Control of a Back-to-Back VSC from Grid Connection to Islanded Modes in Microgrids

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***Abstract*—VSC systems have been deployed in microgrids with two operating modes: grid-connected and autonomous. The initial phase of VSC output voltage after a microgrid switches from the grid-connected mode to the autonomous mode could significantly affect the microgrid performance if there is an induction machine. This paper demonstrates the effect of initial phase selection for VSC systems on dynamic performance of a microgrid. A microgrid consisting of a back-to-back VSC, passive loads and an induction machine is built in PSCAD/EMTDC. The impacts of initial phase of the VSC output voltage on both the induction machine and the VSC system are investigated. The comparison of with and without initial phase consideration demonstrates that both a better transient and steady-state performances are obtained if the initial phase is selected properly.**

***Index Terms*—VSC, microgrid, initial phase, passive network, autonomous mode.**

I. INTRODUCTION

THE distributed generations (DGs) has drawn extensive research interests [1-3]. With environmental and economic concerns, DGs with renewable energies are favorites in forming a microgrid to support local demands [1-2]. A microgrid usually consists of local loads, local power generations, and connection to a strong AC grid [4]. Since microgrids operate in both the grid-connected and autonomous modes, it becomes necessary for the DGs to operate in both grid-connected and autonomous modes.

A voltage source converter (VSC) can meet such requirements as the interface between DGs and microgrid. In addition, renewable energies such as wind farms and photovoltaic panels need VSC systems to convert variable speed ac electricity or dc electricity to constant frequency ac electricity [5]. With its inherent advantage of flexible controllability through PWM power electronic devices, a VSC could operate either in grid-connected or autonomous modes by switching between different control objectives [6, 7] .

For microgrids with passive loads and a synchronous machine, the essential control methodology of the VSC system is to keep power control mode [8] before and after islanding events. Since the synchronous generator can keep the microgrid frequency, there is no need for the VSC to keep the system frequency. The only difference between the grid-connected mode and the autonomous mode is the difference of the reference power values. Those values are dependent on the entire system power balance and bus voltage support. Hence, the overall system benefits from the VSC system with fast active and reactive power control. When the islanded microgrid switches back to the main grid, phase synchronization of the VSC output voltage is required.

Where there is no synchronous generator in a microgrid to keep a constant frequency, a VSC system has to supply the constant frequency and constant voltage for the microgrid. Generally, a VSC operates in active power and reactive power control mode under grid-connected scenario, and in voltage and frequency control mode under autonomous situation. Extensive research has been done in control design for autonomous mode [9-13]. In [9, 10], the autonomous control is achieved based on active power/frequency and reactive power/voltage droop characteristics. In [11-13], the voltage and frequency are controlled directly through classical controllers, and the frequency is controlled by internal oscillator on an open-loop control manner.

In [11-13], the loads are modeled as passive network (*e.g.,* RLC loads). In such scenarios, the initial phase of the VSC output voltage during control mode switching is not a big issue. However, in a more realistic system, a microgrid could consist of pure passive *RLC* loads and machines. In such circumstances, switching between control modes needs to be carried out more carefully.

For a microgrid with induction machines, since the VSC has to provide a system frequency, there is a need for the VSC to switch its control mode from grid-connected to autonomous. At the autonomous mode, the VSC is controlled to keep a constant output voltage with a constant frequency. An internal oscillator will be utilized for frequency regulation under open loop control manner [11-13].

The initial phase of the VSC output voltage selection is critical for the performance both on machines and VSC systems. A slight deviation on initial phase may cause high and long oscillations on speed, torque, voltages, and powers of both the induction machine and the VSC system. Such behavior causes both mechanical and electrical problems to the overall system. Hence, the initial phase of output voltage at the grid-side converter of VSC system should be *synchronized* with the phase before the switching occurs.

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This paper investigates the initial phase control of VSC systems in a microgrid with both induction machines and passive loads. In the sections follow, the paper first introduces the system configuration of a microgrid with a back-to-back VSC system. In Section III, controllers for machine-side and grid-side converters of a DG are designed based on conventional decoupled d-q control mechanism. *An initial phase selection scheme* is developed for grid-side converter. System simulations carried out in PSCAD/EMTDC are presented in Section IV. Section V concludes the paper.

II. A MICROGRID WITH A BACK-TO-BACK VSC INTERFACED DG

A microgrid shown in Fig. 1 is investigated in this paper. A microgrid is connected to an ac grid through a 13.8kV/69kV transformer. Three pure passive *RLC* loads are located at different sites. Two short transmission lines are used to connect the network. Besides the three passive *RLC* loads, an induction machine exists in the microgrid and is located at the site of Load 2. The induction machine in this microgrid operates at the generator mode. A large wind farm is connected to the microgrid through a back-to-back VSC system. The system parameters based on the IEEE Standard 399-1997 are listed in Table I [14].

