*Appendix*

## Simulink Model

### *Model*



Fig. 1 The Simulink model of 24-TR topology

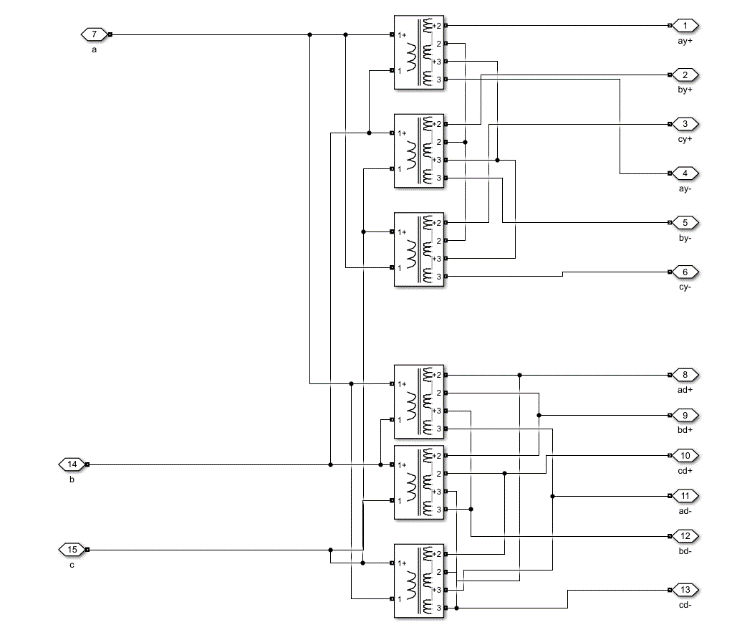


Fig. 2 Detailed Simulink model of 12-pulse phase-shifting rectifier transformers

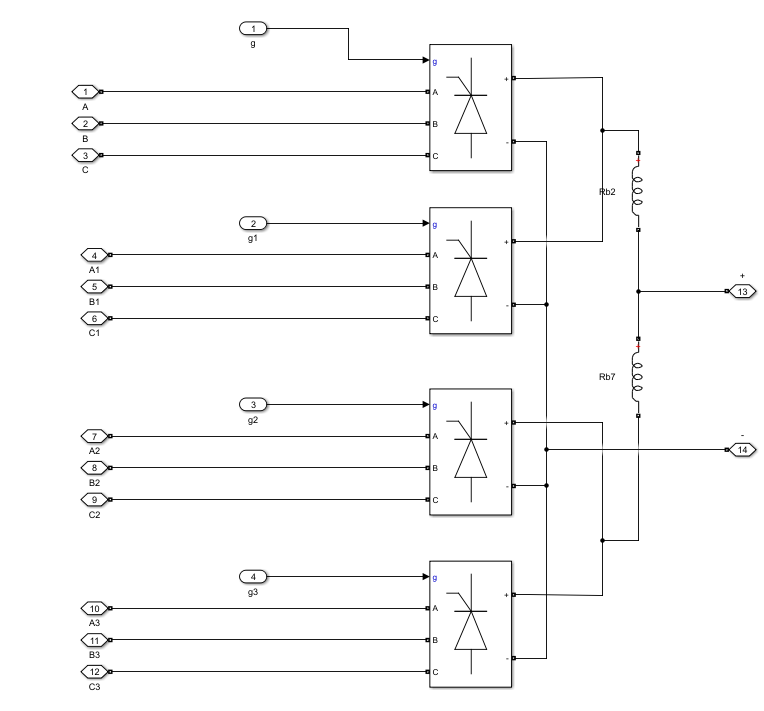


Fig. 3 Detailed Simulink model of a 12-pulse rectifier

Fig. 1 shows the Simulink model of the 24-TR topology, the model parameters like PF in the main body are obtained from this Simulink model. The Simulink model parameters are listed in Table 1. Fig. 2 is the detailed 12-pulse phase-shifting rectifier transformers and two of them consist of 24-pulse phase-shifting rectifier transformers. Fig. 3 is the detailed Simulink model of a cophase counter parallel connection 12-pulse rectifier. The rectifier and the transformer together constitute the completed cophase counter parallel connection 12-pulse converter system. And two of them consist of a completed cophase counter parallel connection 24-pulse converter system.

