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## **PREFACE**

An on-load tap-changer is an indispensable operating equipment for the regulation of power transformers in energy supplying networks. The importance of on-load tap-changers has steadily been increasing with the years. Today, almost all generator-type transformers and power transformers, as for example in Germany, are equipped with on-load tap-changers. Not only is this similarly true for networks of all other industrial states, but also does the energy supply in developing countries more and more ask for regulated power transformers. It can generally be stated that an increase in the density and links of a network goes together with an increase in the necessity for the regulating transformer.

The majority of on-load tap-changers produced today is like the designs of the last decades based on the 1926 patent by Dr Janssen. Innovations in this field are above all dealing with the material used, the reliability, and the switching devices.

Due to the fact that in most industrial companies young engineers have replaced the old, many users' basic knowledge and understanding for on-load tap-changers has decreased. Moreover, the on-load tap-changer is surely not one of the central educational topics at colleges and universities. In the communication between manufacturers and users in every-day routine business deficiencies come up, which can very quickly result in cost-intensive misunderstandings. This experience fostered the decision to offer comprehensive answers to often repeated questions, starting from the very basis and treating the techniques as well as the particularities of on-load tap-changers.

The contents of the book is divided into three sections. The first section (chapters 1 to 3) explains the essential technical basics of the on-load tap-changer, which is done for the diverter switch and the tap selector separately. These "basics" are important for the understanding of regulation, and for selecting the suitable on-load tap-changer for individual applications. The two different principles of on-load tap-changing - resistor-type tap-changing or reactance-type tap-changing - are presented with their variants and commented on in detail regarding their switching principles and the occurring stresses. What follows is a description of the different tap selector designs, with particular focus on their insulation coordination. The basics are completed with an overview of the various possible transformer tap winding arrangements and the characteristics demanded of the on-load tap-changer regarding these arrangements.

The second section (chapter 4) extensively treats the aspects that are to be considered when selecting an on-load tap-changer. Using examples, characteristics are explained and calculation or estimation principles are given with the aim to offer the user the possibility of already including the on-load tap-changer in the design of the transformer, or even in the feasibility study of a project. In detail the basic criteria for the selection of an on-load tap-changer, such as assessment of the insulation and switching abilities, are made clear. Calculation and evaluation criteria are also presented, which enable the transformer manufacturer to assess the critical topics

such as "potential connection of the tap winding during the change-over selector operation" and "leakage inductance of the fine and coarse tap winding" which may have a substantial impact on the selection of an on-load tap-changer.

The third part (chapter 5) deals with special applications. Here, unusual on-load tap-changer designs as well as suitable system solutions for transformers with special regulation requirements are discussed. Large-scale projects, like e.g. phase-shifting transformers and HVDC transformers, or special applications of on-load tap-changers in reactors require the utmost of an on-load tap-changer. Being able to check as early as possible, whether or not a transformer design is working with a certain on-load tap-changer, can mean cutting the costs immensely. The last paragraph of this chapter is on parallel operation of transformers with on-load tap-changers in different positions. Again, the reader will be offered help for assessing the feasibility of such an operation.

The book at hand has been written in the years 1996 to 1999 and is very much orientated on the questions arising in every-day business. The author has been working as manager of the testing department at MR Maschinenfabrik Reinhausen GmbH for several years now. Along with testing new developments his area of responsibility comprises the technical support of other, internal departments as well as external customers. He is principally involved in advisory activities regarding the function and selection of on-load tap-changers for single applications or large-scale projects.

At this point the author would like to thank those, who have helped writing this book, in particular Mr Burkhard Herrmann, MR Maschinenfabrik Reinhausen GmbH, Regensburg, and Mr Julius Ruff (retired), MR Maschinenfabrik Reinhausen GmbH, Regensburg, for their assistance in many discussions on the problems described in the book. The author is also very grateful to Mr Karl Stenzel (retired), MR Maschinenfabrik Reinhausen GmbH, Regensburg, who has proof-read the manuscript, and to Mr Bernhard Kurth MR Reinhausen Manufacturing., Humboldt, Ten, U.S.A., who carried out the revision of the translation into English. Last but not least, the author wishes to thank his wife Sabine for her untiring patience and support during the whole project of this book.

