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TECHNICAL REPORT

colour inside

Performance of unified power flow controller (UPFC) in electric power systems

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PERFORMANCE OF UNIFIED POWER FLOW CONTROLLER (UPFC) IN ELECTRIC POWER SYSTEMS

FOREWORD

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IEC TR 63262, which is a Technical Report, has been prepared by subcommittee 22F: Power electronics for electrical transmission and distribution systems, of IEC technical committee 22: Power electronic systems and equipment.

The text of this Technical Report is based on the following documents:

Draft TR	Report on voting
22F/521/DTR	22F/531/RVDTR

Full information on the voting for the approval of this Technical Report can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

A unified power flow controller (UPFC) adjusts both the active and reactive power of a transmission line by regulating and controlling line impedance, bus voltage and phase angle difference. When addressing a lack of power control methods and the insufficient supporting capacity of dynamic conditions, a UPFC provides an effective solution. Before 2005, there were three UPFC projects around the world: Inez UPFC project installed in 1998 in U.S.A., Kangjin UPFC project installed in 2003 in South Korea, Marcy UPFC project installed in 2004 in U.S.A. (see Annex A).

Ten years later, with relevant technology upgrades and increasing electric power demand, three more UPFC projects have been constructed and placed into service, all in China. They are the Nanjing 220 kV UPFC project installed in 2015, Shanghai 220 kV UPFC project installed in 2017 and Suzhou 500 kV UPFC project also installed in 2017. All these projects are based on the modular multilevel converter (MMC) technology which has successfully mitigated the issue of uneven power flow distribution, improved power supply capacity and the reliability of power supply in related areas. It is believed that with the further growth of electric power demand, UPFC technology will be more extensively applied in the power marketplace.

This document is based on the practical experience of UPFC projects using modular multilevel converter (MMC) which is a most perfect type of a voltage sourced converter (VSC) that can provide technical references for UPFC design, manufacture, test, commissioning, operation and maintenance.

PERFORMANCE OF UNIFIED POWER FLOW CONTROLLER (UPFC) IN ELECTRIC POWER SYSTEMS

1 Scope

This document provides guidelines for applying unified power flow controllers (UPFC) in power systems. It includes letter symbols, terms and definitions, principles and configurations, design rules, performance requirements for key equipment, control and protection, insulation co-ordination, system performance and tests. This technical report applies to the UPFC based on modular multi-level converter (MMC) technology, as well as UPFC based on three-level converter technology.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60071-1, *Insulation co-ordination – Part 1: Definitions, principles and rules*

IEC 60071-5:2014, *Insulation co-ordination – Part 5: Procedures for high-voltage direct current (HVDC) converter stations*

IEC 60076-2, *Power transformers – Part 2: Temperature rise for liquid-immersed transformers*

IEC 60076-3, *Power transformers – Part 3: Insulation levels, dielectric tests and external clearances in air*

IEC 60076-4, *Power transformers – Part 4: Guide to the lightning impulse and switching impulse testing – Power transformers and reactors*

IEC 60700-1, *Thyristor valves for high voltage direct current (HVDC) power transmission – Part 1: Electrical testing*

IEC 61954, *Static var compensators (SVC) – Testing of thyristor valves*

IEC 62501, *Voltage sourced converter (VSC) valves for high-voltage direct current (HVDC) power transmission – Electrical testing*

IEC TR 62543, *High-voltage direct current (HVDC) power transmission using voltage sourced converters (VSC)*

IEC 62751-2, *Power losses in voltage sourced converter (VSC) valves for high-voltage direct current (HVDC) systems – Part 2: Modular multilevel converters*

IEC 62823, *Thyristor valves for thyristor controlled series capacitors (TCSC) – Electrical testing*

3 Terms, definitions and symbols

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1.1
unified power flow controller
UPFC
equipment which has two (or more) voltage sourced converters (VSCs) sharing common DC bus connected to the transmission system in parallel and in series, and can control the line impedance, voltage amplitude and phase angle at the same time

3.1.2
unified power flow controller using modular multi-level converter
MMC-UPFC
UPFC using multi-level converter in which each voltage sourced converter (VSC) valve consists of a number of self-contained, phase voltage sourced converters connected in series

3.1.3
shunt transformer
transformer which is connected between the converter and the AC grid, in parallel with the AC power grid

3.1.4
series transformer
transformer which has a winding in series with the line to change the line voltage and/or phase

Note 1 to entry Other windings such as exciting winding and balancing winding can be chosen by customers.

3.1.5
fast bypass switch
FBS
device connected across the terminals of protected equipment during the turn-off procedure of the bridge(s) and to transfer current form protected equipment during the turn-on procedure of the bridge(s) with fast conduction performance during line fault

3.1.6
thyristor bypass switch
TBS
power electronic switch with anti-parallel connected thyristors between the converter and the series transformer valve-side winding

3.1.7
valve reactor
reactor (if any) which is connected in series to the VSC valve

Note 1 to entry One or more valve reactors can be associated to one VSC valve and might be connected at different positions within the valve.