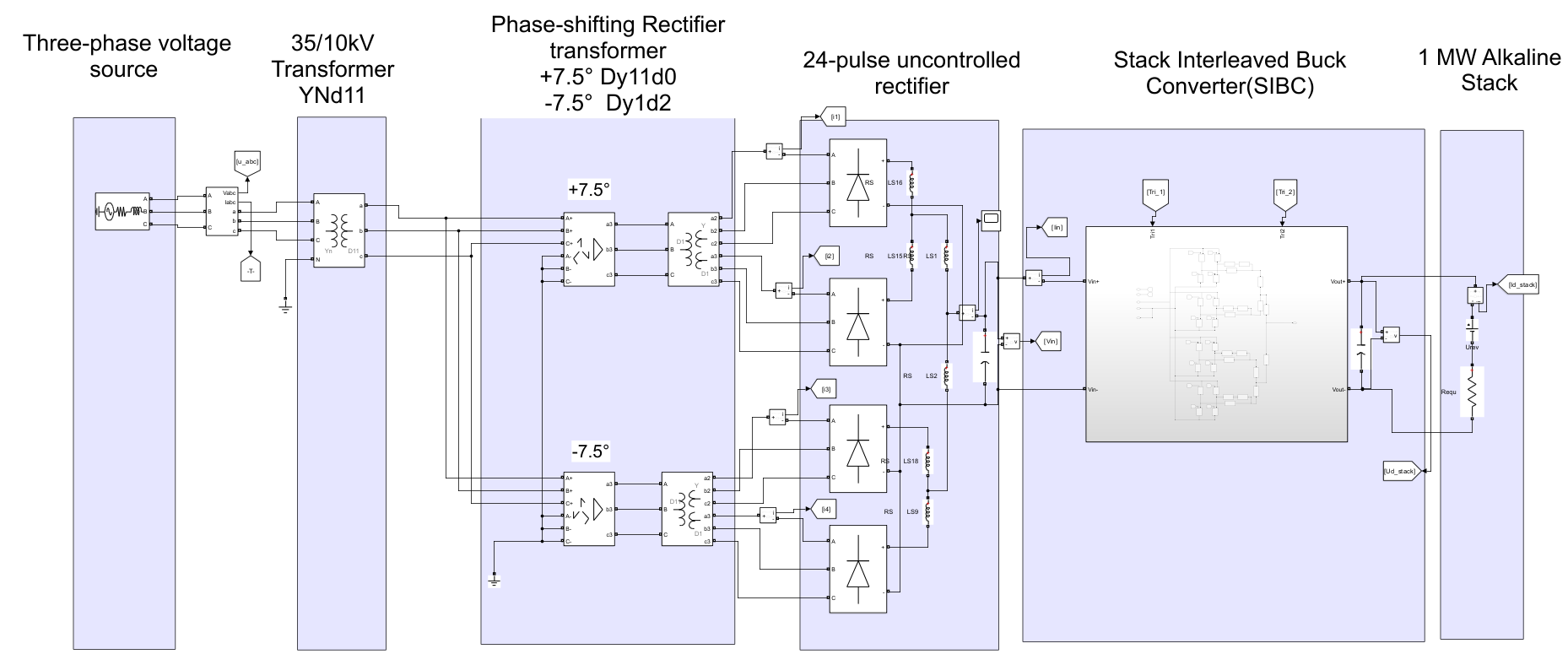


Fig. The Simulink model of 24-SIBC topology

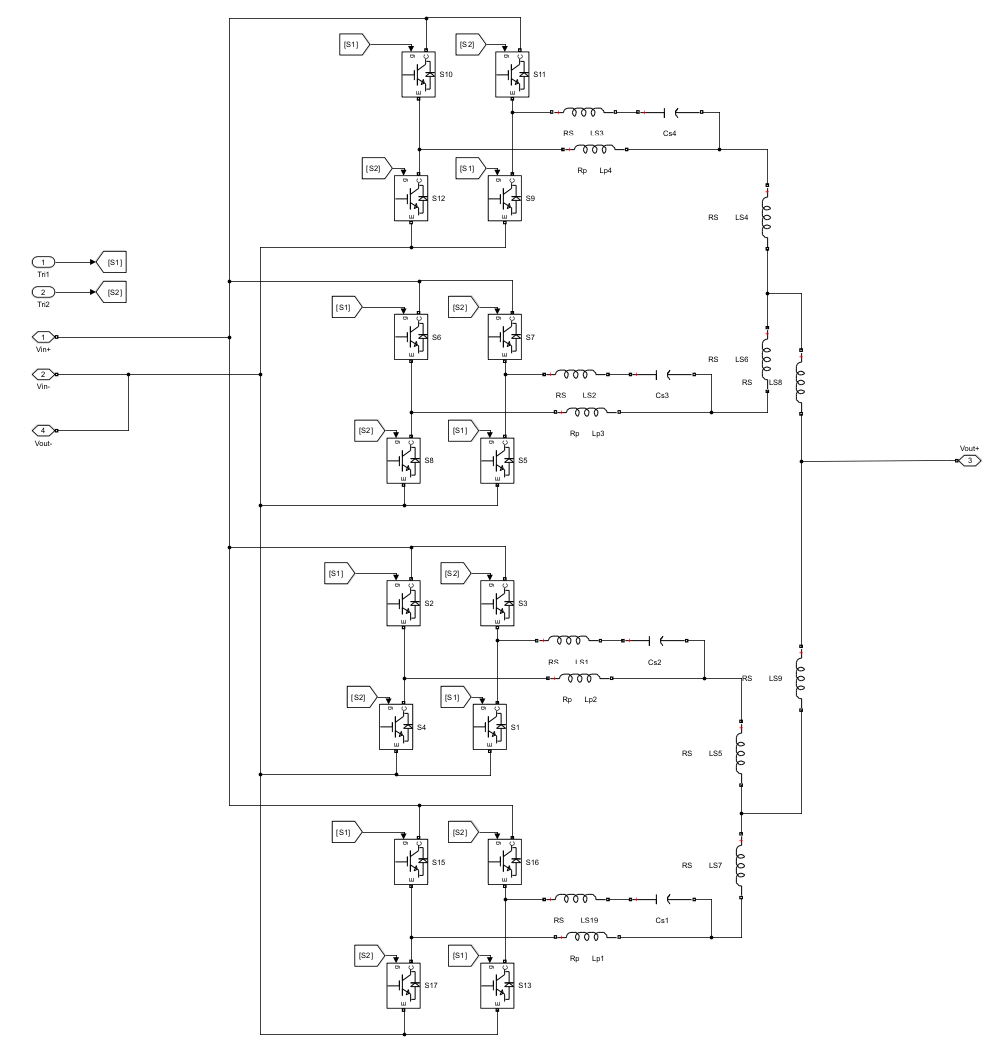


Fig. Detailed Simulink model of Stack Interleaved Buck Converter (SIBC)

Fig. 4 shows the Simulink model of the 24-SIBC topology, the model parameters like PF in the main body are obtained from this Simulink model. The Simulink model parameters are listed in Table 2. Fig. 5 is the detailed Simulink model of Stack Interleaved Buck Converter (SIBC). We parallel four SIBCs to enhance the current carrying capacity.

### *Parameter*

Table The Simulink Model Parameters of 24-TR

|  |  |
| --- | --- |
| Model Parameter | Data |
| Solver | Discrete 1e-5 |
| *Three-Phase Power:* |  |
| Phase-to-phase voltage (Vrms) | 35000 |
| Source resistance (Ohms) | 0.0210 |
| Source inductance (H) | 0.0034 |
| *35/10.5kV Transformer:* |  |
| Winding 1 parameters [R1(pu), L1(pu) ] | 0.0024033, 0.039949 |
| Winding 2 parameters [R2(pu), L2(pu) ] | 0.0024033, 0.040829 |
| Magnetization resistance Rm (pu) | 207.79 |
| Magnetization inductance Lm (pu) | 89.903 |
| *Rectifier:* |  |
| Equilibrium reactor (mH) | 0.4 |
| Filter capacitor (mF) | 50 |
| *Phasing-Shifting Rectifier Transformer:* |  |
| Winding 1 parameters [R1(pu), L1(pu)] | 0.0065, 0.0215 |
| Winding 2 parameters [R2(pu), L2(pu)] | 0.0065, 0.0215 |
| Winding 3 parameters [R3(pu), L3(pu)] | 0.0065, 0.0215 |
| Magnetization resistance Rm (pu) | 588.23 |
| Magnetization inductance Lm (pu) | 147.23 |
| *LC filter:* |  |
| Capacitor (C) | 1.308e-07 |
| Resistance (R) | 1.10586 |
| Inductance (H) | 0.112 |

