Sensors & Transducers, Vol. 175, Issue 7, July 2014, pp. 291-298

Sensors & Transducers

Research on Control Strategy of Complex Systems through VSC-HVDC Grid Parallel Device

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Received: 11 July 2014 /Accepted: 28 July 2014 /Published: 31 July 2014

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Abstract: After the completion of grid parallel, the device can turn to be UPFC, STATCOM, SSSC, research on the conversion circuit and transform method by corresponding switching operation. Accomplish the grid parallel and comprehensive control of the tie-line and stable operation and control functions of grid after parallel. Defines the function select operation switch matrix and grid parallel system branch variable, forming a switch matrix to achieve corresponding function of the composite system. Formed a criterion of the selection means to choose control strategy according to the switch matrix, to accomplish corresponding function. Put the grid parallel, STATCOM, SSSC and UPFC together as a system, improve the stable operation and flexible control of the power system. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: VSC-HVDC, Synchronization paralleling device, Compound system, Control.

1. Introduction

Grid parallel operation on stability of power system has important meaning, for currently grid parallel operation exists problem of slow speed, poor operation security reliability and low automation level, literature [1] proposed a principle and control strategy which use voltage source converter for achieved grid parallel operation, through back-to-back voltage source converter to be tied on both sides of the system, it goes ahead fast independent control of active and reactive power, thus reached adjustment the frequency difference, voltage difference and phase angle difference of both sides of system, and made both sides of system meet rapidly synchronous grid-tied condition, and parallel operation is completed. Through this method it is solved the problem which substations could not be of adjusting frequency and voltage deviations in grid synchronous grid-tied, it can speed up the grid-tied speed, shorten the time, and improve the automation of grid-tied, to realize the synchronous juxtaposition between the grid and the ring side by side. However, grid-connected equipment would exit the system at idle and caused great waste upon grid-tied completion. Literature [2] proposed to method which combined existing Static Synchronous Compensator (STATCOM) technology with the grid parallel device to form a complex system that possess the function of grid synchronous parallel and reactive power compensation. Upon completion of grid-tied, the device can be used as a system of reactive power compensation device. But their function is still somewhat single, and the equipment utilization rate is still slightly low.

In this paper, the composite system to realize the corresponding functions of conversion circuit and control strategy were studied, it can undertake the corresponding circuit switching operations under dispatching command and adopt corresponding control strategy, and STATCOM, SSSC and UPFC functions can be realized, which allow complex system benefits to play, and greatly improve the utilization of grid parallel device.

2. Study for Parallel Devices to Achieve Complex Function of Conversion Circuit

2.1. Conversion Circuit Structure

On the basis of back-to-back grid parallel device [3-4] used in grid parallel main wiring, it is concatenated with a three-phase transformer matching with the capacity of grid parallel device and tie line current, add a circuit breaker and six sets of isolating switch. The circuit is shown in Fig. 1.

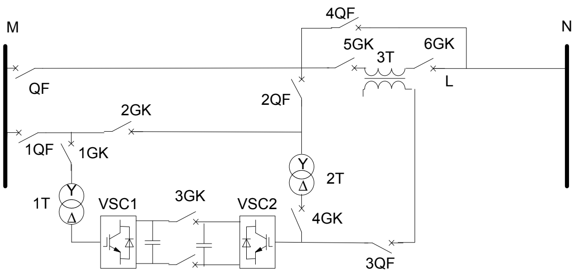


Fig. 1. The transforming circuit of paralleling device reaches compound functions.

The pictures can convert device, circuit of grid parallel device, STATCOM devices, SSSC device and UPFC device by the corresponding circuit brake operation. It can implement the function of the corresponding circuit by corresponding control strategy, realize multiple functions of device, and play to comprehensive benefits.

2.2. The Realization of Grid Parallel Device Circuit

When need to grid parallel operation, 3QF circuit breaker device is separated, respectively isolation switch 2GK, 5GK and 6GK are separated, then close 1GK, 3GK, 4GK, and respectively close circuit breaker device 1QF, 2QF, 4QF. That constitutes grid parallel circuit. It achieved function of grid parallel in control strategy, the circuit breaker device QF is automatically closed and circuit breaker device 1QF, and 2QF are separated when the device grid-tied. Device completed tie grid and exit run. Equivalent circuit is shown in Fig. 2.

