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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- withdrawn,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
$U_{\mathrm{a/b/c}}$	line-to-line AC voltage of the converter
$U_{\mathrm{r\ line\text{-}to\text{-}line}}$	AC voltage of the receiving-end AC system, RMS value
$U_{\mathrm{S\ line\text{-}to\text{-}line}}$	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.

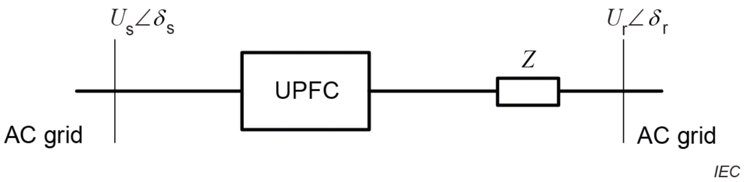


Figure 1 – UPFC used in a two-terminal transmission system

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

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

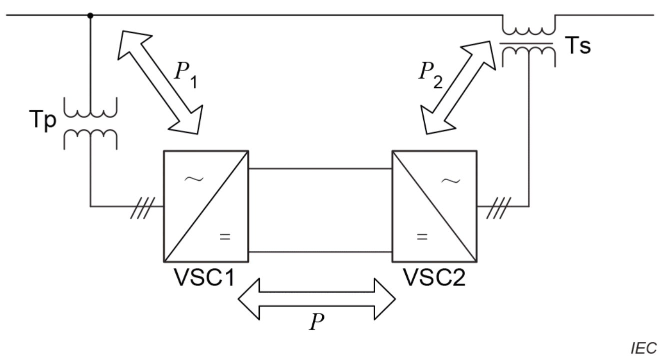
$$Q = \frac{U_s}{X}\left(U_s - U_r\cos(\delta_r - \delta_s)\right) \tag{2}$$

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].

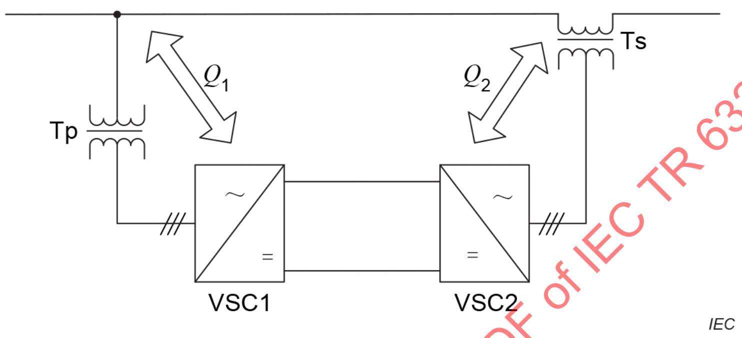
Therefore, the UPFC is able to control the power flow, changing not only reactive power but also active power.

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.



a) Active power flow



b) Reactive power flow

Figure 2 –UPFC power flow schematic diagram

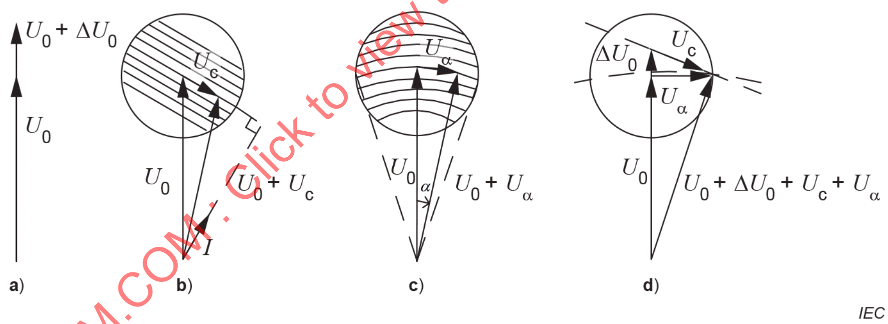


Figure 3 – UPFC control functions

4.2 UPFC configurations

4.2.1 Basic structure

A basic structure diagram of the UPFC is illustrated in Figure 4, consisting of the main circuit (series unit and shunt unit) and a control unit. The main circuit consists of two VSCs connected back-to-back on the DC side, and the AC terminals are connected to the systems via two transformers: VSC1 is connected to the transmission line in parallel via transformer Tp, and VSC2 is connected to the transmission line serially via transformer Ts. VSC1 and transformer Tp are the main shunt unit components. VSC2 and transformer Ts are the main components of the series unit [1] [4] [5].

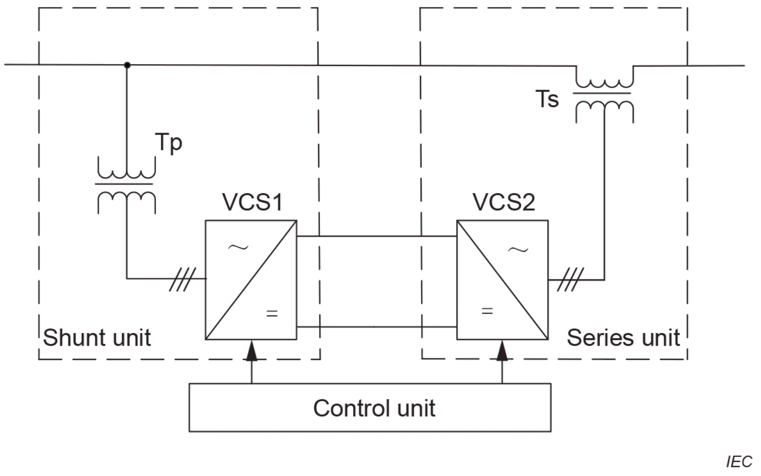


Figure 4 – UPFC structure diagram

4.2.2 UPFC configuration in single transmission line

In a single transmission line, only one UPFC is installed, as shown in Figure 5. The VSC in the shunt unit can be connected with the same side AC bus or connected with other AC bus alone.

The single transmission line UPFC can control the line power flow, regulate the AC voltage in the shunt unit, or provide fast reactive power compensation.

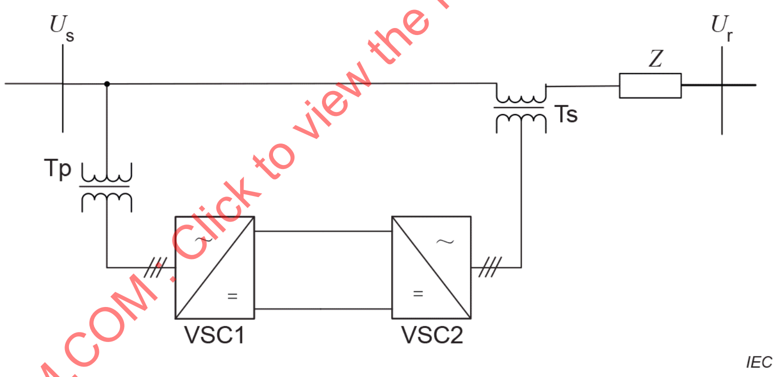


Figure 5 – UPFC configuration in single transmission line VSC

4.2.3 UPFC configuration in double transmission lines

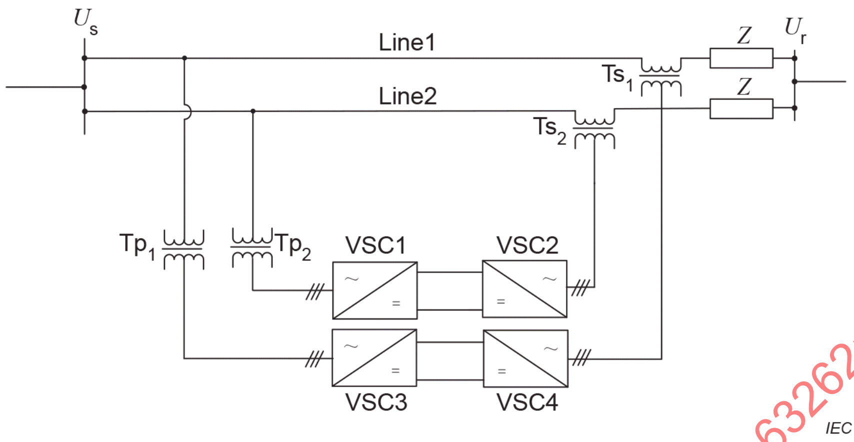
4.2.3.1 General

Double transmission line UPFCs can be composed of multi-terminal UPFCs or multiple single transmission line UPFCs with the double transmission line power flow controlled independently. The basic configuration is divided into non-common DC bus type and common DC bus type.