Table The Simulink Model Parameters of 24-SIBC

|  |  |
| --- | --- |
| Model Parameter | Data |
| Solver | Discrete 1e-5 |
| *Three-Phase Power:* |  |
| Phase-to-phase voltage (Vrms) | 35000 |
| Source resistance (Ohms) | 0.0210 |
| Source inductance (H) | 0.0034 |
| *35/10.5kV Transformer:* |  |
| Winding 1 parameters [R1(pu), L1(pu) ] | 0.0024033, 0.039949 |
| Winding 2 parameters [R2(pu), L2(pu) ] | 0.0024033, 0.040829 |
| Magnetization resistance Rm (pu) | 207.79 |
| Magnetization inductance Lm (pu) | 89.903 |
| *Rectifier:* |  |
| Equilibrium reactor (mH) | 10 |
| Filter capacitor (mF) | 10 |
| *Phasing-Shifting Rectifier Transformer:* |  |
| Winding 1 parameters [R1(pu), L1(pu)] | 0.0065, 0.0215 |
| Winding 2 parameters [R2(pu), L2(pu)] | 0.0065, 0.0215 |
| Winding 3 parameters [R3(pu), L3(pu)] | 0.0065, 0.0215 |
| Magnetization resistance Rm (pu) | 588.23 |
| Magnetization inductance Lm (pu) | 147.23 |
| *LC filter of SIBC:* |  |
| Capacitor C1 (mF) | 0.1 |
| Capacitor C2 (mF) | 200 |
| Inductance L1 (mH) | 0.4 |
| Inductance L2(mH) | 0.4 |

## The proof of proposition 1 and proposition2

### *The proof of* proposition *1*

The parameters of equations (3)-(5) in the main body are listed in TABLE II. Substitute equations (3)-(5) of the main body into equation (6) of the main body to get equation (1). The partial derivative of  with respect to *I* and *T* are expressed as equation (2) and equation (3) respectively.

Fig. 4 shows the partial derivative of  with respect to *I* when *T* is 80℃. The partial derivative is greater than zero when , and the partial derivative is less than zero when . Fig. 4 proves that  presents a first-positive-then-negative correlation as .

Fig. 5 shows the partial derivative of  with respect to *T* when *I* is 5kA. The partial derivative is always greater than zero when . Fig. 5 proves that  monotonically positive correlation as .

TABLE II The parameters of equations (3)-(5)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  |  |  |  |  |
| 123V |  |  |  |  |
|  |  |  |  |  |
|  |  |  |  | 33.33kWh/kg |







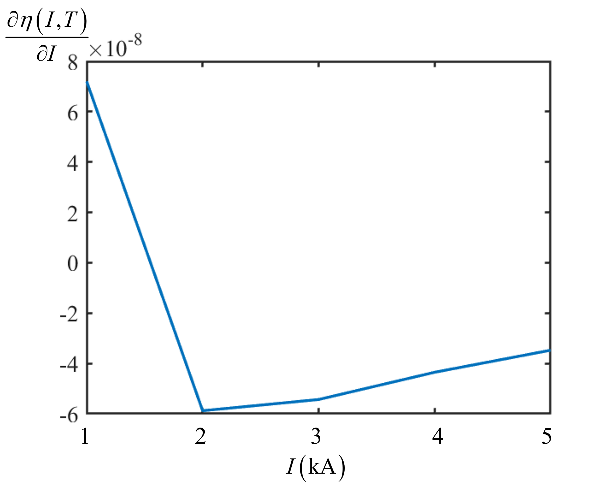


Fig. 6 The partial derivative of  with respect to *I* (T = 80℃)

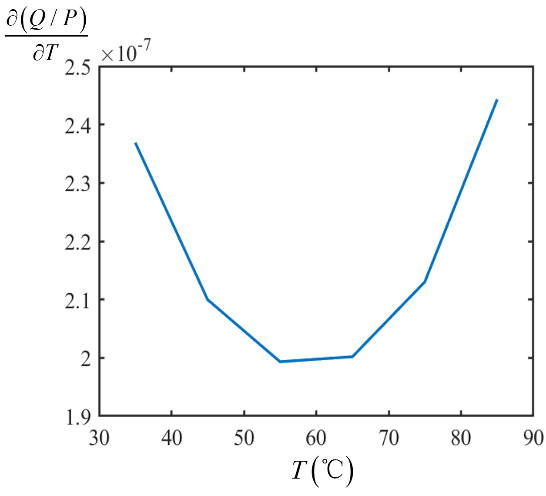


Fig. 7 The partial derivative of  with respect to *T* (*I* = 5kA)

### *The proof of* proposition *2*

The parameters of equations (8)-(13) in the main body are listed in TABLE III.