[SOURCE: IEC 62747:2014, 7.22, modified – The words "of the controllable voltage-source type" have been deleted from the definition, as well as the two last sentences of the note to entry.]

3.1.8
bypass operation time
time from the occurrence of the fault to the bypass switch being completely closed

3.1.9
multiple valve unit
MVU
single structure comprising more than one valve

[SOURCE: IEC 60633:2019, 6.3.2, modified – The notes to entry have been deleted.]

3.1.10
shunt unit
unit consisting mainly of a shunt transformer and a shunt converter, which achieves the function of a static synchronous compensator (STATCOM)

3.1.11
series unit
unit consisting mainly of a series transformer and a series converter, which achieves the function of a static synchronous series compensator (SSSC)

3.2 Symbols

C	sub-module capacitance
C_{VSC}	VSC DC capacitor
Tp	shunt transformer
Ts	series transformer
$U_{\text{a/b/c}}$	line-to-line AC voltage of the converter
$U_{\text{r line-to-line}}$	AC voltage of the receiving-end AC system, RMS value
$U_{\text{S line-to-line}}$	AC voltage of the sending-end AC system, RMS value
U_0	UPFC pre-compensation voltage
ΔU_0	compensation voltage by voltage regulation
U_{c}	compensation voltage by impedance regulation
U_{α}	compensation voltage by phase angle regulation
U_{d}	DC line-to-line voltage of the DC bus
U_{VN}	line-to-ground voltage of AC side of VSCs, RMS value
V_{u}	upper arm voltage
V_{d}	lower arm voltage
X	transmission line inductance
Z	transmission line impedance
δ_{s}	sending-end voltage angle
δ_{r}	receiving-end voltage angle

4 Principles and configurations

4.1 Basic principles

The UPFC can be equivalent to a voltage source that can adjust amplitude and phase angle ranging from 0° to 360°.The line current flows through this voltage source, resulting in the exchange of active and reactive power between the voltage source and the AC line. The structure of a UPFC used in a two-terminal transmission system is shown in Figure 1.

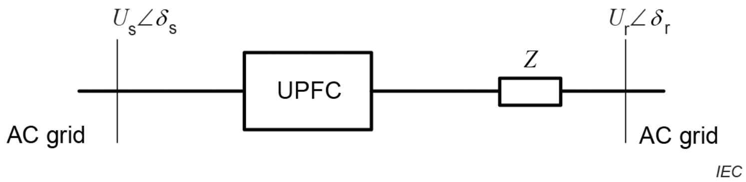

Figure 1 – UPFC used in a two-terminal transmission system

The active and reactive power of transmission lines are as follows :

$$P = \frac{U_s U_r}{X} \sin(\delta_s - \delta_r) \qquad (1)$$

$$Q = \frac{U_s}{X}\left(U_s - U_r \cos(\delta_r - \delta_s)\right) \qquad (2)$$

The UPFC regulates the line power flow by changing U_s, U_r, δ_s, δ_r and X. A UPFC power flow schematic diagram is shown in Figure 2. For active power, it is absorbed or generated by the UPFC shunt converter VSC1 via shunt transformer Tp from the connection point, and is transmitted via the DC side of the UPFC and series converter VSC2, ultimately delivered to transmission lines via the series transformer Ts. The UPFC provides an active power transmission channel for the line, enabling the total active power line transmission capacity to be increased or decreased. For reactive power, power exchange occurs on the Tp and Ts through the VSC1 and VSC2. There is no reactive power exchange between VSC1 and VSC2 [1][1].

Therefore, the UPFC is able to control the power flow, changing not only reactive power but also active power.

The various control functions of the UPFC are briefly illustrated in Figure 3. The UPFC voltage regulation function is shown in Figure 3 a), where the UPFC series compensation voltage ΔU_0 has the same phase as U_0 or its opposite, only regulating the amplitude of the voltage, instead of changing the phase of the voltage. Owing to the flexible control of series output voltages, the UPFC can easily achieve voltage regulation. Series compensation in UPFCs is the same as general series compensation. As shown in Figure 3 b), the series part has no active power exchange with transmission lines, so offset voltage U_c should be perpendicular to the line current I. Figure 3 c) shows a phasor diagram of the phase angle compensation, which changes the voltage phase angle, but does not change its magnitude. UPFC compensation voltage is indicated on the arc shown in Figure 3 c). Hence, a UPFC is equivalent to a phase shifter. Figure 3 d) shows a phasor diagram of UPFC comprehensive functionality, integrating former three functions, which changes the amplitude and phase of the voltage according to system operation [2] [3].

1 Numbers in square brackets refer to the Bibliography.