4.2.3.2 Non-common DC bus type

The non-common DC bus type UPFC consists of two sets of back-to-back connected VSCs. The double-line power flow can be controlled by the two series unit VSCs independently.

The non-common DC bus type UPFC has a simple structure as shown in Figure 6. When a shunt unit VSC fails or overhauls, the corresponding series unit VSC can operate in the SSSC mode, which is still able to meet the requirements of double-line power flow control and AC system voltage control in shunt unit. However, the two shunt unit VSCs need to be controlled coordinately, and the shunt and series VSCs cannot act as backup to each other, resulting in the inefficient use of VSCs, which has an impact on reliability.



Key

Tp_1 shunt transformer connected with line1

Tp_2 shunt transformer connected with line2

Ts_1 series transformer connected with line1

Ts_2 series transformer connected with line2

Figure 6 – UPFC configuration with non-common DC bus

4.2.3.3 Common DC bus type

In the common DC bus type UPFC, the VSCs are connected with a common DC bus to reduce the number of VSCs, as shown in Figure 7. In normal operation, two VSCs are connected to the series unit to control the power flow of the double transmission lines individually, and one VSC is connected to the shunt unit to support the line power flow and improve the shunt AC system reactive power reserve capacity. If a critical shortage of grid reactive power occurs, all VSCs can be connected to the AC system in parallel to steady the grid voltage.

Therefore, the three VSCs can serve as spares for each other, which makes it easy for the converter valve to overhaul and isolate the fault area, making the operating mode more flexible by adjusting the AC switch.

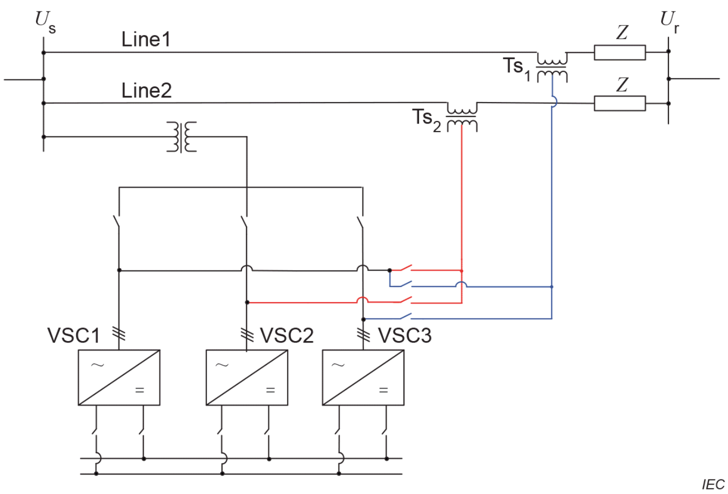


Figure 7 – UPFC configuration with common DC bus

4.2.4 UPFC configuration in multiple transmission lines

The UPFC configuration in multiple transmission lines can be deduced by analogy.

5 Design rules

5.1 Proposal selection

The principles of proposal selection for a UPFC mainly include the following [6].

a) In feasible UPFC schemes, it is necessary to consider the power grid needs for the active and reactive power control of a UPFC and factors such as site condition and corridor. Feasible UPFC site schemes should be agreed with customers. In addition to the site selection rules of conventional substations, for the purpose of UPFC site selection, it is essential to consider at least the following aspects:
   - a region with mature power grid framework but limited land resources;
   - a combined view of the present situation and future plans of the power system, comprehensively considering the control effect and efficiency of running a UPFC;
   - a realization of larger flow adjustment with smaller VSCs' capacity.

b) Developing corresponding grid connection proposals for each installation site and determining a UPFC capacity of each proposal by electrical calculation.

c) Analysing the adaptation of each proposal, including:
   – for an uncertain power supply during planning period in service (or decommissioning), analysing whether a UPFC can satisfy the power system needs for active and reactive power control.
   – for an uncertain transmission and transformation project during planning period, analysing whether a UPFC can satisfy the power system needs for active and reactive power control if the project is in operation.
   – for important operation mode adjustment that may occur during planning period, analysing whether a UPFC can satisfy the system needs for active and reactive power control after operation mode adjustment.

d) Technical and economic comparisons through the unit capacity increasing transmission capacity, reactive voltage support capability, occupancy of social resources, investment and annual cost. Detailed information of the Nanjing UPFC project can be found in Clause A.8.

5.2 Parameter selection and coordination

Parameter selection and parameter coordination mainly include the following.

a) The voltage in the UPFC series unit should be considered the different steady-state operation modes in a target year and a planning year. Different voltage and power flow control targets can be obtained by calculation.

b) The rated current of the UPFC series unit should match line current.

c) The capacity of the UPFC series unit equals the product of maximum voltage in the series unit and rated current and satisfies the power flow control demand.

d) The short-circuit current tolerance level should not be lower than the short-circuit current tolerance level of the connected system in maximum operation mode. The short-circuit current duration should match the system short-circuit current duration.

e) The series transformer of the UPFC has over-excitation capacity under maximum short-circuit current of connected system. Over-excitation duration should match operation time of by-pass switch and operation time of line breakers if the bypass switch loses efficacy.

f) An FBS is used to protect the UPFC series unit, for example the thyristor bypass switch (TBS) combined with a fast mechanical bypass switch (MBS). The operation time of the

FBS is usually designed according to the engineering system requirements. In principle, the shorter the operation time, the more effective it is to isolate the fault to protect the equipment.

g) The capacity of the UPFC shunt unit satisfies requirements of active power exchange of series unit demands, system reactive power demands, and AC voltage control demands at the same time.

h) In DC field, determine DC voltage according to the capacity of VSCs, VSC valve-side voltages of series and shunt transformer.

6 Performance requirements for key equipment

6.1 General

The main components of a UPFC include VSCs, VSC valve water cooling systems, series transformers, shunt transformers, FBSs, circuit breakers, valve reactors, starting resistors, current and voltage measuring devices, control and protection equipment, etc. The following describes only the performance requirements of VSCs, series transformers, shunt transformers, FBSs and converter valve cooling systems. The performance requirements of control and protection devices are described in Clause 8. Moreover, other devices can refer to the corresponding publications.

6.2 Voltage sourced converters (VSCs)

6.2.1 General

The VSC is the key component between the UPFC and the grid for exchanging active and reactive power. It generally consists of VSC valves and other components. According to the topological structure, the technical solutions for the UPFC VSC are the three-level multiplicity converter and the modular multi-level converter.