TABLE III parameters of equations (8)-(13) in the main body

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| *K* |  | *a* | *b* | *c* |  |  |  |  |
| 104 | 10.465kV |  | 1.353 | 91940 | -0.6738 | 0.5065 | 0.6339 | 0.2756 |

Substitute equations (8)-(13) of the main body into equation (14) of the main body to get . As for convenient, we use the monotonicity of  to proves the theorem 1 since The monotonicity of  is opposite to that of .

Fig. 6 shows the partial derivative of  with respect to *I* when *T* is 80℃. The partial derivative is less than zero when , and the partial derivative is greater than zero when . Fig. 5 proves that presents a first-negative-then-positive correlation as .

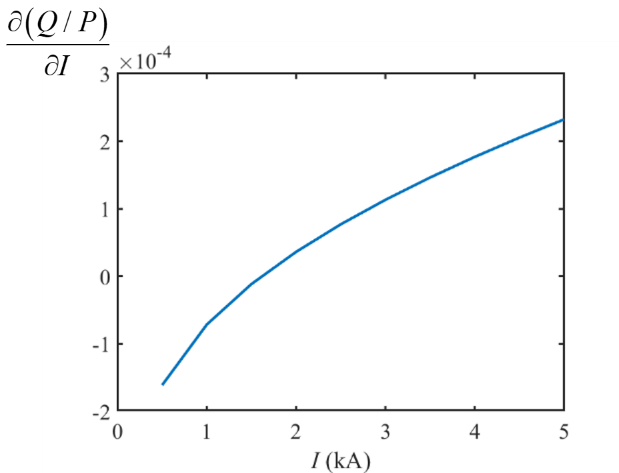


Fig. 8 The partial derivative of  with respect to *I* (T = 80℃)

Fig. 7 shows the partial derivative of  with respect to *T* when *I* is 5kA. The partial derivative is always greater than zero when . Fig. 7 proves that  monotonically negative correlation as .

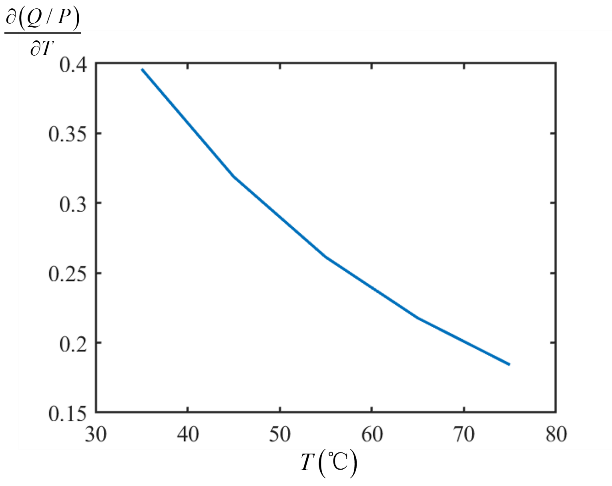


Fig. 9 The partial derivative of  with respect to *T* (*I* = 5kA)

## The parameters of other equations

The parameters of equation (8):

,,

The parameters of equation (23) and (24):









The parameters of equation (25):

,,,,,

## Fitting error

To make sure the compatibility of the PF expression that suitable for the controller, cross-terms related to different stacks are not reserved to improve solvability. The fitting error of PF of a 10-stack P2H load is shown in Fig. 4 in the main body. Therefore, cubic polynomial piecewise formation (25) in the main body with the discretization of  is adopted with the fitting error below 2%.