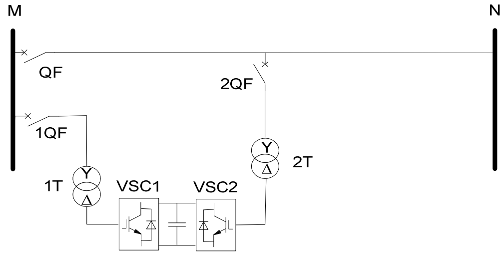


Fig. 2. Equivalent diagram of transforming to paralleling device.

2.3. Transfer to STATCOM Circuit

For different actions, we can complete the three different structures of circuit of STATCOM. On the state of completion of device grid-tied quit running, we keep the same structure, separate 3GK, disassemble parallel devices VSC-HVDC to two identical independent VSC circuit, then close circuit breaker 1QF, and form a circuit of STATCOM circuit, which is regarded as main circuit with VSC1 and whose capacity is half of the capacity of grid parallel device, and connected to the power grid on the M. when device completed tie grid and exit run, we keep the same structure, separate 3GK closed 2GK, close the circuit breaker 1QF, formed two STATCOM for grid-connected which is regarded as main circuit with VSC1 and VSC2 and whose capacity is half of the capacity of grid parallel device, then connected to the power grid on the M, parallel devices to STATCOM equivalent circuit is shown in Fig. 3.

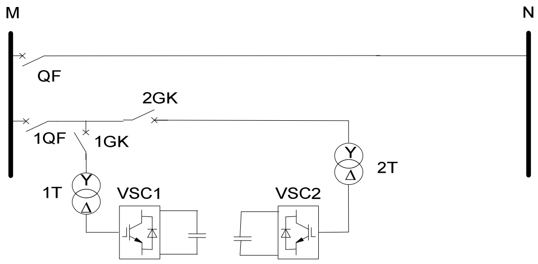


Fig. 3. Equivalent circuit diagram of transforming to STATCOM.

2.4. Realize the UPFC Circuit Structure

When device completed tie grid and exit run, we keep the same circuit structure, disconnect 2QF, and 3QF, and 1QF, separate 4GK, and 2GK, and exit transformer T2, then close 5GK, 6GK, 3GK, and 1GK, and close circuit breaker device 3QF, then close circuit breaker device 1QF, and separate 4QF. This operation can achieved inputs of UPFC device. Changing corresponding of control strategy can achieved function of unified power flow controller. Device of UPFC equivalent circuit is shown in Fig. 4.

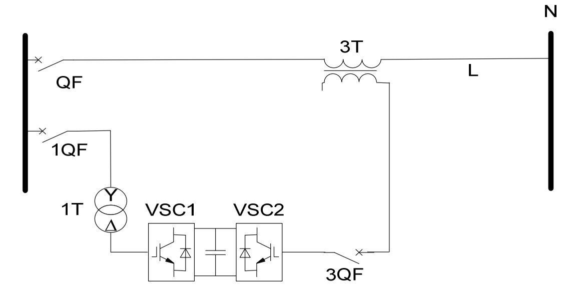


Fig. 4. Equivalent circuit diagram of transforming to UPFC.

2.5. Realize the SSSC Circuit

When device completed tie grid and exit run, we keep the same circuit structure, thus switching States of the system are as follows: circuit breaker 1QF, 2QF, 3QF is in the off position, 2GK, 5GK, 6GK isolation switch is in the off position, other switches are in the on position. In this State, open 3GK, 4GK in turn, respectively close 5GK, 6GK, then close circuit breaker switch 3QF, and finally open 4QF. That completed the conversion of SSSC circuit, SSSC equivalent circuit of parallel devices is shown in Fig. 5.

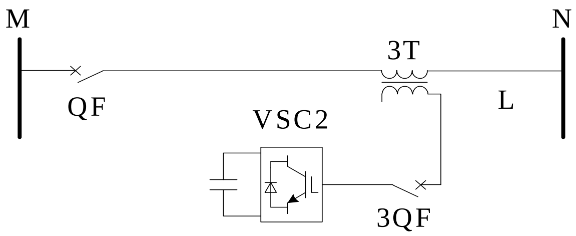


Fig. 5. Equivalent circuit diagram of transforming to SSSC.