6.2.2 Three-level converters

The basic topologies of the three-level converters include the diode clamped type three-level converters and the flying capacitor type three-level converters. Taking the diode clamped type and IGBT as an example, the main circuit topology is shown in Figure 8. There are two voltage dividing capacitors in the left side with the same capacitor value. The central point of the two capacitors is the neutral point, which divides the DC voltage into 3 levels: $U_d/2$, 0, and $-U_d/2$. See IEC TR 62543 for details.

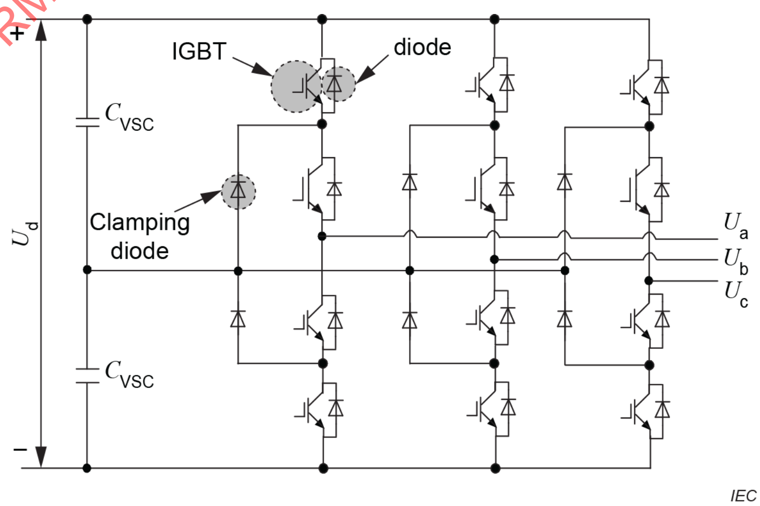


Figure 8 – Typical three-level converter topology

6.2.3 Modular multi-level converters (MMCs)

The typical main circuit topology of a three-phase MMC is shown in Figure 9, which contains six converter arms. Each arm consists of many sub-modules (SMs) and a valve reactor in series. The connection point of the two valve reactors is the AC output of the corresponding phase arm. An SM generally applies a half-bridge structure or full-bridge structure composed of power electronic switches with a DC storage capacitor in parallel.

Each SM is equivalent to a controlled two-level voltage source, so each arm is equivalent to a controlled multi-level voltage source. By changing the number of SMs on the upper and the lower arms, a desired AC voltage output can be simulated. More details are given in IEC 62751-2. The dotted line is an ideal AC voltage sine wave while the actual generated waveform is a multi-level step wave, as shown in Figure 10. When the levels are sufficient, the actual waveform is very close to the ideal sine waveform and has almost no lower harmonics.

1.1.1 Performance requirements of VSCs

a) Current tolerance

The current tolerance capability of the VSCs should consider the level of the normal operating current and transient overcurrent for the device, especially for the self-turn-off switches, capacitors and so on, including amplitude, duration, number of cycles, current rise, etc. Meanwhile, the sufficient safety margin should also be considered.

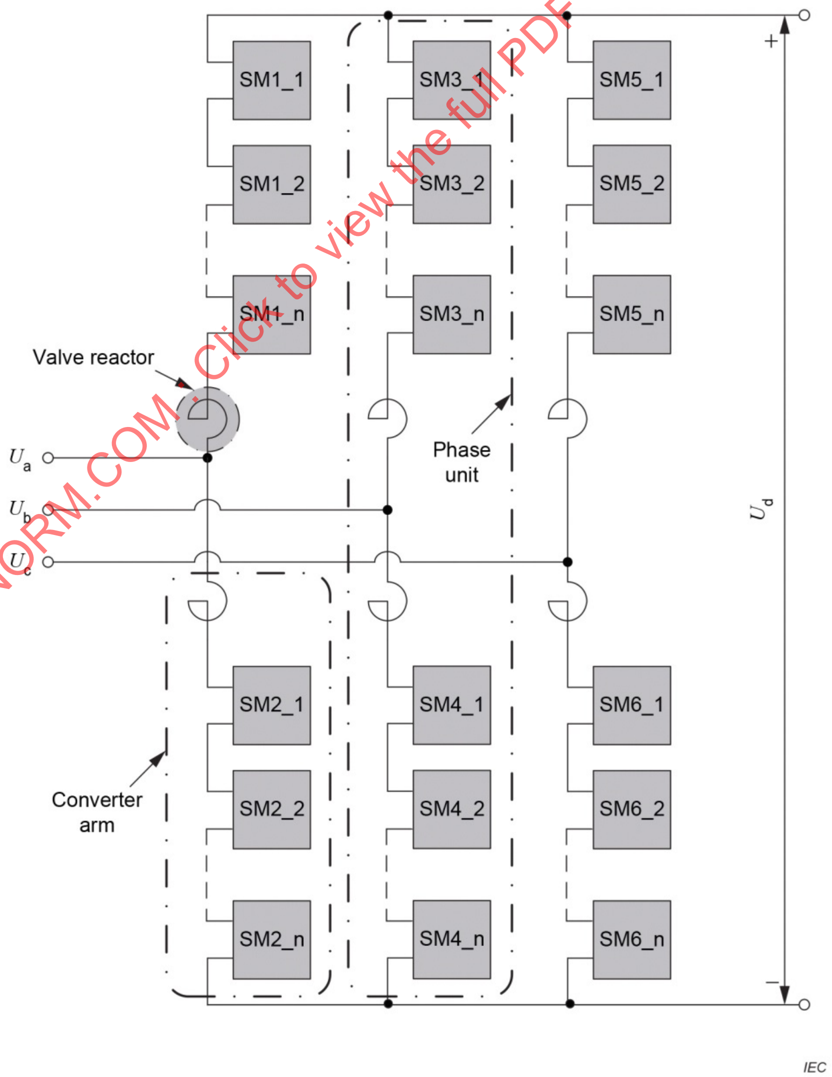


Figure 9 – Typical MMC topology

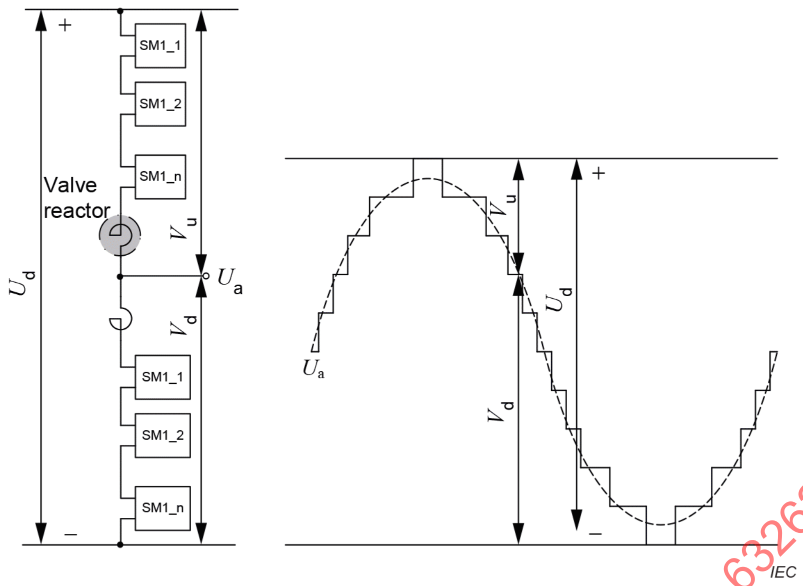


Figure 10 – Single-phase voltage waveform on the AC side

b) Harmonics

Harmonics are mainly generated by the VSCs in a UPFC. The valve reactor is applied to restrict the harmonic. The design parameter of the valve reactor is mainly determined by di/dt and amplitude of the fault current, as well as the total harmonic distortion (THD) of the load current. During design phase, the VSCs' topology, especially including the number of multi-level and control strategy like switch frequency, are required to satisfy the harmonic requirements of power grid and customers. The calculation methods of harmonics are proposed in IEC TR 62543.

c) Valve cooling requirements

Due to the large heat flux of valve device, the high performance cooling system is needed. Cooling methods may include water cooling, air cooling and natural cooling. The general requirements of the cooling system should be agreed with customers, and should be designed according to the system performance and converter valve performance.