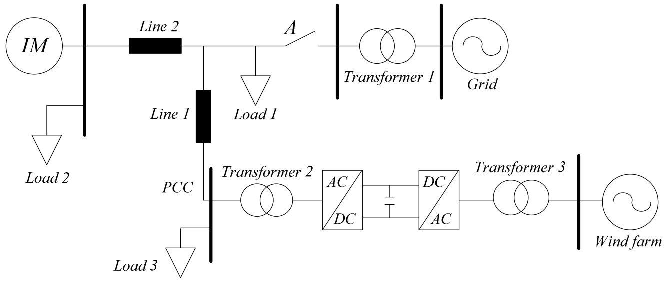


Fig. 1. A microgrid with a back-to-back VSC based DG.

The back-to-back VSC system is studied in this paper in both grid-connected and autonomous modes. The VSC system operates in grid-connected mode as long as Switch A is closed. A control mode switching within the VSC system is required if there are faults occurring at the main grid side. Switch A will be open to isolate the faults. At this circumstance, the VSC system should operates in the autonomous mode. Under grid-connected mode, the induction machine generates 5.5MW while the active power output command of the VSC system is 2.7MW. The total load demand is 15 MW. Hence, the microgrid absorbs 6.8MW from the main grid.

At the autonomous mode, the power supply from the grid is not available. The wind farm is assumed to have a capability to provide 20MW to the microgrid at its maximum. The VSC system will deliver 9.5MW to the microgrid at the autonomous mode. The modification of active and reactive power generation is achieved automatically by the machine-side converter. The grid-side converter now operates at voltage and frequency control mode.

As Fig. 1 shows, a back-to-back VSC system primarily consists of two VSC stations, two AC filters, two transformers, DC capacitor banks and DC transmission cables [6, 7]. A back-to-back VSC system operates this way: the machine-side converter transmits power from the machine side to the DC link. The power is then delivered to the grid-side converter through DC cables, and the grid-side converter transmits the power to another AC system. Both converters are controlled using PWM schemes. This VSC system is also able to inject reactive power to AC system, thus to support the AC voltage [6, 7].

TABLE I SIMULATION SYSTEM PARAMETERS

Quantity	Value
AC grid voltage	69kV (L-L RMS)
Transformer 1	13.8kV/69kV, 15MVA, leakage 8%pu
Transformer 2, 3	13.8kV/13.8kV, 20MVA, leakage 10%pu
DC-link voltage	±25kV
Load 1	4MW+0.8MVar at 13.8kV
Load 2	5MW+1.015MVar at 13.8kV
Load 3	6MW+1.218MVar at 13.8kV
Transmission line 1	980ft, (0.044+j0.0359)ohm
Transmission line 2	1187ft, (0.052+j0.0436)ohm

With conventional control strategies [15, 16], each VSC station has two degrees of control freedom. For the machine-side converter, one degree is to control active power flow while the other is arbitrary reactive power injection or AC voltage control. For the grid-side converter, one degree is to control DC-link voltage while the other degree is arbitrary reactive power injection or AC voltage control.

For the grid-side converter, active and reactive power control mode is applied at the grid-connected mode. At the autonomous mode, the machine-side converter is switched to control DC-link voltage and reactive power injection while the grid-side converter controls AC voltage and frequency [11-13]. The control mode switch leads to several problems which need to be considered during and after the AC grid disconnection event. The consideration is mainly the *coordination with other rotating machines*.

III. CONTROLLER DESIGN

The control system of VSC consists of two loops. One loop is inner current control loop; the other is either active power control loop or DC-link voltage control loop, which is based on the station operating condition (rectifier/inverter) [7]. However, when the VSC system is supplying a passive network, the control strategies need to be modified. Then, the machine-side converter controls DC-link voltage, while the grid-side converter is responsible for AC voltage and frequency control.

A. Machine-side converter control

When supplying a passive network, the machine-side converter controls DC-link voltage, which is similar as the grid-side converter does when supplying an active network. A decoupled d-q direct current control strategy has been developed in [15, 16].

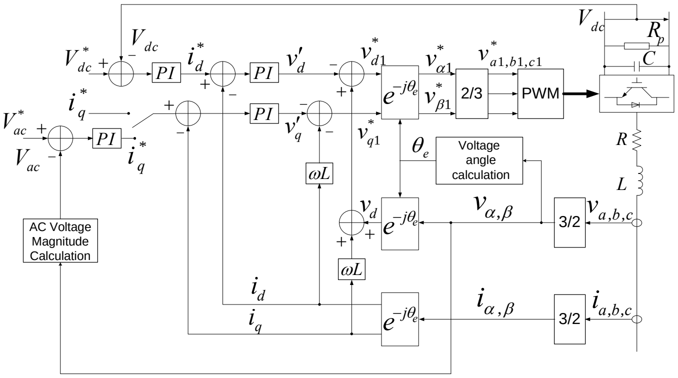


Fig. 2. Machine-side converter control strategy.