Regensburg, December 1999

Dr. Axel Krämer

## 1 HISTORICAL SURVEY

The method to change the ratio of transformers by means of taps on the winding is as old as the transformer itself. From a very early stage, transformers with a turn ratio changeable within certain limits have been used for electrical power transmission, since this is the most simple method to control the voltage level as well as the reactive and active power in electrical networks. At the beginning of the development it was sufficient to have tappings connected to bushings outside the transformer tank, which were connected according to the necessity of the network. A more comfortable way was to connect the tappings to tap switches - today called "off-circuit" or "no-load tap changers" - which could only be actuated when the transformer was de-energized. Obviously, this simple device only permitted occasional corrections of the transformer ratio. It was not possible to control voltage drops caused by load changes in the network. At that stage these parameters could only be controlled at the generating plant.

To solve this problem, switching devices were needed which permitted the change of the turn ratio of transformers under load condition, i.e. without interrupting the load current. Such switching devices - today called "on-load tap changers" (OLTC) - were introduced to transformers more than 70 years ago. The demand for OLTCs became an urgent necessity in the 1920ies, when power consumption took a sharp upward trend, which required the interconnection and expansion of the electrical networks. The very rapid development brought, within a few years, solutions which were quite satisfactory in regards to operating safety and efficiency. The development of OLTCs was accelerated over the years due to the steady increase of the transmission voltage and power.

The introduction of OLTCs improved the operating efficiency of electrical systems considerably and this technique found acceptance worldwide. Today, in Germany for example, almost all generator and power transformers are equipped with OLTCs. In other industrialised countries the situation is comparable. In general the percentage of transformers equipped with OLTCs is increasing with the increase of the load density and interconnection of electrical networks. In addition, OLTCs applied in industrial process transformers as regulating units in the chemical and metallurgical industry is another important field of application.

Table 1-1 shows a survey of the typical number of operations for various applications. These range from some hundred to around 300,000 operations per year while the rated currents range from approximately 50 to 3000 Amps. [Breuer, Stenzel 1982]

Today's state of the art OLTC has reached such a high level of reliability that it is safe to state that its mechanical life expectancy is equivalent to that of the transformer. Exceptions may be applications in industrial process transformers. However, even on such applications experience shows that with proper maintenance several million operations can be obtained.

**Table 1-1:** Survey of number of operations for various applications

Power transformer	Transformer data			Number of operations of OLTC per year		
	Power range	Voltage range	Current range	min.	mean	max.
	MVA	kV	A			
Generator	100-1300	110-765	100-2000	500	3000	10000
Interconnection	200-1500	110-765	300-3000	300	5000	25000
Distribution	15-400	60-525	50-1600	2000	7000	20000
Electrolysis	10-300	20-110	50-3000	10000	30000	150000
Chemistry	1.5-80	20-110	50-1000	1000	20000	70000
Arc furnace	2.5-150	20-230	50-1000	20000	50000	300000

The problem to be solved when changing taps under load is how to connect the tappings of the transformer winding successively to the same output terminal without interrupting the load current. During the load transfer operation between to adjacent taps, both taps must be temporarily connected to the output terminal. To avoid a short circuit of the winding transition impedances, which can be reactors or resistors, are inserted. Two basic principles have been invented and are still used today - the slow motion reactor switching principle and the high speed resistor switching principle. Today both principles have been developed into reliable OLTCs.

The reactor type OLTC has its development origin in the USA, but also in Germany inventions were applied for a patent in 1905 and 1906. Because of the fact that the reactor switching principle causes a 90 degree phase shift between the switched current and the recovery voltage arising at the switching distance, the reactor type OLTC is less suitable for large step voltages. In addition to this the costs of transition reactors increase considerably with higher step voltages. Thus the reactor switching principle over the years has lost the remarkable importance it had in the beginning of the OLTC development. In the late 1940ies many OLTC manufacturers abandoned the production of OLTCs with this switching principle. However, in the USA the reactor principle is still used in a large scale and reactor type OLTCs are still under production.

The high-speed resistor type OLTC has its origin in the invention of Dr. Jansen of a diverter switch and a tap selector, which were patented in 1926. The transition impedance is been carried out with ohmic resistors. With this principle the current switched and the recovery voltage are in phase. This lightens the quenching of the arc in the current zero. The transition resistors have to be dimensioned only for a short-time loading which enables an economic use of OLTCs in case of higher step voltages and power.

Though the reactor principle has also proven itself, its application is limited to lower voltages, whereas the resistor principle dominates in the high voltage field or in special applications like HVDC-transformers, Phase-Shifting transformers or EHV-transformers. The reactor principle OLTC in these fields can only be applied by means of booster transformers, which make its application more difficult in regards to

transport weight, transport size and profile and overall economic considerations compared to the resistance principle OLTC.