3. The Control Strategy of Compound System Research

3.1. Matrix Model of Complex System Control Research

Set a control strategy of control selection switch k. Grid parallel devices based on the value of k determine appropriate control strategies [5], and implement corresponding composite function. K values associated with converter circuit topologies, and associated participating in circuit breakers with isolating switches state, so we can generate a switch matrix.

Define a branch switch variable K_{li} based on grid-tied bus M, tie line L and bus N, a compound system based on VSC-HVDC grid parallel devices [6] installed in substation A in the system S_1, and synchronous grid-tied through its L, M, and N. Schematic diagram is shown in Fig. 1, in order to facilitate the analysis and description. According to the order of participation in the function transformation and the layout of spatial relationships, Fig. 1 was redrawing as shown in Fig. 6.

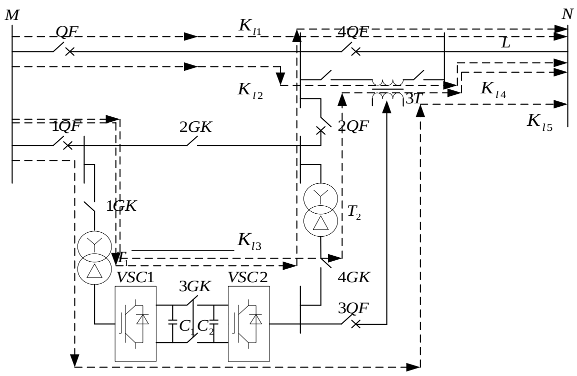


Fig. 6. Schematic diagram of switch layout in the compound system.

According to compound system function transformation and the corresponding switching operation, it realized grid-tied, UPFC, SSSC and STATCOM device, as can be seen from the Fig. 6, there are 5 pathways from bus M after a tie line to the bus N, and respectively defined as K_{li} (i=1, 2, 3, 4, 5).

The result of the logic and in branch K_{li} participating in all the circuit switch operation status (set that switch is close to 1, open to zero value, which obtained by the switch status signal acquisition) is the value of K_{li}, so the composite system function transformation results corresponding branch switch value as shown in Table 1.

Table 1. The value of branch switch with relevant device function.

Device functions \ **K_{li} value**	K_{l1}	K_{l2}	K_{l3}	K_{l4}	K_{l5}
Grid-tied	0	0	1	0	0
UPFC	0	1	0	0	1
STATCOM	1	0	0	0	0
SSSC	0	1	0	0	0
STATCOM and SSSC	0	1	0	0	0
Exit after grid-tied	1	0	0	0	0

Based on logic calculated value from Table 1 branch switch we can easily determine device work in state grid-tied or the function of the UPFC, but about whether the device is to work in the STATCOM, SSSC and its composite state cannot be determined. In order to comprehensively determine the working state of the device to input, this paper introduces the concept of switch matrix [7-8]. The switch matrix K_k is determined that it participate in the function transformation in composite system of grid parallel device, and realize each corresponding circuit transformation to pour brake operation of the circuit breaker, isolating switch, combination switch operating state sequence. The columns of the matrix K_k show the order of grid-tied device on-off by the point of parallel bus bar M switch from left to right; Line show the parallel branch number from bus bar M to the tie line L, the intersection of ranks is the actual location in the complex system of grid-tied device. The element which can not correspond actual switch position in the matrix corresponding always default to have virtual switches but in the off state value (0).

In order to introduce to describe the switch matrix, according to Fig. 6 this paper redraw Fig. 7, according to the circuit breaker and isolating switch position in Fig. 7 of complex system of grid-tied, and the circuit switch position, the matrix of six orders square $K_K = (k_{ij})_{6\times6}$ is defined. Based on the definition, switch matrix K_k is the:

$$K_K = \begin{pmatrix} K_{QF} & 0 & 0 & 0 & K_{4QF} & 0 \\ 0 & 0 & 0 & 0 & K_{5GK} & K_{6GK} \\ 0 & 0 & 0 & K_{2QF} & 0 & 0 \\ K_{1QF} & 0 & K_{2GK} & 0 & 0 & 0 \\ 0 & K_{1GK} & 0 & K_{4GK} & 0 & 0 \\ 0 & 0 & K_{3GK} & 0 & K_{3QF} & 0 \end{pmatrix}$$

