



Strategy Design and Transient Analysis of ITER PPEN Transformer On-Load Tap Changer During Converter Operation

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Abstract

Three identical three-winding main step down transformers rated at 300/250/150 MVA are installed in ITER Pulsed Power Electrical Network (PPEN) to distribute power to three independent 66 kV and 22 kV busbars for feeding Coil Power Supply System (CPSS). The On-load Tap Changer (OLTC) is installed in primary side of PPEN main step down transformer to limit the voltage in required range under the control of Reactive Power Compensation and Harmonic Filter (RPC&HF) system. A comprehensive OLTC tap changer strategy has been proposed to maintain the 66 kV busbar voltage with consideration of hysteresis band to avoid strategy instability. The circuit models of OLTC tap changer transient processes have been built to analyze the terminal voltage transients quantitatively in both amplitude and phase. And the dynamic performance during OLTC tap transition has been verified to be in accordance with the analysis by simulation. And during future campaign, the most critical situation for CPSS is that the plasma operation system would give step voltage reference from minimum to maximum or vice versa to CPSS according to the operation scenarios. Hence, the converter system operation robustness has been verified by simulation on MATLAB/SIMULINK during PPEN OLTC tap changer transition in the case of this most critical situation during plasma operation.

Keywords ITER · Coil power supply · OLTC control · Hysteresis band · Converter operation robustness

Introduction

A double circuit incoming 400 kV line connects to three main step-down transformers of ITER Pulsed Power Electrical Network (PPEN) to feed Coil Power Supply System (CPSS) with the short circuit power of around 11.7 GVA [1].

As shown in Fig. 1, the power is distributed to 66 kV and 22 kV busbars by PPEN transformers with On-load Tap Changer (OLTC) to provide maximum 500 MW active pulsed power [2]. However, only around 200 Mvar pulsed reactive power can be supplied because of the stringent voltage variation constrain at 400 kV line, therefore, Reactive Power Compensation and Harmonic Filter (RPC&HF) is needed [1].

The RPC&HF systems which connected to each three 66 kV busbars are based on Static Var Compensation (SVC) technology to provide the dynamic reactive power compensation to mitigate the voltage variation and eliminate the harmonic distortion [1, 3]. The RPC&HF Controllers also integrated PPEN transformer OLTC Tap changer control strategy to stabilize the 66 kV busbars voltage.

ITER CPSS receives AC power from PPEN to provide controlled DC voltage/current for plasma initiation, current control, shape control and position control [4]. The typical configuration of converter circuit which consists of AC/DC converters, External Bypass, Earthing Switch (ES),

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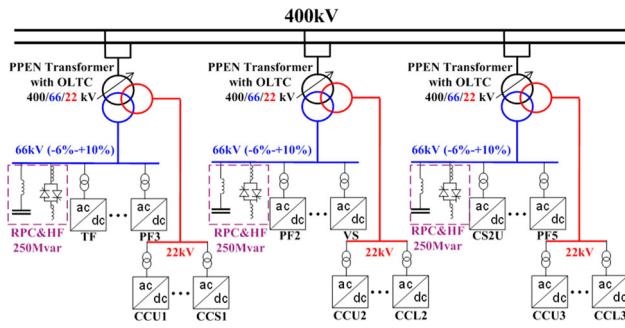


Fig. 1 ITER pulsed power electrical network

Disconnecting Switch (DS), PMS (Protective Make Switch), FDU (Fast Discharge Unit), SNU (Switching Network Unit), complex DC busbars and Earthing Fault Detection (EFD) circuit [5].

PPEN Transformer OLTC Tap Changer Strategy Design

PPEN Transformer and On-Load Tap Changer

As shown in Fig. 2, The PPEN transformer is three-phase three-winding transformer, the ratio is 400/66/22.5 kV, with on-load tap changer installed at primary side.