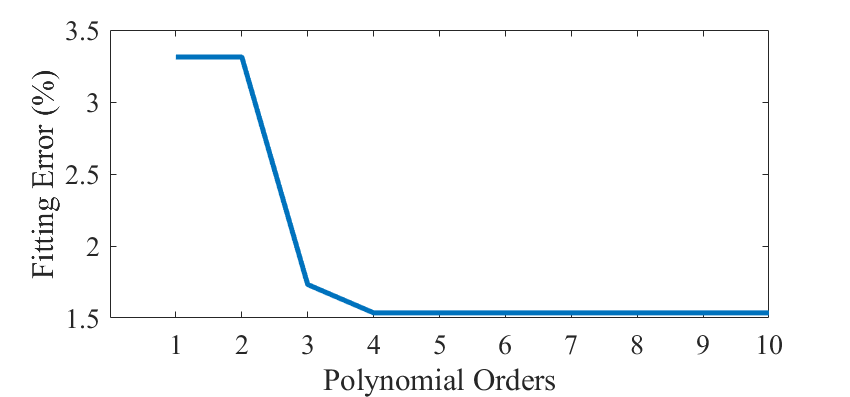


Fig. 10 The relationship of the fitting error with polynomial orders

## Detailed analyses of PF characteristics



(a) 24-TR topology



(b) 24-SIBC topology

Fig. 11 The PCI topologies

In this section, PF Characteristics of a two-stack P2H system are obtained and analyzed based on the simulation. Then, they are involved in the scheduling to compare the optimal strategies with two typical converters.

1. Comparison of PF Characteristics

Fig. 12 and Fig. 13 present the PQ characteristics of a two-stack P2H system with 24-TR and 24-SIBC PCI topology, respectively. Fig. 14 shows the PF characteristics of a two-stack P2H system. The top and bottom rows represent the PF value with one stack. Fig. 14 plots the operating temperature and the operating current of the first stack on the horizontal axis against those of the second stack on the vertical axis. The colorbar is listed in the righthand, and different color mapped to Fig. 14 represents various PF values. The results reflect the following rules.

|  |  |
| --- | --- |
|  |  |
| (a) | (b) |

Fig. 12 The PQ characteristics of 24-TR topology, (a) under different I with fixed T=75oC; (b) under different T with fixed I=5kA.

|  |  |
| --- | --- |
|  |  |
| (a) | (b) |

Fig. 13 The PQ characteristics of 24-SIBC topology, (a) under different I with fixed T=75oC; (b) under different T with fixed I=5kA.