6.3 Series transformer

6.3.1 General

The series transformer is an important component for exchanging power between converter and AC system. It connects the MMC and transmission lines, isolating the MMC and AC system, limiting the short-circuit fault current, protecting the VSC valve.

Series transformers are similar to conventional transformers, but owing to their series structure, and the transmission line current flowing through grid-side windings, they have additional requirements in terms of connection mode, insulation level, short-circuit ability and ensuring over-excitation tolerance, and they can exhibit unique characteristics in design, manufacturing and operation.

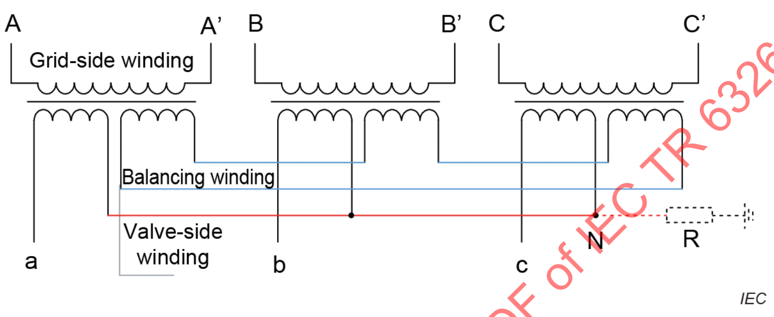
6.3.2 Winding connection mode

The structure of the series transformer is special. The grid-side windings are connected in series to the three-phase line, requiring six ports to connect a three-phase transmission line. The valve-side windings are connected to the MMC, with three ports in star or delta connections. The typical structure of series transformer winding is shown in Figure 11.

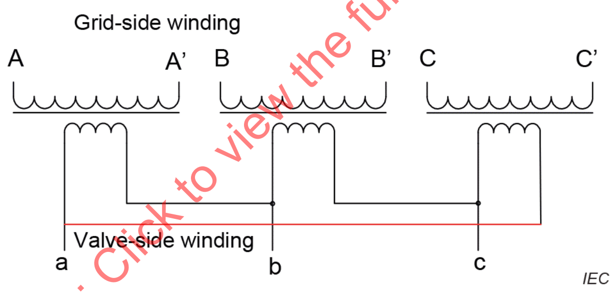
If the transformer valve-side winding in series uses the star connection with the neutral point connected to the ground by resistance, the third-order harmonic current has the flow path, making the electromotive force close to a sinusoidal shape. If required, the balancing winding needs to be added to reduce the fault valve-side voltage after the line fault. It can also provide third-order harmonic flow path and change the transformer zero sequence impedance. The structure of the series transformer with star connection in valve-side winding is shown in Figure 11 a).

If the valve-side winding of the series transformer has a delta connection, the third-order harmonic current flows between the three-phase windings, and the zero-sequence current in the grid-side winding is related to the AC system. When using this connection mode, the UPFC needs an additional artificial ground structure. The structure of the series transformer with delta connection in valve-side winding is shown in Figure 11 b).

Other winding connections are also acceptable if they can meet the requirements of the engineering and customers.



a) Star connection in valve-side winding



b) Delta connection in valve-side winding

Figure 11 – Typical structure of series transformer winding

6.3.3 Insulation level

The insulation level between the series transformer grid-side winding and the ground is not related to rated voltage, but rather to terminal insulation level. The insulation level is determined by the AC system.

Grid-side windings of series transformers string into the transmission line separately without any grounding connection, and although the injection voltage is small (i.e., the voltage between both ends of the windings is not high), its grid-side terminal to ground winding at insulation level should match the line voltage.

The terminal voltage of the series transformer winding is small during normal operation, but it will change abruptly, with large voltage spanning when a ground fault occurs in the export series transformer, and so the transformer winding insulation level should clearly satisfy fault insulation requirements.

6.3.4 Short-circuit capability

The series transformer operates in the AC line in series, resulting in the system short-circuit current being easy to bear. Therefore, three factors should be considered:

- the leakage impedance of the series transformer can limit the system short-circuit current to the required value;
- the voltage loss on the series transformer should not be too great for normal operation;
- the residual voltage on the AC bus at short circuit should be checked.

6.3.5 Over-excitation tolerance

When a fault occurs in the system, regardless of the operating state of the winding on the series transformer valve side, whether open circuit or short circuit, the grid-side winding terminal of the series transformer withstands a large mutation voltage, which produces serious over-excitation in the transformer iron core. If the core temperature rises, there is a grave risk of damage to the transformer. Therefore, the series transformer should have a strong over-excitation tolerance.

6.3.6 DC biasing

During the design phase, the following aspects should be taken into account:

- grid-side winding should be able to withstand the long-term DC current from the AC grid;
- the neutral point of the valve-side winding should be able to withstand a certain amount of DC biasing current which includes the short-term DC current resulting from the DC pole-to-ground fault of the converter and the long-term DC current caused by controlling the inherent error.

6.4 Shunt transformer

6.4.1 General

The shunt transformer in the UPFC together with the converters achieves the conversion between the AC system and the DC system, isolating the AC system and the DC system, limiting the short-circuit current, and protecting the converter valve from damage.

The principle and structure of the shunt transformer are the same as those of the conventional on-load regulation transformer, but there are differences in winding connection and on-load voltage regulation.

6.4.2 Winding connection

The general requirement of UPFC operation is that the zero-sequence current produced by an AC grid fault should not flow into the converter side, so the shunt transformer should limit short-circuit current on valve side and cut off the zero sequence current paths between the power supply side and the converter.

In the case of a neutral point ungrounded electric network, if the shunt transformer grid-side winding uses a delta connection, the valve-side winding should use a star connection and neutral point grounding. In this way, the zero-sequence current path is cut off, and meets the grounding requirements of the UPFC. If the grid-side winding adopts a star connection without a neutral point, the valve-side winding adopts a star connection with the neutral-point grounding that can cut off the zero-sequence current path, and meets the grounding requirements of the UPFC. A typical winding structure of the shunt transformer is shown in Figure 12. A Δ/Y_n winding structure is shown in Figure 12 a), and a Y/Y_n winding structure is shown in Figure 12 b).

In practice, the connection mode of the shunt transformer should be considered by transformer manufacturing, the design of the UPFC, operational characteristics and engineering requirements.

6.4.3 On-load voltage regulation

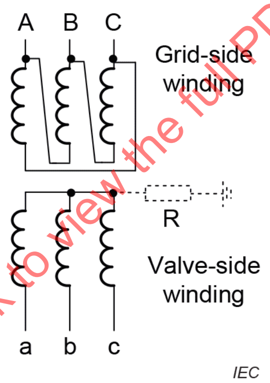
The shunt transformer is connected to the system bus, and the voltage changes with the system operating mode and load fluctuations. The shunt transformer may be equipped with an on-load voltage regulation device, which depends on engineering and customer requirements. Generally, the appropriate tap position is determined according to the grid-side voltage variation range of the shunt transformer.