There are many varieties of OLTCs of different manufacturers and much discussion has taken place over the years in regards to in-tank versus compartment type OLTC. The traditional and current practice in the UK is to use separate compartments for the transformer, tap selector and diverter switch oil. One point of view is that this design has been advantageous on occasions where DGA has been used to locate any incipient faults or when transformers have had to be replaced due to faults initiated in the tap changer. The other point of view is that due to the inferred superior quality a separation of the oil in the transformer main tank and the tap selector is not necessary and will increase the costs and the volume of the transformer. [Fyvie et al. 1996]

With the increasing importance of OLTCs, demands for standardization grew and resulted in the first IEC standard for OLTCs, which was published in 1966 (IEC Publication 214). This standard has been revised twice in 1976 and 1989. The 3. edition of the IEC Publication 214 from 1989 is still valid and is called IEC Publication 60214 today. In the year 2000 it is planned to have a new revised edition of this standard, which will cover then not only OLTCs but also off-circuit tap-changers. The new standard (fourth edition) will be get the number 60214-1.

Together with the second edition of IEC Publication 214 an "application guide for on-load tap changers" was worked out and was published as IEC Publication 542 in 1976. The amendment No. 1 to this standard was published in 1988. This standard also is renumbered to 60542. Together with the latest revision of IEC Publication 60214 the application guide will be revised too and will get the number IEC Publication 60214-2.

IEC 60214 was adopted by CENELEC and published with a few modifications in 1992 as HD 367 S2:1992. This standard is valid in the countries of the European Community. This harmonization document (HD) becomes in 1998 a European standard EN 60214. In the USA in 1995 the IEEE standard C57.131.1995 was published. In it slight modifications to IEC, mainly caused by the inclusion of reactor type OLTCs, were introduced. Some major deviations from the IEC Publication 60214 show the national standards JEC 2220 of Japan from 1988 (refer to Table 1-2) and of China. [Goosen 1996]

**Table 1-2:** OLTC standards differences

	Number of operations	
	IEC Publication 60214 / 1989	JEC 2220 / 1988
Service duty test cl 8.2.1 of IEC 60214	50 000	200 000
Breaking capacity test cl. 8.2.2 of IEC 60214	40 at 2·I	10 at 1.5·I 3 without interval
Mechanical endurance test cl. 8.5.1 of IEC 60214	500 000	800 000

In addition to the mentioned IEC standards 60214 and 60542 the following IEC publications can be applied particularly or are quoted in these publications:

- 60060 (High-voltage test techniques)
- 60076-1 (Power transformers, Part 1: General)
- 60076-3 (Power transformers, Part 3: Insulation levels and dielectric tests)
- 60076-4 (Power transformers, Part 4: Tappings and connections)
- 60076-5 (Ability to withstand short circuit)
- 60137 (Bushings for alternating voltages above 1000 V)
- 60947-1 (Degrees of protection of enclosures for low-voltage switchgear and controlgear)
- 60270 (Partial discharge measurements)
- 60296 (Specification for unused mineral insulating oils for transformers and switchgear)
- 60354 (Loading guide for oil-immersed transformers)

During the CIGRÉ SC12 Colloquium held in June 1995 in Malmö, Sweden, a workshop on on-load tap-changers took place. Many specialists from all over the world participated and the following conclusions were made [*Goosen 1996*]:

- The present state-of-the-art tap changing process is still acceptable.
- Analysis of future generation and transmission projects indicates that the available OLTCs are adequate for the requirements with respect to the transformer MVA-ratings and the highest system voltages.
- Barrier boards to separate the tap selectors from the main tank oil are used in a few countries. These barrier boards are available up to highest system voltages of 275 kV for the connection of line-end applications. To avoid any disturbing influence using gas-in-oil analysis of the transformer, the separate diverter switch oil compartment has to be oil tight as specified in the IEC 60214.
- Transformer and OLTC manufacturers for years have successfully been using zinc oxide varistors (ZnO) inside transformers for over-voltage protection.
- New insulating and cooling liquids for medium power transformers, provided as PCB-replacements, are under discussion, but none of them is in general used as insulating medium in regulating transformers. The Colloquium agreed that there is no need for a general use or a running investigation.
- Regulating transformers insulated with SF<sub>6</sub> gas, are produced in Japan, and are also in service in Jordan and several countries of South East Asia.

This background allows us to assume that the present state-of-the-art tap-changing process and the basic technology will be acceptable also in the future.