distortion in the network winding current, caused by the absence of a half-period saturation regime. The present work eliminates this deficiency by implementing counter-parallel connection of network winding sections and a delta-connected compensation winding.

Mastering the production of three-limb magnetically controlled shunt reactors with half-period saturation requires solving a number of unresolved scientific problems. The quantitative dependencies of electromagnetic characteristics on core geometry parameters have not been established in the literature; design optimization methods minimizing active material cost under rated operating conditions have not been developed; and a quantitative comparison of three-limb and four-limb designs under identical electromagnetic specifications has not been performed.

Thus, the relevance of this dissertation is determined by the need to establish the relationships between the electromagnetic characteristics of the three-limb magnetically controlled shunt reactor and the magnetic core design parameters ensuring half-period saturation with minimum harmonic distortion, and to develop a design optimization methodology — as the scientific foundation for organizing domestic production.

Practical significance.

The results of this work provide the scientific basis for developing technical documentation for manufacturing a pilot-scale 110 kV, 25 MVar magnetically controlled shunt reactor at Asia Trafo JSC and Kentau Transformer Plant JSC. The established regularities allow operating point shifts to be estimated without iterative simulations when core geometry parameters are changed, substantially reducing design effort. End-users of the results include KEGOC JSC, AZhK JSC, and regional power grid companies of the Republic of Kazakhstan.

Objective of the dissertation research.

To improve the efficiency of reactive power compensation in high-voltage and extra-high-voltage power grids by developing a three-limb magnetically controlled shunt reactor with optimal design parameters, based on establishing the relationships between the magnetic core design and operating parameters that ensure half-period saturation with minimum harmonic distortion of the network winding current.

Scientific objectives:

- To analyse existing reactive power compensation methods, magnetically controlled shunt reactor designs, and current research in the field; to formulate unresolved scientific problems.

- To develop a physical prototype of the three-limb magnetically controlled shunt reactor and experimentally investigate its electromagnetic characteristics under various DC bias regimes.

- To develop a verified simulation model of the three-limb magnetically controlled shunt reactor in Matlab Simulink; to establish the degree of agreement between the model and the physical experiment.

- To investigate the influence of magnetic core design parameters (cross-sectional area S and limb length L_s) on the network winding current and total harmonic distortion; to establish the governing regularities.

- To develop a design optimization methodology for the three-limb magnetically controlled shunt reactor minimizing active material cost under rated operating conditions, and to verify it for a 110 kV, 25 MVar reactor.

– Based on the optimization results for the three-limb design, to identify an electromagnetically equivalent four-limb design and to perform their quantitative techno-economic comparison.

– To investigate the dynamic performance of a 110 kV magnetically controlled shunt reactor and to identify a method for improving its transient response without design modification.

Research methods.

The work employs: methods of theoretical electrical engineering; physical and simulation modelling; harmonic analysis; computational experiment design; surrogate modelling based on Gaussian Process regression; Bayesian optimization with Expected Improvement acquisition function; techno-economic analysis.

Scientific novelty of the dissertation:

1. The invariance of the minimum total harmonic distortion (THD_{min}) of the network winding current to the magnetic core geometry of the three-limb magnetically controlled shunt reactor is established for the first time: THD_{min} = 0.17–0.33% for all configurations in the range $S \in [0.12, 0.16] \text{ m}^2$ and $L_s \in [2.325, 2.800] \text{ m}$, regardless of geometry. The geometry determines only the position of the operating point along the current axis, but not the current quality at that point.

2. A linear dependence of the optimal network winding current on the limb cross-sectional area with a sensitivity coefficient of 0.1 A/cm² invariant to limb length ($R^2 = 0.990\text{--}0.999$) is established, along with a nonlinear dependence on limb length. The additive separability of S and L_s influences allows the operating point shift to be estimated without additional simulations when the core geometry is changed.

3. A two-stage design optimization methodology is developed for the three-limb magnetically controlled shunt reactor: full factorial experiment on a uniform grid with parabolic THD(I_{co}) fitting, followed by Bayesian optimization with a Gaussian Process surrogate model ($R^2=1.0$, Matérn 5/2 kernel). The methodology identified the optimal design: $S^*=0.155 \text{ m}^2$, $L_s^*=2.325 \text{ m}$, active material cost \$106,648, and confirmed its global character.