6.4.4 DC biasing

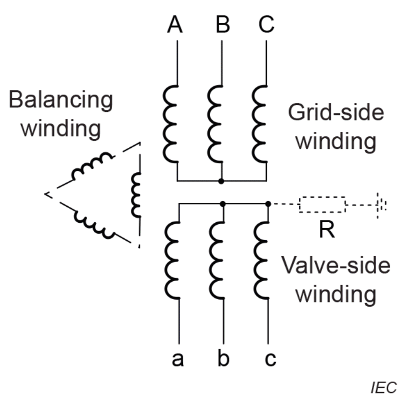
During design phase, the neutral point should be able to withstand a certain amount of DC bias current which includes the short-term DC current resulting from the DC pole-to-ground fault of the converter and the long-term DC current caused by controlling the inherent error.

6.4.5 Harmonics and over-excitation tolerance

During design phase, the impact of harmonics and shunt transformer over-excitation of shunt transformers are similar to traditional transformers. The detailed requirements are referenced in IEC TR 62543.



a) Δ/Y_n type



b) Y/Y_n type

Figure 12 – Typical winding structure of the shunt transformer

6.5 Fast bypass switch (FBS)

An FBS is used to protect the series transformer and the series converter. When a line, a transformer, or a converter is in a faulty condition, an FBS can conduct immediately. And the series side of the converter can be bypassed to isolate the converter valve from the AC system. In this way, the interaction of the AC system and the valve fault zone can be avoided to improve the system reliability.

A TBS is a kind of FBS; the structure diagram of the TBS is shown in Figure 13. It consists of multiple anti-parallel connected thyristors to ensure that the fault current flows in both directions. The performance requirements for TBS are as follows.

a) The bypass operation time during short-circuit fault needs to meet the requirements of engineering and customers, for example, it is not greater than 5 ms in the Nanjing UPFC project. Additionally, the shortening of the bypass operation time is beneficial for the UPFC system.
b) The TBS short duration time of grid-side or valve-side bypass switch usually takes into account the operation time of the low-voltage/high-voltage bypass switch and the circuit protection action time, which is determined according to the user's requirements. It is not less than the switching operation time, such as 500 ms in the Nanjing UPFC project. After the MBS is closed, the TBS turns off. Thus, the TBS does not require cooling equipment.
c) TBS rated voltage and insulation level are the same as those of the series transformer valve-side winding.
d) The maximum short-circuit current of the TBS is proportional to the maximum short-circuit current of the series transformer grid winding, and adapts the current of the three-phase short-circuit fault at the export of the series transformer in design.

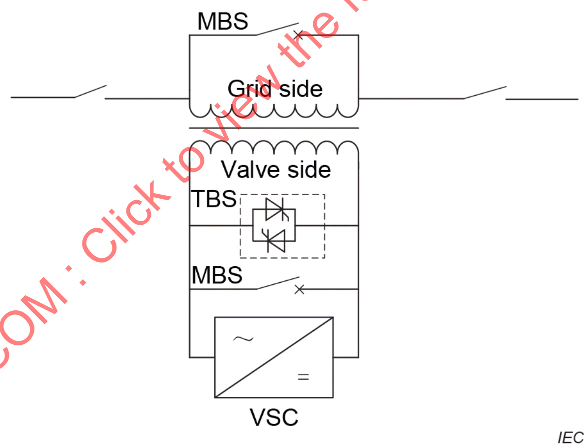


Figure 13 – Typical structure of TBS

7 Control and protection

7.1 Control system of UPFC

7.1.1 Basic requirement

According to different functions, the control system of UPFC can be divided into multiple subsystems. These subsystems intercommunicate via standard interfaces and realize complete control functions.

In general, the converter control device and valve control device are equipped independently for the series converter and shunt converter. Generic products with main stream technologies are chosen as main components and auxiliary equipment of the control system, considering their reliability, maintainability, openness and expandability.

7.1.2 Configuration requirements

It is recommended that the control system should adopt a dual configuration scheme. The control system executes orders given by the active system.

The dual control devices and their related measurement circuits, signal input and output circuits, communication circuits should be completely independent.

The standby control system should follow the key control information of the active control system in real time, to ensure the smooth switch of the active control system and the standby control system.

7.1.3 Functions of control system

Software of the control system can be designed in the hierarchical and distributed structure, following the principle of modularization or object-oriented. The software suite consists of system software (including operating system), application software, network management software, database management software, man machine interface software, etc. [3].

Control functions of UPFC generally include the following.

a) System control

Coordinate the control objects and targets of different converters, and mainly achieve the coordination control among substations and among different converters.

The system level control functions include: power coordination control of power grid, power control of transmission interface, emergency power control and emergency voltage control of power grid, reactive power-voltage automatic control, etc.

According to the requirements of power grid operation control, UPFC can also provide damping control, harmonic control, etc.

b) Converter control

Mainly accomplish the multiple basic control functions of converters, such as:

– shunt converter control includes: DC voltage control, reactive power control, AC voltage control (steady and transient) and overload limitation (optional) of shunt converter, tap control of the shunt transformer (optional);

– series converter control includes: active power control, reactive power control, impedance control, emergency current control and overload limitation (optional), etc., of transmission line.

c) Valve control

Primarily implement control and monitoring of the valves.

The valve level controller addresses the reference voltage or number of SMs which should be put into operation given by the converter control level, and then sends trigger signals to the controllers of each SM.

In addition, the valve level controller can collect the status information of each SM, realizing the functions of control and monitoring of valves.

d) Other control

Other control functions include sequence control of UPFC and fault ride-through control of shunt converter and series converter, etc.

Additional control functions are optional, including power transfer from one transmission line to another, fast recovery of UPFC system, overload control, and damping oscillation control, etc.

7.2 Protection system of UPFC

7.2.1 Basic requirements

UPFC protection is configured with respect to shunt protection area and series protection area. It should protect all the equipment in corresponding area. The cooperation should be considered between converter protection functions and valve protection itself.

The UPFC protection system should employ measures in configuration and function to avoid mal-operation and fail-to-trip. Failure of any single element should not lead to the mal-operation or fail-to-trip of protection. UPFC protection should include a complete self-monitoring function to ensure 100 % coverage rate of self-inspection.

7.2.2 Configuration requirements

The protection system generally adopts dual configuration or two out of three configurations, to ensure reliability. Measures serving to avoid mal-operation of protection should be accomplished in each set of the protection. The protection should pick up the trip independently.

The protection scope of each set of protection systems should cover the whole specified area and independently take charge of all the equipment or area completely and accurately. Each set of protection systems should be independent of each other in physical circuits and electrical circuits. Out of operation of any set of protection systems due to failures, maintenance or other reasons should not affect other sets of protection systems and leave no influence on normal operation of the whole UPFC system.

The measuring points should ensure that there are overlaps between adjacent protection scopes, and there is no dead zone. Accuracy and dynamic measurement scope of measurement equipment should be consistent with that of protection functions.