H. V					
TAP %	VOLTAGE V	CURRENT A	TAP CONNECTION	TAP POSITION	
+10	440000	393.6	1	K—+	1
+8.75	435000	398.2	2		2
+7.5	430000	402.8	3		3
+6.25	425000	407.5	4		4
+5	420000	412.4	5		5
+3.75	415000	417.4	6		6
+2.5	410000	422.5	7		7
+1.25	405000	427.7	8		8
			9		9A
RATED	400000	433	k	K—+/K—	9B
			1		9C
-1.25	395000	438.5	2	K—-	10
-2.5	390000	444.1	3		11
-3.75	385000	449.9	4		12
-5	380000	455.8	5		13
-6.25	375000	461.9	6		14
-7.5	370000	468.1	7		15
-8.75	365000	474.5	8		16
-10	360000	481.1	9		17
M. V					
RATED POWER MVA	VOLTAGE V	CURRENT A			
250	66000	2187			
L. V					
RATED POWER MVA	VOLTAGE V	CURRENT A			
150	22500	3849			

Fig. 2 PPEN transformer nameplate data

According to the OLTC parameters as shown in Table 1, 66 kV busbar regulation voltage of each gear is 0.825 kV.

The OLTC shall be able to operate manually and automatically to compensate the voltage fluctuations on the control of RPC&HF systems to maintain 66 kV busbar voltage in required range for ensuring the RPC&HF system to generate enough reactive power, as well as helping the AC/DC converters to output enough DC voltage inside and outside of the plasma pulse.

OLTC Tap Changer Strategy Design

OLTC control is performed by RPC&HF system through regulation of tap changer to adjust the ratio, thereby adjust step-down transformer secondary side voltage in proper range to prevent 66 kV busbar over-voltage or under-voltage.

As shown in Fig. 3, the OLTC tap changer is designed with considering following basic rules.

- OLTC tap only can be adjusted (up or down) one gear per time.
- Time delay has to be inserted between tap transitions.
- Hysteresis band has to be considered to avoid unstable strategy oscillation.

The required operation range of 66 kV busbar voltage is from 62 (− 6%) to 72 kV (10%). As shown the parameters in Table 2, the operation zone of 66 kV busbar voltage is from 63.65 to 70.35 kV, it is slightly narrower than the required operation range in order to decrease the possibility of being operated out of operation range.

Firstly assume that the initial position of tap is in the middle. If the 66 kV voltage is higher than U_{upper} and lower than $(U_{upper} + 0.825)$, which lasts more than t_1 , the controller sends out gear-up command to OLTC to raise one gear. And during the time of t_1 , if the voltage falls back to lower than $(U_{upper} - 0.825)$, the Timer1* will be reset to avoid fault adjustment. And the 0.825 kV hysteresis band between start and reset of the timer will avoid

Table 1 On-load tap changer parameters

Parameter	Value
Maximum number of operating positions	19
Gear number	17
Mid-positions	3
Ability to tap	$\pm 8 \times 1.25\%$
Total regulation range	$\pm 10\%$
Rated tapping voltage	4000 V
Rated through current	700 A