4. A threshold compensation winding voltage $U_{ko_thr} \approx 25 \text{ kV}$ is established, above which further increase in winding turns does not reduce THD_{min}. This regularity is invariant to core geometry.

5. Based on the proven THD_{min} invariance, the first quantitative comparison of three-limb and four-limb armored magnetically controlled shunt reactor designs under identical electromagnetic specifications is performed. The three-limb design is shown to require 26.4% lower active material costs (dominant factor: average network winding turn radius 435 mm vs. 667 mm in the four-limb design).

Reliability of the results is confirmed by:

1. Experimental studies on physical prototypes of the three-limb magnetically controlled shunt reactor using calibrated measuring instruments registered in the State Metrology Register of the Republic of Kazakhstan.

2. Agreement between physical and simulation modelling results according to the mean absolute percentage error (MAPE) criterion: no more than 5.0% for network winding current and 2.5% for total harmonic distortion — within acceptable tolerances for nonlinear ferromagnetic devices.

3. Application of mathematically rigorous optimization methods (Gaussian Process, Bayesian Optimization) with verification of the global character of the found optimum.

4. Publication of principal results in peer-reviewed journals, including Electric Power Systems Research (Scopus, 78th percentile).

Propositions submitted for defence:

1. Physical prototypes of the three-limb magnetically controlled shunt reactor with DC bias and results of experimental investigation of their electromagnetic characteristics.

2. Verified simulation model of the three-limb magnetically controlled shunt reactor in Matlab Simulink (MAPE 5.0%/2.5%) and the DC bias modelling methodology.

3. Regularities of the influence of magnetic core design parameters on the electromagnetic characteristics of the magnetically controlled shunt reactor: invariance of THD_{min} to geometry and linear dependence of I_{co_opt} on S with coefficient 0.1 A/cm².

4. Two-stage design optimization methodology based on Gaussian Process and Bayesian optimization. Optimal design: S^{*}=0.155 m², L_s^{*}=2.325 m, THD=0.284%, active material cost \$106,648.

5. Results of quantitative comparison of three-limb and four-limb magnetically controlled shunt reactor designs under identical electromagnetic specifications: active material cost of the three-limb design is 26.4% lower.

6. Method for improving the transient response of a 110 kV magnetically controlled shunt reactor by including an optimal resistance R^{*} in the network winding circuit without any design modification.

Publications.

The principal results of the dissertation are reflected in 5 scientific publications: 3 articles in domestic journals from the KOKSON recommended list; 1 conference paper published in the Scopus database; 1 article in Electric Power Systems Research (Scopus, 78th percentile). As co-author, results are recorded in 2 Patents of the Republic of Kazakhstan for utility models on shunt reactor designs. Dissertation structure and scope.

The dissertation comprises an introduction, 6 main chapters, a conclusion, a list of references, and appendices.

Chapter 1 provides an analysis of magnetically controlled shunt reactor designs, including the history of three-limb reactor applications, and a review of current research. Unresolved scientific problems are formulated.

Chapter 2 describes the physical prototype of the three-limb magnetically controlled shunt reactor with half-period saturation, the experimental test bench, and

the results of electromagnetic characteristic investigations under various bias regimes.

Chapter 3 presents the Matlab Simulink simulation modelling methodology, model verification against physical experiment data (MAPE 5.0% and 2.5%), and investigation of dynamic performance and transient response.

Chapter 4 presents the results of parametric analysis of the 110 kV magnetically controlled shunt reactor: regularities of limb cross-section and length influence, invariance of THD_{min} to core geometry, and the compensation winding voltage threshold.

Chapter 5 contains the winding design calculations for the optimal 110 kV, 25 MVar magnetically controlled shunt reactor. The results serve as the basis for the active material cost model used in the optimization problem of Chapter 6.

Chapter 6 presents the two-stage design parameter optimization using Gaussian Process and Bayesian optimization, identification of the optimal design ($S^*=0.155 \text{ m}^2$, $L_s^*=2.325 \text{ m}$), and quantitative comparison of three-limb and four-limb designs.