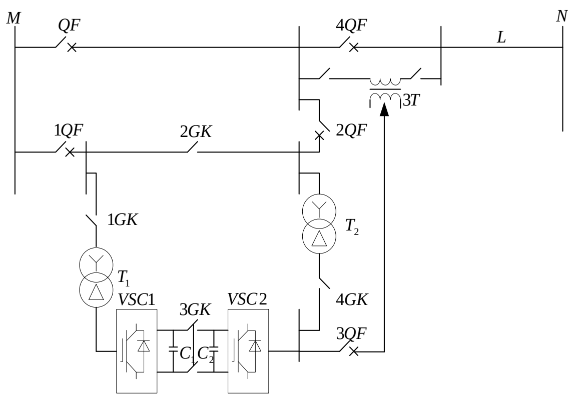


Fig. 7. Schematic diagram of matrix switch layout in compound system.

Then according to the complex system is converted to the principle of the corre-sponding grid-tied, STATCOM, SSSC [9] and UPFC device circuit to form the corresponding switch matrix operation, expressed as follows:

1. Switch matrix of the grid-tied device operation K_{BW}

$$K_{BW} = \begin{pmatrix} 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \end{pmatrix}$$

2. Switch matrix of the SSSC device K_{SS}

$$K_{SS} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{pmatrix}$$

3. Switch matrix of the UPFC device K_{UP}

$$K_{UP} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 0 \end{pmatrix}$$

4. Switch matrix of the STATCOM1 device K_{T1}

$$K_{T1} = \begin{pmatrix} 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

5. Switch matrix of the STATCOM2 device K_{T2}

$$K_{T2} = \begin{pmatrix} 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

6. Switch matrix of the STATCOM3 device K_{T3}

$$K_{T3} = \begin{pmatrix} 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

7. The switch matrix of both STATCOM and SSSC input K_{TS}

$$K_{TS} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{pmatrix}$$

8. The switch matrix when device completed tie grid and exit run K_{BQ}

$$K_{BQ} = \begin{pmatrix} 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \end{pmatrix}$$

The switch matrix K_K was blocked as follows:

$$K_K = \begin{pmatrix} K_{QF} & 0 & 0 & 0 & | & K_{4QF} & 0 \\ 0 & 0 & 0 & 0 & | & K_{5GK} & K_{6GK} \\ 0 & 0 & 0 & K_{2QF} & | & 0 & 0 \\ - & - & - & - & | & - & - \\ K_{1QF} & 0 & K_{2GK} & 0 & | & 0 & 0 \\ 0 & K_{1GK} & 0 & K_{4GK} & | & 0 & 0 \\ 0 & 0 & K_{3GK} & 0 & | & K_{3QF} & 0 \end{pmatrix}$$

Commanding $K_K = \begin{pmatrix} K_A & K_B \\ K_C & K_D \end{pmatrix}$, as we can see from partitioned matrix, other function block matrices K_A are the same, it is characterized by the matrix element $K_{34} = 1$. But $K_{11} = 0$, and it is just the reverse to block matrix K_A. This feature can distinguish grid-tied realized or other features in unit conversion. The criterion was selected by the function conversion switch matrix and branch variable values forming device working mode as follows:

1. Grid-tied pattern criterion is $K_1 = \overline{K}_{11} K_{34} K_{l3}$, this pattern is grid-tied;

2. SSSC partitioned matrix K_{li} is zero and partitioned matrix of other function K_C is not zero. Cooperating with branch variables K_{li} it can make SSSC device input criterion $K_2 = K_{56} \overline{K}_{63} K_{l2}$. In this pattern, SSSC works, and VSC2 was started working on SSSC mode;

3. UPFC partitioned matrix K_B, K_D is respectively the same to SSSC partitioned matrix K_B, K_D. The characteristic of K_B, is that K_{25}, K_{26} is to 1 and other are to zero. And the characteristic of K_D is that K_{56} is to 1 and other are to zero. Cooperating with branch variables K_{li} it can make UPFC device input criterion $K_3 = K_{l2} K_{l5}$, and startup VSC2 work on SSSC mode;

4. There are four ways in STATCOM. The partitioned matrix K_B, K_D of the switch matrix K_{T1}, K_{T2} K_{T3} is the same. The characteristic of K_B is that K_{15} is to 1 and other are to zero. The characteristic of K_D is to zero. Combining with the respective partitioned matrix and cooperating with branch variables K_{li} it can make STATCOM device input criterion. The criterion is $K_4 = \overline{K}_{11} K_{34} K_{41} K_{52} \overline{K}_{63} K_{l1}$, VSC2 was started working on STATCOM mode if conditions of satisfaction.