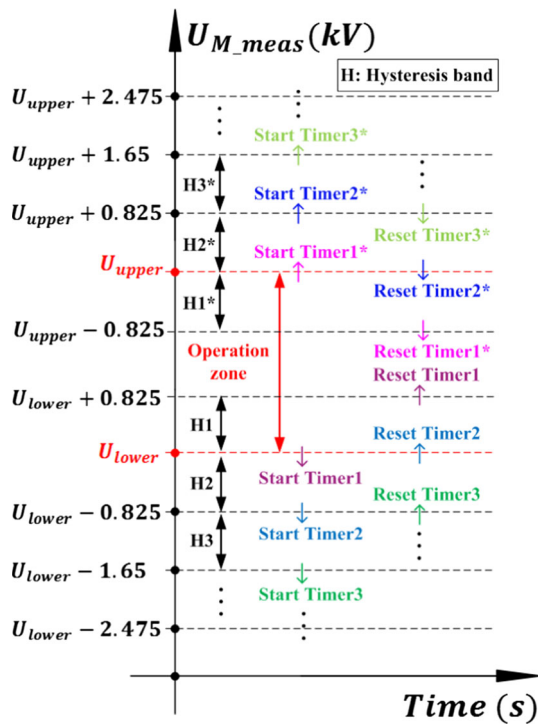


Fig. 3 Tap changer strategy with hysteresis band

Table 2 Parameters of OLTC tap changer strategy

Name	Description	Value
U_{M_meas}	66 kV busbar measured voltage	Measured
U_{lower}	Lower voltage limitation	63.65 kV
U_{upper}	Upper voltage limitation	70.35 kV
H	Hysteresis band	0.825 kV
t_1	Delay time of Timer1/Timer1*	9 min
t_2	Delay time of Timer2/Timer2*	6 min
t_3	Delay time of Timer3/Timer3*	3 min

the control strategy oscillation in the case of 66 kV busbar voltage fluctuation.

If the 66 kV voltage is higher than ($U_{upper} + 0.825$), and lower than ($U_{upper} + 1.65$), both timer1* and timer2* are activated, and the gear-up command will be sent to OLTC no matter which timer reaches the time first, then reset timer1* and timer2*, and reappraise the 66 kV AC voltage. The rules are applicable in the other voltage range in the case of overvoltage. And vice versa, the strategy is the similar when the 66 kV voltage is lower than U_{lower} .

Transient Analysis of OLTC Tap Transition

Tap Transition Process

The OLTC main components include contact system (main contacts, main switching contacts, transition contacts, etc.), transition impedance, reversing change-over selector, gearing, drive mechanism and so on. Figure 4 shows the simplified OLTC tap changer transient process from tap 5 to tap 6. The transition impedance in the form of resistor bridges adjacent taps for transferring load from one tap to the other without interrupting the current. The phase and amplitude of OLTC terminal voltage will be changed because of the transition resistors. As a consequence, the phase and amplitude of 66 kV busbar voltage is also changed during tap transition process.

Circuit Analysis During Transition

As described previously, in order to analyze the phase shift and amplitude variation of voltage quantitatively, the OLTC circuit models of five processes have to be built, which are shown from Figs. 5, 6, 7, 8 to 9. And the symbols are described in Table 3.

Two directions of tap up and tap down are applicable in OLTC tap changer. As shown in Fig. 4, tap up equivalent to increase the 66 kV busbar voltage, the direction is from N to N + 1. Tap down equivalent to decrease the 66 kV busbar voltage, the direction is from N to N - 1. These two directions induce the different tap-changer terminals voltage during the transient process. In the following