7.2.3 Functions of protection system

Under fault conditions, the UPFC protection system should change the control strategy or remove fault elements to as few as possible, ensuring the minimum influence of fault on system and equipment. The UPFC protection system fulfils the protection on converters, DC area, AC connection bus, series and shunt transformers. UPFC protection function areas in the Nanjing UPFC project are shown in Figure 14.

a) The following functions can be configured for UPFC converter area.
   - Overcurrent protection of converter arm: It detects faults in converter valves and DC grounding short circuit, and achieves fault isolation according to specific strategy.
   - Circulation current protection of converter arm: It can be configured for MMC based converter valve. It detects circulation current caused by control system or faults according to the measuring points in the upper and lower converter arm. Likewise, it achieves fault isolation according to specific strategy.
   - Differential protection of valve reactors: It detects faults of reactors with the measuring points at both sides of reactors and achieves fault isolation according to specific strategy.
   - Differential protection of valves: It detects grounding faults of valves with the measuring points at both sides of valves and achieves fault isolation according to specific strategy.
   - AC overcurrent protection in connection line of converter: It detects faults in the valve-side AC connecting line and the equipment on the connection line, converter valves and DC grounding short circuit and achieves fault isolation according to specific strategy.

b) The following functions can be configured for the UPFC DC area:

– Abnormal DC voltage protection: It detects the abnormal DC voltage with the voltage measuring points in DC lines and achieves fault isolation according to specific strategy.

– DC undervoltage and overcurrent protection: It detects faults of DC bus bipolar short circuit with the voltage and current measuring points in DC lines and achieves fault isolation according to specific strategy.

c) The following functions can be configured for UPFC AC connection bus area:

– Differential protection of AC connection bus: It detects faults in AC connection area between transformer and valves with current measuring points at the valve side of transformer and grid side of converter and achieves fault isolation according to specific strategy.

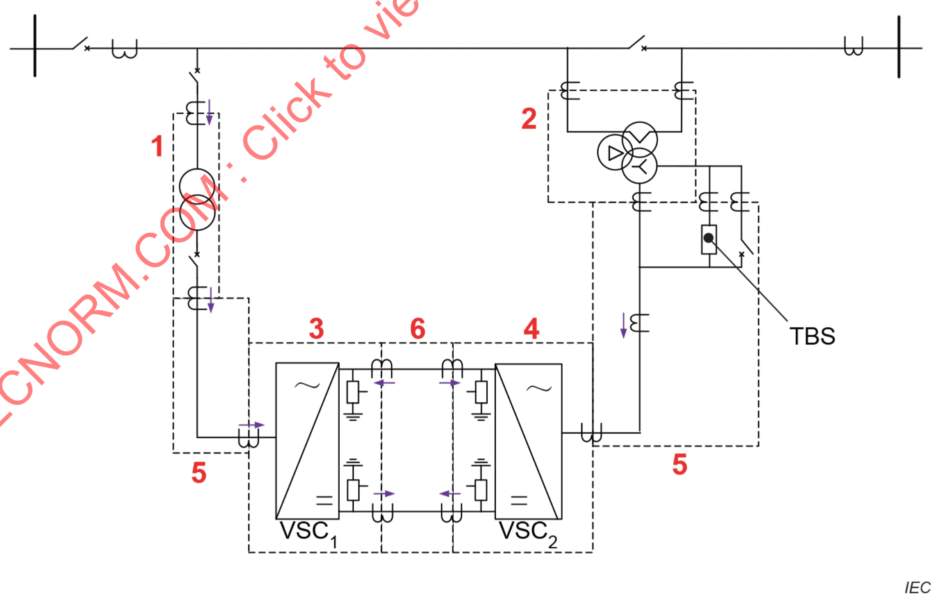
– Protection of zero sequence component at valve side: It detects grounding faults in AC lines in the valve side of the transformer with voltage measuring points in the lines and achieves fault isolation according to specific strategy.

Independent protection equipment whose protection functions can be configured according to the characteristics of its access system can be equipped for series and shunt transformers.

There would be overlap among protection scopes of UPFC converter protection, transformer protection and transmission line protection. Protection functions should cooperate with each other to ensure the safety of transmission lines, UPFC equipment and the power system.

7.3 Requirements on UPFC monitoring system

Configuration of the UPFC monitoring system is adapted to the project major loop and its operation mode. Higher information capacity and processing ability are required. The monitoring system should apply measures of vertical encryption and horizontal isolation to avoid the invasion of external illegal signals and orders. The system ought to ensure safety of the protection and control equipment network with thorough secrecy.



Key

1	shunt transformer protection area	4	series converter protection area
2	series transformer protection area	5	AC connection bus protection area
3	shunt converter protection area	6	DC protection area

Figure 14 – UPFC protection function areas

The monitoring system generally possesses the following functions:

a) collection of power system operation data and equipment operation information;
b) monitoring of power system status and equipment status;
c) operation and control: operation and control inside the substation, dispatching operation and control, sequential control and interlock, operation visualization;
d) information analysis and alarming: data identification, fault analysis, alarming function, message recording;
e) operation management: authority management, equipment management, protection fixed value management.

7.4 Requirements on communication interfaces

Requirements on communication interfaces in the control and protection system include:

a) Standard digital communication interfaces are supposed to connect control and protection hosts to the related measurement systems, facilitating the transfer of switching values and analog signals from measurement systems to the hosts.
b) Interfaces can be configured to satisfy the field requirements among different control devices and between control devices and protection ones. Information used for real time cooperation among devices can apply high speed control bus or shunt hardware interfaces. General status information may exchange through station local area network (LAN) or field bus.
c) Interfaces and communication among auxiliary secondary equipment and control and protection devices can be configured based on project requirements and specific device conditions.
d) The dual control hosts should intercommunicate via the standard network bus. Thus the standby system is able to follow the status of the active system in real time and system switch can be realized smoothly. In addition, the dual control hosts ought to have the interface with switching logic in order to realize the system switching function. Interfaces among equipment of redundant protection and the primary system are recommended to be independent.

8 Insulation co-ordination

8.1 Principles of insulation co-ordination

8.1.1 General

The primary objectives of insulation co-ordination according to 6.1 in IEC 60071-5:2014 are as follows:

- to establish the maximum steady state, temporary and transient overvoltage levels to which the various components of a system may be subjected in practice;
- to select the insulation strength and characteristics of equipment, including the protective devices used to ensure a safe, economic and reliable installation in the event of overvoltages.

8.1.2 Insulation co-ordination procedure

The general insulation co-ordination procedure for a UPFC includes the following:

a) analysing the characteristics of a UPFC;
b) evaluating the insulation performance of each device;
c) calculating the various overvoltages of UPFC on the AC side and DC side of a UPFC;
d) selecting the primary configuration of the arresters;
e) optimizing the insulation co-ordination design by iterative assessment of equipment insulation and arrester requirements;

f) determining the protective scheme and insulation level.

8.1.3 Arrester protective scheme

The basic principles of selecting the arrester arrangement for a UPFC are as follows:

a) overvoltages generated on the AC side should be limited by arresters on the AC side;
b) overvoltages generated on the DC bus or earth electrode line should be limited by DC arresters on the DC side;
c) critical components should be directly protected by arresters connected close to the components.

Based on the principles above, a unified power flow controller using a modular multi-level converter (MMC-UPFC) divided into six areas to arrange arresters is shown in Figure 15. The arrester protective scheme is shown in Table 1.