5. The criterion of STATCOM2 is $K_5 = K_{41} K_{43} K_{54} \overline{K}_{63} K_{l1}$, and VSC2 was started working on STATCOM mode;

6. The criterion of STATCOM3 is $K_6 = K_{41} K_{43} K_{54} K_{52} \overline{K}_{63} K_{l1}$, and both VSC1 and VSC2 were started working on STATCOM mode;

7. STATCOM and SSSC were simultaneously put into work mode. Compared with the SSSC partitioned matrix and this one, only K_C is different, and K_C is not to zero. The criterion is $K_7 = K_{41} K_{52} \overline{K}_{63} K_{l2}$. If conditions of satisfaction, both VSC1 and VSC2 were need to start. VSC1 was worked on STATCOM mode and VSC2 was worked on SSSC mode;

8. Grid parallel device completed tie grid and exit running mode. Compared with the STATCOM partitioned matrix and this one, only K_C are different, and K_C are also not to zero. The criterion is $K_8 = K_{63} K_{l1}$. If conditions of satisfaction, both VSC1 and VSC2 were need to close. The device is in standby mode.

3.2. Compound Control Strategy of the System

According to the switching matrix and branch variable operating device model selection criterion, we can choose switch through a multi-channel access, to select the corresponding control strategies to complete the function of the corresponding composite system. The control strategy is shown in Fig. 8.

According to the flowchart of compounding system control, first, start the converters and identify the running mode of paralleling device according to the dispatching commands. If the dispatching command is to run in paralleling mode, parallel device will determine Device Control Strategy based on that whether the switching matrix satisfies the criterion condition, then judge whether it meets paralleling conditions according to the frequency difference, voltage difference and phase angle difference. If the conditions are satisfied, then switch on the breaker of synchronous paralleling point and exist the converters, so the paralleling operations are finished; if the conditions are not satisfied, then determine the direction and amount of transmission power according to the frequency difference, voltage difference and phase angle difference in order to satisfy the conditions. Control the VSC on both sides according to the direction and amount of power, and the power switch control pulses is produced by adopting space vector modulation technology [10-11]. When the system frequency and voltage trend to be stable after transmitting certain power for certain time t, the previous steps are repeated until it meets the paralleling conditions, so the paralleling operations are finished. If the dispatching order needs to realize other functions, change the control strategy to run in corresponding mode according to the corresponding switch matrix criterion value, then the controller adopts the corresponding control strategy to realize its function; otherwise quit running and in the state of standby or halt.

4. Simulation

According to the system shown in Fig. 6, model is built using PSCAD/EMTDC, as shown in Fig. 9.

The simulation results in the literature [2] has been done, and it shows that after the grid accomplishes the paralleling and conversion, there are some minor fluctuations in frequency difference between System 1 and System 2. After the transition, the voltage difference between System 1 and System 2 have slight fluctuations in near 2 kV, then it becomes 0 after the system is stable. When the grid accomplish the paralleling, at the same time the dispatching order execute the corresponding switching operations to switch into STATCOM circuit, the phase Angle difference in achieving change which converted to near zero.