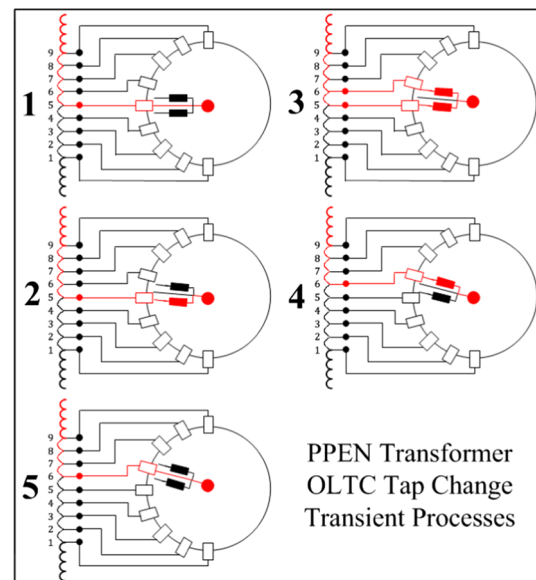


Fig. 4 Transient process of OLTC tap transition

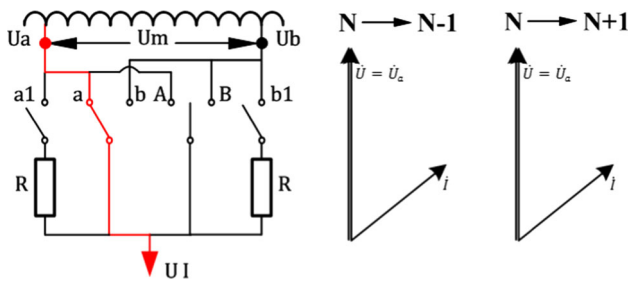


Fig. 5 Circuit and vector diagram of process 1

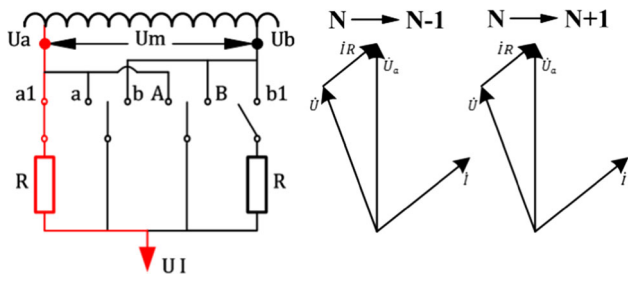


Fig. 6 Circuit and vector diagram of process 2

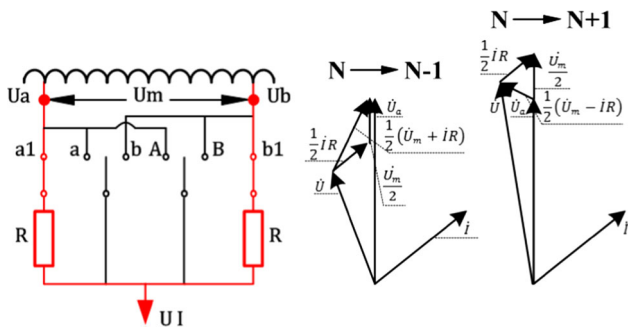


Fig. 7 Circuit and vector diagram of process 3

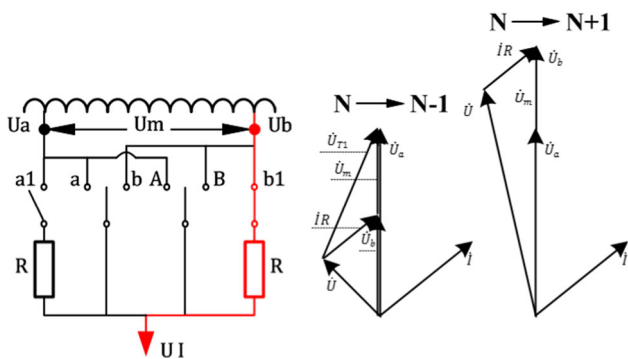


Fig. 8 Circuit and vector diagram of process 4

analysis, the reversing change-over selector is assumed at K + position.

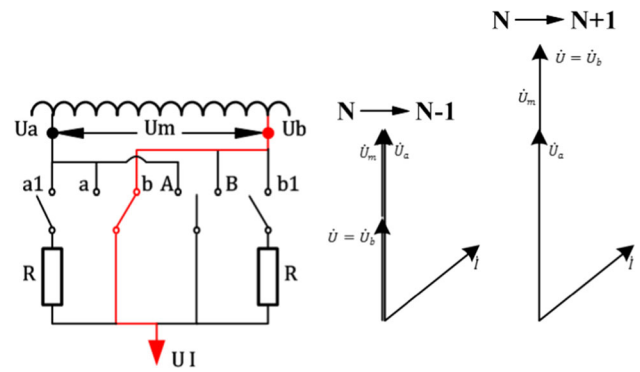


Fig. 9 Circuit and vector diagram of process 5

Table 3 Symbol description

Symbol	Description
A, B	Main contact
a, b	Main switching contact
a1, b1	Transition contact
Ua, Ub	Voltage of tapping
U	Voltage of tap-changer terminals
I	Current of tap-changer terminals
Um	Step voltage
R	Transition resistor

Process 1 Analysis

Before changing the tap, load current flows through main contact A. Then the A is switched off to transfer load current to main switching contact a as shown in Fig. 5. In this process, the phase and amplitude of \dot{U} is equal to \dot{U}_a in both directions.