Table 1 – Arrester protective scheme for an MMC-UPFC

No.	Name of arresters	Letter symbols	Protecting objects	Protecting areas
1	Arrester of grid side of shunt transformers	A	Equipment on AC bus	Grid side of shunt transformers
2	Arrester of valve side of shunt transformers	AF, AFL1	Valve-side windings of shunt transformers (AF) and bridge-arm reactor (AFL1)	Valve side of shunt transformers
3	Arrester of AC side of VSCs	VL	Equipment at AC side of VSCs	AC side of VSCs
4	Arrester of DC side of VSCs	DL	Equipment on DC bus	DC side of VSCs
5	Arrester of valve side of series transformers	AFL2	Valve-side windings of series transformers	Valve side of series transformers
6	Arrester between two ends of TBS	AT	TBS, valve-side windings of series transformers	
7	Neutral point arrester of series transformers	AO	Neutral point of series transformers and resistor at neutral point	
8	Arrester of balancing winding of series transformers	AP	Balancing winding of series transformers	
9	Arrester of grid side of series transformers	AK, AL	Terminal insulation between grid winding of series transformers (AK), main insulation of series transformers (AL)	Grid side of series transformers

8.2 Voltages and overvoltages in service

8.2.1 Maximum operating voltage

According to the system configuration and operation characteristics of a UPFC, its rated voltages and maximum operating voltages can be defined from six areas as shown in Figure 15.

The maximum voltages of each area can be determined according to the following principles.

a) Grid side of shunt and series transformers: the rated voltages of grid side of shunt and series transformers and their maximum voltages depend on the voltages of the AC system they are connected to.

b) Valve side of shunt and series transformers: maximum operating voltages of valve sides of series and shunt transformers U_{M} can be calculated by the following equation:

$$U_{\text{M}} = kU_{\text{N}} \tag{3}$$

where

U_{N} is the rated voltage of valve sides of shunt and series transformers;

k is a coefficient considering reactive current flow, the chosen transformer impedance and operation mode, etc., for example, k = 1,15.

c) AC side of VSCs: the maximum operating voltages of AC side of VSCs U_{VN} can be calculated using the following equation:

$$U_{\text{VN}} = \frac{M}{\sqrt{2}} \frac{U_{\text{d}}}{2} \tag{4}$$

where

M is the voltage modulation ratio – the ratio between peak value of AC phase voltage to half of the converter DC voltage.

d) DC side of VSCs: taking into account the neutral voltage fluctuation in operation, measurement error and other factors, it is feasible to set the maximum operating voltage at DC side as 1,05 times the rated DC operating voltage.

8.2.2 Sources of overvoltages

Sources of overvoltages of a UPFC include:

a) overvoltages at grid side of series and shunt transformers mainly caused from lightning overvoltage, circuit breaker operations, and short-circuit faults from connected AC grid;

b) overvoltages at valve side of the series and shunt transformers caused by overvoltages at grid side and faults at valve side;

c) overvoltages at AC side of VSCs and two ends of valves mainly caused by faults in bridge-arm, AC side of VSCs, grid side and valve side of series and shunt transformers;

d) overvoltages at DC side of VSCs mainly because of ground faults on DC lines and short-circuit faults between two DC lines.

8.3 Determination of the required withstand voltages (U_{rw})

To ensure the safety of the equipment under overvoltage, the withstand level of equipment insulation should be higher than the protective level of arresters. In addition, the insulation performance of the equipment can be affected by many factors, such as the aging of the insulation material, weather (rain, fog, etc.), high altitude, pollution, arrester aging, etc. Thus, a coefficient of more than 1 is needed between the required insulation withstand voltage of the equipment and the protective level of arresters. Selecting an appropriate indicative value will not cause unnecessary economic waste and ensure the security and stability of the system. According to the above principles, the indicative values of the Nanjing UPFC are shown in Table 2, and are in accordance with IEC 60071-5. Table 2 provides a set of indicative values for this factor which may be used as design objectives if not specified by the user or the relevant product committees.

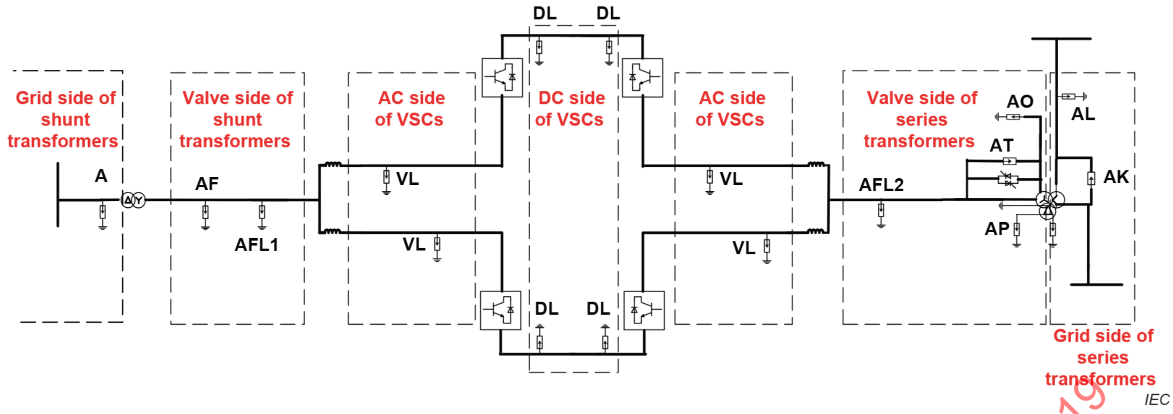


Figure 15 – Example of arresters protecting areas for an MMC-UPFC

Table 2 – Indicative values of ratios of required impulse withstand voltage to impulse protective level

Type of equipment	Indicative values of required impulse withstand voltage/impulse protective level[a b]	
	RSIWV/SIPL	RLIWV/LIPL
AC switchyard including busbars, outdoor insulators, and other conventional equipment	1,2	1,25
AC filter components	1,15	1,25
Transformer grid side	1,20	1,25
Transformer valve side	1,15	1,20
VSCs	1,15	1,15
DC valve hall equipment	1,15	1,15
TBS	1,15	1,15

Key

LIPL lightning impulse protective levels

RLIWV required lightning impulse withstand voltage

RSIWV required switching impulse withstand voltage

SIPL switching impulse protective levels

The indicative values of the Nanjing UPFC are only examples, which should be a consensus between suppliers and customers.

[a] Indicated values are stated for general design objectives only. Appropriate final ratios (higher or lower) can be selected according to the chosen performance criteria.

[b] Indicative ratios are on the basis that any equipment is directly protected with a surge arrester.

The rated withstand voltage values are equal to or larger than the required withstand voltage values. For AC equipment, the rated withstand voltages correspond to standard values as stated in IEC 60071-1. For HVDC equipment, there are no standardized withstand voltage values and the rated withstand voltages are desirable to the feasible values. AC, DC and impulse voltage should be considered in DC applications [7].

9 System performance

9.1 General

The system performance of a UPFC mainly includes steady-state performance, dynamic performance and fault ride-through performance [8].

9.2 Steady-state performance

9.2.1 General

The steady-state performance of a UPFC generally includes steady state of transmission line power control, steady state of reactive power compensation or voltage control, and overload.

9.2.2 Steady state control requirement of transmission line power

The maximum deviation of transmission line power between the reference value and the measured value under UPFC control is chosen according to system needs, for example less than ±1 %.

9.2.3 Steady state control requirement of reactive power compensation and voltage control

In the reactive power control mode of the UPFC, the maximum deviation between the measured reactive power of the shunt converter and the reference value is chosen according to system needs, for example, less than ±1 %. The following expression is used to calculate the steady-state error:

$$E(\%) = \frac{M_\mathrm{C} - M_\mathrm{R}}{M_\mathrm{N}} \times 100\ \% \tag{5}$$

where

E is the steady-state error;

M is the measuring value;

M_R is the reference value;

M_N is the nominal value.