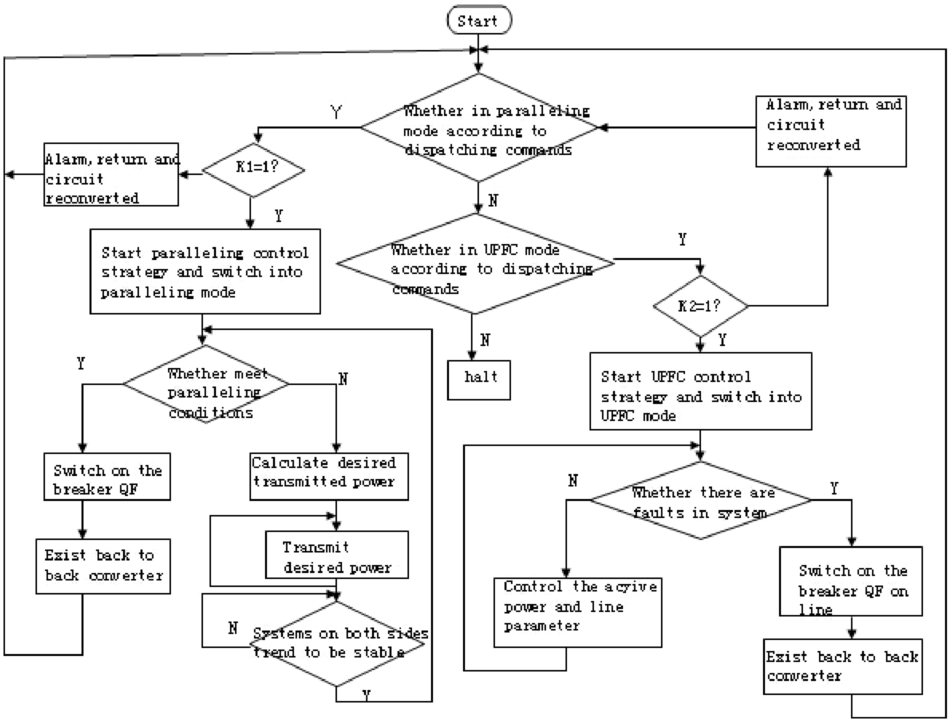


Fig. 8. The flowchart of compounding system control strategy.

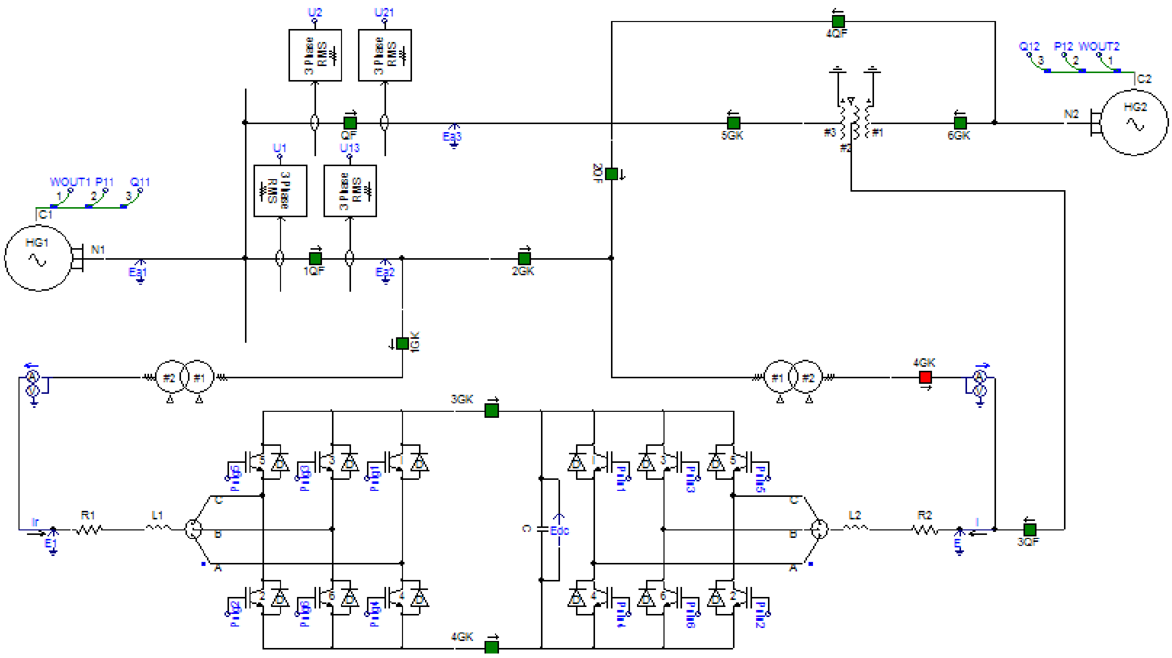
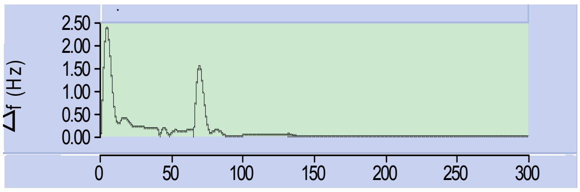
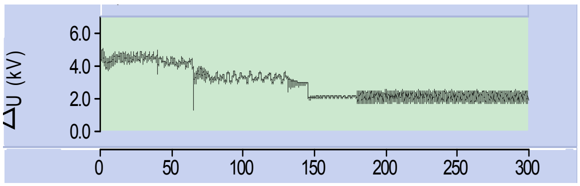


Fig. 9. Complex system simulation model diagram.