$$\dot{U} = \dot{U}_a \tag{1}$$

Process 2 Analysis

During this process, transition contact a1 is switched on and main switching contact a is switched off. Consequently, an arc is generated, then load current flows through transition resistor R after arc extinguished. Thus, recovery voltage $\dot{U}_r = \dot{I}R$ is generated across the main switching contact a. Hence, the tap-changer terminals voltage can be calculated by the following equation.

$$\dot{U} = \dot{U}_a - \dot{I}R \tag{2}$$

The vector diagram can be described in Fig. 6 according the equation above.

Process 3 Analysis

As shown in Fig. 7, the transition contacts a1 and b1 are both connected. Therefore, a circulation current is generated by the step voltage \dot{U}_m .

$$\dot{I}_c = \dot{U}_m / 2R \tag{3}$$

Meanwhile, in the direction from N to N - 1, the current \dot{I}_{a1} which flows through a1 can be described.

$$\dot{I}_{a1} = \frac{\dot{I}}{2} + \dot{I}_c = \frac{1}{2} \left(\dot{I} + \frac{\dot{U}_m}{R} \right) \tag{4}$$

As a consequence, the tap-changer terminal voltage can be obtained.

$$\dot{U} = \dot{U}_a - \dot{I}_{a1}R = \dot{U}_a - \frac{1}{2} (\dot{U}_m + \dot{I}R) \tag{5}$$

In the direction from N to N + 1, the current \dot{I}_{a1} which flows through a1 can be obtained.

$$\dot{I}_{a1} = \frac{\dot{I}}{2} - \dot{I}_c = \frac{1}{2} \left(\dot{I} - \frac{\dot{U}_m}{R} \right) \tag{6}$$

Therefore, the tap-changer terminal voltage can be obtained.

$$\dot{U} = \dot{U}_a - \dot{I}_{a1}R = \dot{U}_a + \frac{1}{2} (\dot{U}_m - \dot{I}R) \tag{7}$$

Process 4 Analysis

In this process, transition contact a1 is switched off with arcing. Then the load current transfers to transition contact b1 after arc extinguished.

In the direction from N to N - 1, the recovery voltage across a1 can be described as follows.

$$\dot{U}_{T1} = \dot{U}_m + \dot{I}R \tag{8}$$

And the tap-changer terminal voltage can be calculated.

$$\dot{U} = \dot{U}_a - \dot{U}_m - \dot{I}R \tag{9}$$

In the direction from N to N + 1, the tap-changer terminal voltage can be obtained.

$$\dot{U} = \dot{U}_a + \dot{U}_m - \dot{I}R \tag{10}$$

Process 5 Analysis

As shown in Fig. 9, main switching contact b is switched on, and the load current transfers to branch b. Then switch off transition contact b1. At last, main contact B closes and load current transfers to branch B. The transition is finished.

In the direction from N to N - 1, the tap-changer terminal voltage is described below.

$$\dot{U} = \dot{U}_b = \dot{U}_a - \dot{U}_m \tag{11}$$

In the direction from N to N + 1, the tap-changer terminal voltage is described below.

$$\dot{U} = \dot{U}_b = \dot{U}_a + \dot{U}_m \tag{12}$$

Voltage Fluctuations Calculation

OLTC regulates the AC voltage in both up and down directions with five processes. Therefore, the tap-changer terminal voltage fluctuates four times to reach the final voltage. Hence, voltages of 66 kV busbar and 22 kV busbar fluctuate synchronously. Phase and amplitude variation are both exist in the voltage fluctuations. In order to clarify the severity of voltage fluctuations, the maximum phase shift and maximum amplitude variation have to be assumed and calculated.

According to the supplier’s information, the transition resistor R is 5.36 Ω; the step voltage U_m is 2.9 kV. The primary side rated current of PPEN transformer is 433A. Assume that the PPEN transformer is running on full load.