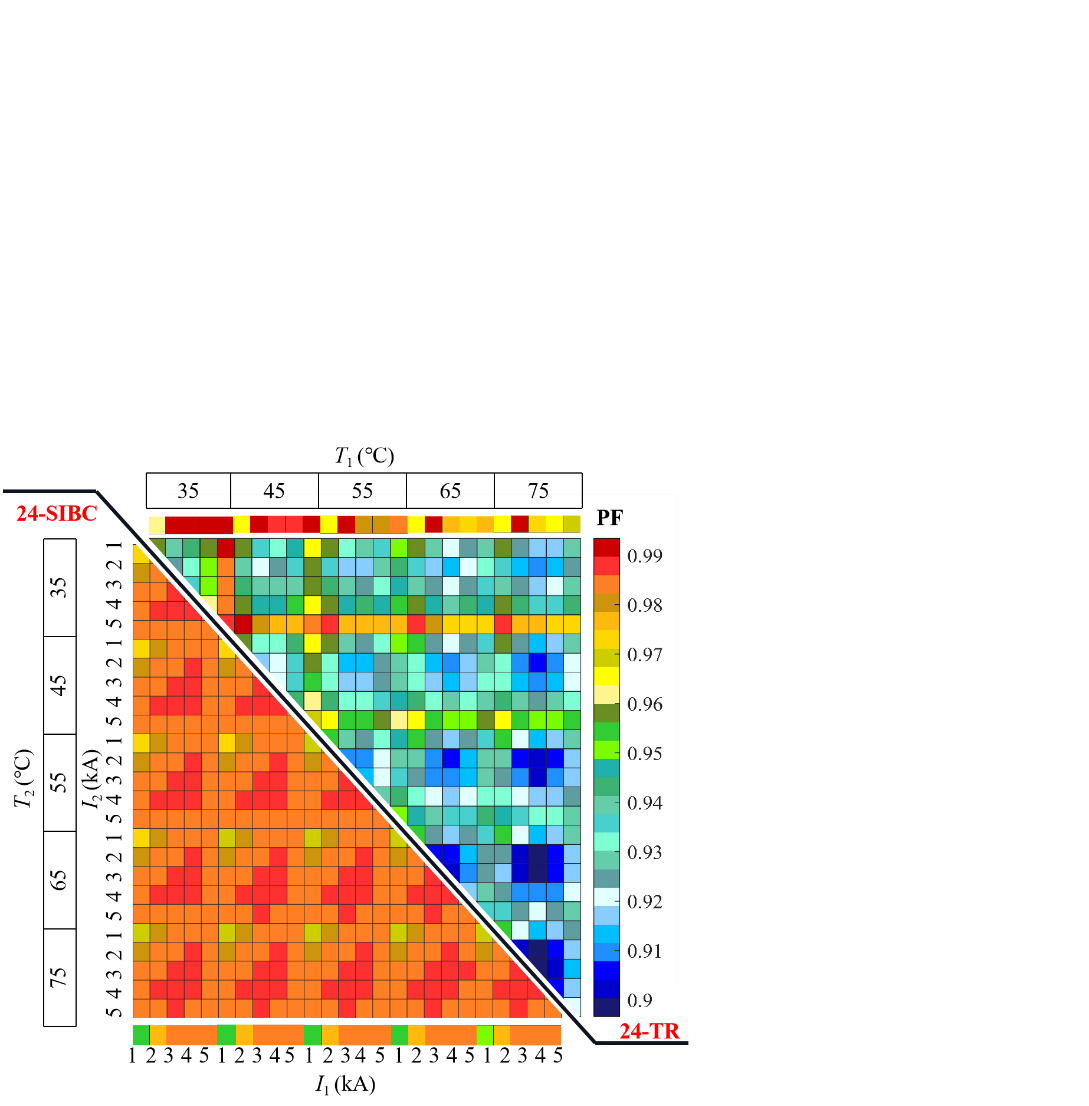


Fig. 14 PF characteristics of a two-stack P2H system

1) The overall performance. In general, it can be observed from Fig. 12 and Fig. 13 that the average reactive power of the 24-TR topology is higher than that of the 24-SIBC topology in the case of variable I or variable T conditions. Therefore, the average PF of 24-TR is lower than that of 24-SIBC, as shown in Fig. 14.

2) The effect of. The two topologies reflect opposite tendencies of the effect of  on PF characteristics. For the 24-TR topology, Fig. 12(a) shows that as  increasing from 1 kA to 5 kA, while  is 5 kA, the distortion components  increase from 0.56 MW to 0.94 MW. In contrast, the phase shift component  shows the opposite effect. The increase in  requires the rectifier to boost the voltage output, which is achieved by reducing the firing angle and also the ratio of  to. Therefore, PF of 24-TR topology first decreases dominated by  and then increases dominated by  with the increase of, as shown in Fig. 14. For the 24-SIBC topology, dominates at low-load level, resulting in an increasing tendency of PF. However, as  further increasing, gradually dominates PF with a positive correlation with, which results in a decreasing tendency of PF at high-load levels. The above phenomenon explains that the PF of the 24-SIBC topology first increases and then decreases with the increase of  shown in Fig. 14.

3) The effect of T. Compared to the effect of I, T shows a minor influence on PF characteristics. For the 24-TR topology, Fig. 12(b) shows that  is positively correlated to T from 35 ℃ to 75 ℃. On the other hand, the increasing of T results in the lower output voltage of the rectifier achieved by increasing the firing angle, which that  is also positively correlated to T. Therefore, for the 24-TR topology, the lower, the higher PF, as shown in Fig. 14. For the 24-SIBC topology, Fig. 13(b) shows that both  and  are negatively correlated to T. Therefore, the higher, the higher PF. But we can also conclude that the effect of  on the PF of 24-SIBC can be ignored, because the difference between PFmax and PFmin while stacks both operate at 5 kA is only 0.0015.

In summary, PF characteristics of 24-TR and 24-SIBC topology present an opposite tendency within the operating ranges of  and . However, the production increases first and then decreases with  increasing, and is positively correlated with, which is consistent with PF of 24-SIBC and opposite with PF of 24-TR. It hints that for 24-TR PCI, the scheduling strategy needs to balance the production target and compliance constraints in real working conditions.