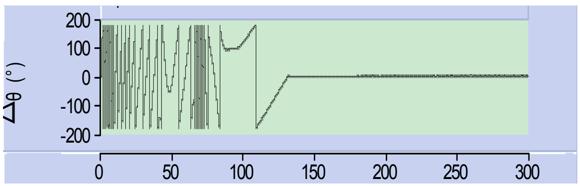
When the device quits paralleling and transfers to UPFC mode, the simulation results is shown in Fig. 10. Section 1.4 shows us how circuits breaker work with isolating switch.



(a) The conversion process frequency difference between System 1 and System 2



(b) The voltage difference on both sides of the conversion process system



(c) The phase Angle difference on both sides of the conversion process system

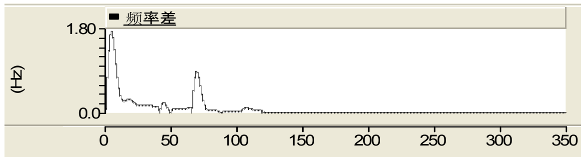
Fig. 10. Simulation result of complex system turn paralleling grid to UPFC model.

From the simulation we can know that complex systems had a little impact on the whole system when grid paralleling mode switched into UPFC mode. The transformation of circuit would not result in system sectionalizing. The system is in a state of relative stability. The voltage that the series side of UPFC injected in the power system lead to voltage difference of system circuit. Frequency difference and phase angle difference had slight and short fluctuations, and then they return to the stable value of zero. Therefore, above simulation results proved that this method, which grid paralleling mode switched into UPFC mode, is effective and feasible.

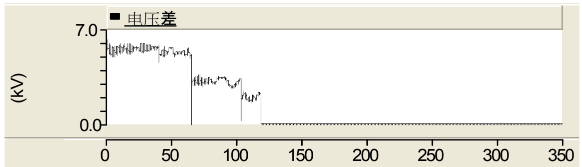
When the device quits paralleling and transfers to SSSC mode, the simulation results is shown in Fig. 11. Section 1.5 shows us how circuits breaker work with isolating switch.

From the simulation we can see that frequency difference on both sides decreases gradually. The frequency difference had some fluctuations and finally converged in the process of grid paralleling.

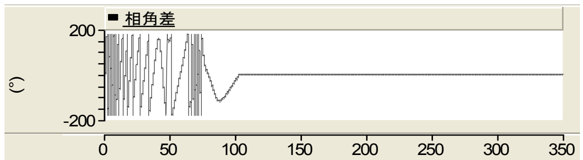
When power system switched into SSSC mode, the frequency difference had some fluctuations and finally converge. As the power transmission, in the process of grid paralleling voltage difference decreased. When power system switched into SSSC mode, voltage difference had certain mutations, and then tended to 0. Phase angle difference on both sides is near 0 after grid paralleling. Simulation results proved that this method, which grid paralleling mode switch into SSSC mode, is and feasible.



(a) The conversion process frequency difference between System 1 and System 2



(b) The voltage difference on both sides of the conversion process system



(c) The phase Angle difference on both sides of the conversion process system

Fig. 11. Simulation result of complex system turn paralleling grid to SSSC model.

5. Conclusions

This paper researched Paralleling set, and realized switching circuit function of UPFC, STATCOM and SSSC etc. Through switching circuit, the device can transfer the corresponding device. Also it defined the functional selection switch matrix operation and the variables of Grid system branch, and formed a composite system corresponding to the function of switch matrix. Then, it can be formed criteria of Select device working mode operation strategy through switching matrix. According to these criteria, we can choose the corresponding device operating control strategy and achieve its corresponding function. One compound system can be expanded using back-to-back VSC-HVDC paralleling set, so that it carry out the integrated control of the tie line after interconnection and interconnection and the integration of system stable operation and control functions after interconnection. After grid connection at the same time, it will be unified STATCOM, SSSC, and UPFC device in together, enhanced power system with stable operation and the flexibility of control. Meanwhile, this research finding greatly improved the utilization rate of the device and it can play an important role in comprehensive benefit excepting grid connection.

Acknowledgements

Project supported by the National Natural Science Foundation of China (Grant No. 51077109).

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