Calculation During OLTC Tap Down

As shown in Fig. 10, the vector diagram of tap-changer terminal voltage indicates the fluctuations very clearly. And every vector is described by an equation which has been described previously. The maximum amplitude changing happens when \dot{U} and \dot{I} are in the same direction. And the maximum phase shift happens when the angle between \dot{U} and \dot{I} is 90°. Therefore, as shown in Table 4, the maximum phase shift and amplitude changing during every process can be easily obtained.

Calculation During OLTC Tap Up

As shown in Fig. 11, there are also five processes and four transients during OLTC tap up, but the transient trend is different from OLTC tap down. It can be observed that

Fig. 10 Vector diagram of tap-changer terminal voltage from N to N - 1

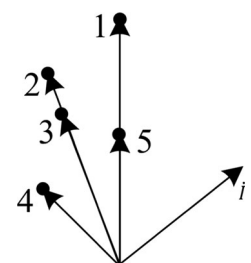
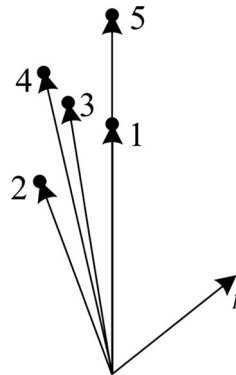


Table 4 Maximum voltage fluctuations form N to N - 1

Process	Max phase shift	Max amplitude variation (pu)
1	0°	0
2	0.57°	0.996% decrease
3	0.287°	1.126% decrease
4	0.58°	2.251% decrease
5	0	1.25% decrease

Fig. 11 Vector diagram of tap-changer terminal voltage from N to N + 1



voltage decrease only exists during process 2. And voltage increase happens in the other processes.

This phenomenon can also be calculated according to previous analysis as shown in Table 5.

Simulation Validation

As shown in Fig. 12, simulation model of three-phase OLTC regulating transformer has been built with consideration of transient processes by MATLAB/SIMULINK to verify the analysis and calculation. Three Multi-Winding Transformer blocks with PPEN transformer parameters is selected to simulate the transient processes of tap changer. In case that it implements a transformer where the number of windings can be specified in the primary side (left side windings) which is corresponding to the real PPEN transformer, and the simplified equivalent circuit is shown in

Table 5 Maximum voltage fluctuations form N to N + 1

Process	Max phase shift	Max amplitude variation (pu)
1	0°	0
2	0.57°	0.996% decrease
3	0.283°	0.13% increase
4	0.563°	0.26% increase
5	0	1.25% increase

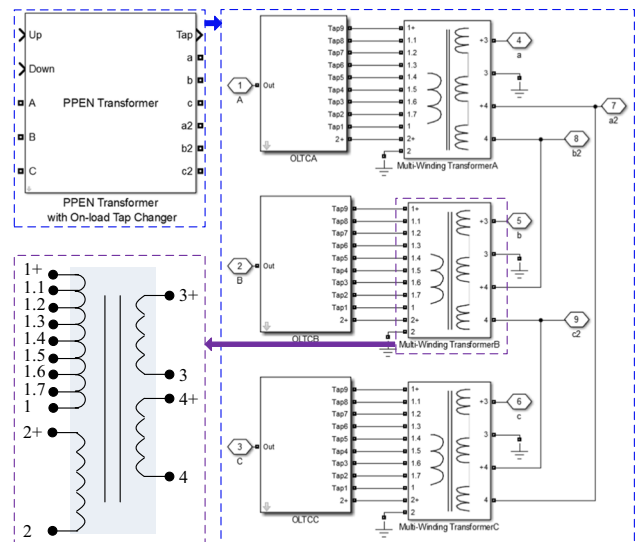


Fig. 12 Simulation model of PPEN OLTC transformer

bottom left of Fig. 12. And three corresponding OLTC modules which integrated two transition resistors are applied to fulfill the processes indicated in Fig. 4.