9.2.4 Overload capacity requirement

In the UPFC, the design of the converter valve, valve reactor, series transformer and shunt transformer should consider the continuous or short-time overload tolerance. The specific value is determined according to the project requirements. For instance, the overload capacity for the converter valve is 1,05 p.u. for long time operation, 1,1 p.u. for 2 h and 1,2 p.u. for 3 s, where p.u. means "per unit" and the basic unit is the rated power (see IEC TR 61000-2-14:2006, 3.13).

9.3 Dynamic performance

The general requirements should be agreed with customers and suppliers based on power grid, control object and control strategies. Generally, the active and reactive step responses are required in dynamic performance. For instance, the dynamic performance is set as follows.

a) When failure occurs in a power grid and meets UPFC fast control start-up condition, the UPFC can respond quickly within the allowable range of capability.

b) The UPFC has fast control ability of active and reactive power. When the AC system is disturbed, the power can be regulated by the emergency power control, or the voltage support can be supplied by the AC voltage control on the grid side.

c) The reactive power step in the UPFC system has no significant influence on the active power, the DC voltage, the reactive power output or voltage of the shunt side.

d) The active power step in the UPFC system has no significant influence on reactive power, DC voltage, reactive power output or voltage of the shunt side.

e) When oscillations occur in AC systems, they should be limited by the damping oscillation function of the UPFC system.

9.4 Fault ride-through performance

The general requirements of UPFC fault ride-through performance are as follows.

a) When the voltage is reduced under a certain value, the UPFC system can continue to operate through fault ride-through control without tripping from the grid, and can provide reactive power support.

b) When AC grid failure occurs, the shunt converter can ensure continuous operation by ensuring the remaining voltage at grid side. The setting of remaining voltage is based on the requirements of system and customers, such as 10 % in the Nanjing UPFC project.

c) When the series converter stops operating in a serious fault, it should be isolated very quickly after relay protection action; if a transient fault occurs in a line or occurs in the nearby line, the converter should be restarted within a short duration after the fault is eliminated.

10 Tests

10.1 General

A testing protocol should include the off-site tests of converter valves, FBS, transformers, control and protection equipment and other components, and UPFC onsite tests. Off-site tests consist of type tests and routine tests.

10.2 Off-site tests of main components

10.2.1 Converter valve

The converter valve transfers power between AC and DC systems. It should withstand normal operating voltage and current, as well as the impulse voltage and over-current resulting from the valve trigger system malfunctions or system failure. The details of the converter valve tests are given in IEC 62501, and the main type test items are shown in Table 3.

Table 3 – Main test items of converter valve

No.	Test type	Test items	Test objects
1	Operational test	Maximum continuous operating duty test	Valve or valve section
2		Maximum temporary over-load operating duty test	Valve or valve section
3		Minimum DC voltage test	Valve or valve section
4	Dielectric test	Valve support DC voltage test	Valve support
5		Valve support AC voltage test	Valve support
6		Valve support switching impulse test	Valve support
7		Valve support lightning impulse test	Valve support
8		MVU DC voltage test to earth	MVU
9		MVU AC voltage test	MVU

No.	Test type	Test items	Test objects
10		MVU switching impulse test	MVU
11		MVU lightning impulse test	MVU
12		Valve AC- DC voltage test	Valve (or valve section if agreed between supplier and purchaser)
13		Valve switching impulse test	
14		Valve lightning impulse test	
15	Other tests	IGBT overcurrent turn-off test	Valve or valve section
16		Short-circuit current test	Valve or valve section
17		Test for valve insensitivity to electromagnetic disturbance	Valve (or valve section if agreed between supplier and purchaser)

10.2.2 Fast bypass switch (FBS)

FBSs are used to isolate valves from an AC line converter when failure occurs in line or converter. TBS is one of the most widely used switches for FBS applications. The FBS prevents interaction between the AC system and the broken-down valve zone. At present there are no applicable standards for testing thyristor valves for the FBS. TBS is one of the most widely used FBS applications. Guidance for specifying the type tests is given in IEC 60700-1, IEC 61954 and IEC 62823, although not all clauses of these International Standards will be applicable. The main test items are shown in Table 4.

Table 4 – Main test items of TBS

No.	Test type	Test items	Test objects
1	Dielectric test	Valve support AC voltage test	Valve support
2		Valve support switching impulse test	Valve support
3		Valve support lightning impulse test	Valve support
4		Valve AC voltage test	Valve
5		Valve switching impulse test	Valve
6		Valve lightning impulse test	Valve
7	Operational tests	Minimum AC voltage test	Valve or valve-section
8		Maximum continuous operating duty test	Valve or valve-section
9	Valve fault current test	One-loop fault current test with re-applied forward voltage	Valve or valve-section
10		Multiple-loop fault current test without re-applied forward voltage	Valve or valve-section

10.2.3 Transformers

The transformers in the UPFC can be divided into two types: shunt transformers and series transformers. Both have the same interconnect function, structure, and experimental content. Their winding to ground insulation is also the same, but the dielectric tests are different because series transformers have the full insulation structure. The details of tests are in IEC 60076-2, IEC 60076-3, IEC 60076-4 and the main test content is shown in Table 5.

Table 5 – Main test items of transformers

No.	Test type	Test items	Test objects
1	Dielectric test	Insulation resistance and absorption ratio measurement test	Check whether the transformer is affected by dampness, dirt, or other penetrating agents overall or in part, or on its surface
2		Dielectric loss factor and capacitance measurement test	Check whether the transformer is affected by dampness overall, or degraded by the effects of oil, sludge, or serious local defects, etc.
3		Power frequency withstand voltage test	Verify the winding terminal when it is vertical to ground, and check winding and winding insulation resistance strength
4		Lightning and switching impulse test	
5	Dielectric test	Induced voltage withstand test	
6	Operational test	Winding resistance measurement test	Check the welding quality of the winding, whether the tap-changer is in good contact, and whether there is any short circuit between the winding layers
7		Voltage ratio measurement and connection group designation test	Test whether the winding voltage qualifies. Confirm that the numbers of windings of each tap shunt coils or line are the same, and judge that each connection of the lead and tap-changer is correct
8		Load test	Test whether short-circuit impedance and load loss tests qualify. Judge the winding deformation or short circuit between stocks
9		No-load test	Examine the partial or whole defect conditions of a magnetic circuit, and judge the short-circuit conditions of winding interterms
10		Temperature rise test	Examine local overheating conditions of tank, structure, and the joints between leads and drive pipes, as well as leads and tap-changers
11		Short-circuit withstand test	Test withstand ability of transformer mechanical strength under the condition of heavy current
12		Sound-level measurement test	Test transformer-rated run-time sound level and sound power level, to prevent noise pollution
13	Performance test	Winding deformation test	Test the winding deformation during transportation, installation, and operation
14		On-load transformer tap switch test	Verify switch control performance, insulation level, and reliability
15		Three-phase transformer zero sequence impedance measurement test	Provide a theoretical basis for setting safeguard measures

10.3 Onsite commissioning test

10.3.1 General

The purpose of the UPFC commissioning test is to comprehensively assess the function of all the equipment in the project and check the performance of the UPFC system to ensure the safe and reliable operation.

10.3.2 Converter energizing test

The converter energizing test is mainly to verify the transformer valve-side voltage phase sequence, amplitude, and transformer ratio by checking the valve-side voltage, valve-side