As shown in Fig. 13, the PPEN transformer operates on full load. And the simulation results indicate voltage shifts very clearly; there are five processes and 4 transients as described in Fig. 10. Therefore, it can be concluded that the analysis and calculation correspond to the real OLTC tap down behavior.

As shown in Fig. 14, the tap up from position 9 to position 10 has been simulated under the full load operation of PPEN transformer. The simulation results indicate the voltage oscillation trend conforms to the analysis above. Therefore, it can be concluded that the analysis and calculation conform to the real performance during OLTC tap up.

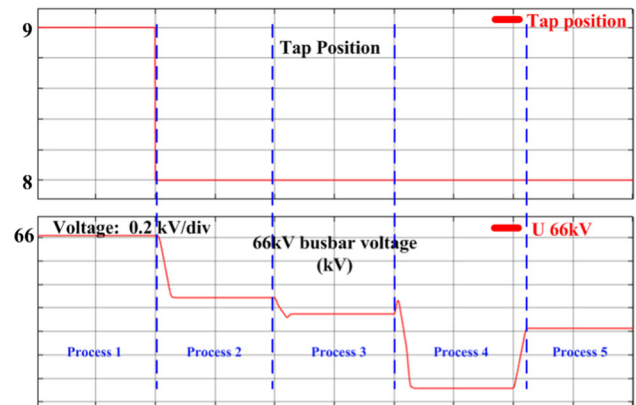


Fig. 13 Transient processes simulation of OLTC tap down

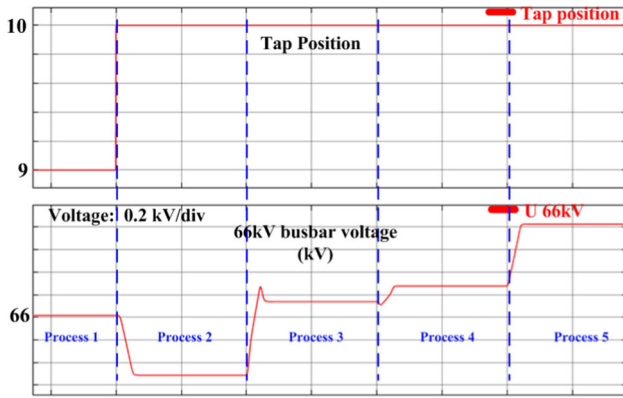


Fig. 14 Transient processes simulation of OLTC tap up

Converter Operation Robustness During OLTC Tap Transition

Converter Model Description

As shown in Fig. 15, the basic ITER PF AC/DC converter unit comprises four 6-pulse bridges decoupled by external inductors, supplied by two phase-shifting transformers to provide 12-pulse operation. In 12-pulse operation, two positive bridges (CB1 and CB2) or negative bridges (CB3 and CB4) operate to supply the coil with bidirectional current.

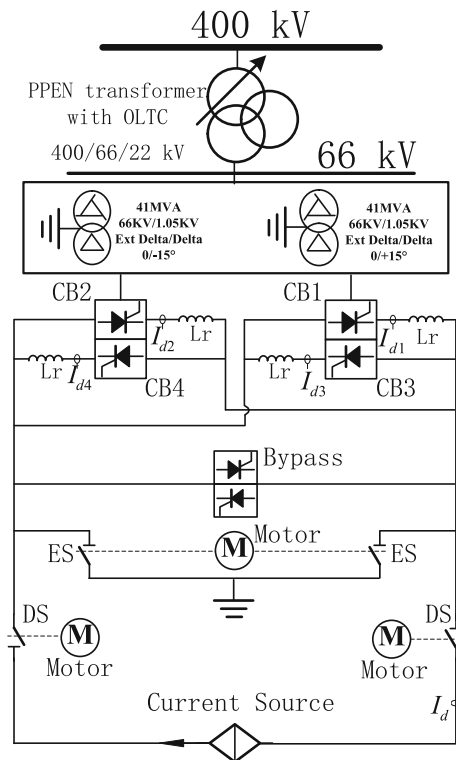


Fig. 15 Circuit topology of one PF converter unit

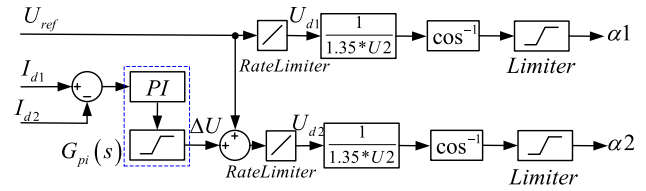


Fig. 16 Schematic diagram of 12-Pulse control strategy

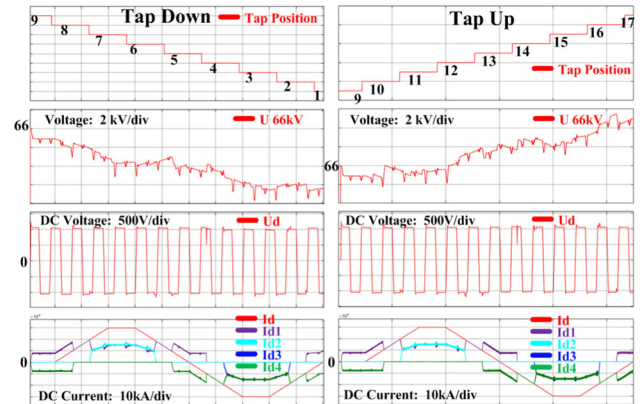


Fig. 17 OLTC Tap changer simulation results during maximum voltage fluctuation

The key point in 12-pulse operation is how to control unbalance current in two converter bridges. As shown in Fig. 16, in 12-pulse operation, CB1 is the main bridge to follow the reference voltage U_{ref} and CB2 takes charge of unbalance current control by the output of PI controller ΔU with the measurements of two converter bridges' currents. Then two firing angles α_1 and α_2 are calculated to transmit to CB1 and CB2. A rate limiter is applied for limiting the rapid voltage variation to avoid the un-controlled unbalance current caused by the phase shifting of two parallel bridges. And the limitation of firing angle, which is from 30° to 135° , is also used to prevent commutation failure in normal 12-pulse operation.

Converter Operation Robustness Validation

According to the analysis above, the main effect to the converters is phase shift and amplitude variation of 66 kV busbar voltage during transient processes of OLTC tap transition. In order to verify the converter system robustness, the simulation model of PF converter system with three-phase OLTC regulating transformer has been built, the simulation circuit is shown as Fig. 15. In order to evaluate the system robustness during OLTC tap transition on the most critical situations of plasma operation, the step change of DC voltage reference from +1050 to - 1050 V with the period of 0.4 s has been used. And the current

source is integrated in the circuit to force the converter system accomplish one cycle of 4-quadrant operation.

As shown in Fig. 17, the tap is regulated among position 1–9 in both up and down directions on the most critical situation. It can be observed that the converter system can withstand all the transients in both circuit and control strategy.

Conclusion

The OLTC technology is usually applied in the steady state electric substation to increase power factor and reduce the active power loss [6]. But in ITER, the load is totally different and it is significant to study the reliability of safety using the OLTC during the pulse operation of the converter loads. Hence, the PPEN transformer OLTC tap changer control strategy has been developed with consideration of 66 kV busbar voltage stability. Several timers with different time delay have been selected corresponding to the severity of over-voltage and under-voltage, and hysteresis band is considered to reset the timers for avoiding strategy instability.

The OLTC tap changer transient processes have been analyzed to obtain the terminal voltage transients quantitatively in both amplitude and phase. And the converter system robustness during PPEN OLTC tap changer has been verified by simulation.

According to all the analysis, calculations and simulations above, it can be concluded that The PPEN

transformer OLTC tap changer control strategy can be accepted and the converter system can withstand the 66 kV busbar voltage transients during PPEN OLTC tap transition.

Now The PPEN transformer has been installed on ITER site. And the RPC&HF system is still under manufacture in China. The tap changer strategy and the converter system robustness will be tested in future integrated test in ITER.

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