Figure 2 shows the overall machine-side converter control strategy. In which, the *d* and *q* axis current references are generated from DC-link voltage control and reactive power control loops, respectively.

B. Grid-side converter control

When supplying a passive network, the grid-side converter is used to control AC voltage and frequency. Two PI controllers can be used to regulate the *d* and *q* axis component of PCC voltage respectively. Fig. 3 depicts the AC voltage control strategy.

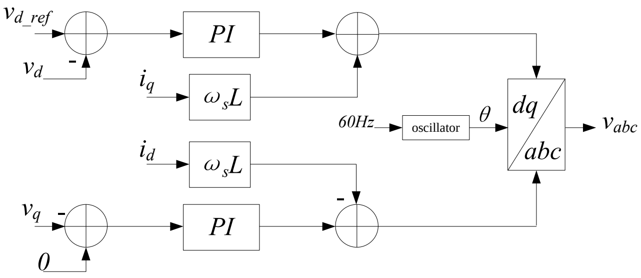


Fig. 3. AC voltage control strategy of the grid-side converter.

The frequency of the AC voltage generated by VSC is controlled by the grid-side converter. An internal oscillator is used to generate the angle θ, which ensures the output frequency is 60Hz and is sent to *dq to abc* transformation block for PWM signals generation [17].

C. Initial phase control

In [11, 12], only passive network is considered. Rotating machines are not considered. However, in a more realistic system, induction machines may be included in microgrids, which affect the transient performance during mode switching period. Hence, the selection of initial phase for internal oscillator in Fig. 3 should be considered carefully. It should be pointed out that, if the microgrid only consists of pure passive *RLC* load, the initial phase of oscillator is not a critical factor for system performance.

Fig. 4 illustrates the initial phase selection during control mode switch. In which, a PLL (Phase lock loop) is used to track the exact phase of PCC voltage. When the grid-side converter operates in grid-connected mode, the output of PLL is sent to the *dq to abc* transformation block directly. However, if the grid-side converter is required to switch to autonomous mode after a disconnection event, the selection of initial phase is accomplished as shown in Fig. 4, where t_{switch} is the time instant when control mode switch occurred. The *Hold* block records and holds the output phase of PLL at t_{switch}, and then sends it to the oscillator as the initial phase, after that, the control unit under autonomous mode is activated. Subsequently, the frequency of VSC output voltage is determined by internal oscillator and PLL is not required for grid-side converter.

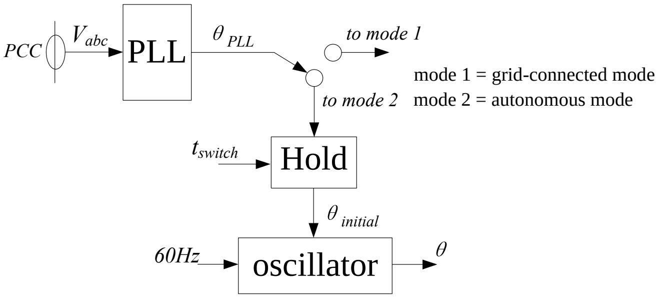


Fig. 4. Selection of initial phase during control mode switch.

IV. SYSTEM EVALUATIONS IN PSCAD/EMTDC

The main grid is disconnected from the microgrid at 8s due to some severe faults which require isolation, and the control mode of VSC system switches to autonomous after 50ms [8, 13]. To investigate the effects of various initial phase selections on system performance, comparisons are made based on: a) initial phase is determined as shown in Fig. 4, and b) initial phase is set to 0 degree.

Fig. 5 demonstrates the induction machine speed performance under different initial angle $\theta_{initial}$. The red line is speed performance of induction machine after main grid disconnection without initial phase consideration, while the blue line is the case with initial phase consideration. It can be noted that, the induction machine speed has a significant oscillation if $\theta_{initial}$ is simply set to 0 degree. The transition is much smoother if $\theta_{initial}$ tracks the value at the point of control mode switch occurred.

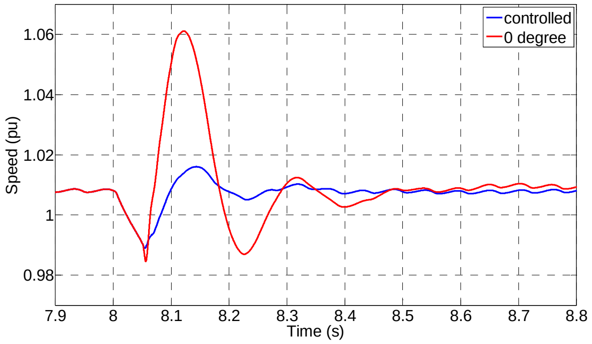


Fig. 5. Induction machine speed waveform.

Fig. 6 shows the induction machine torque waveform under different $\theta_{initial}$, which has similar result as speed performance shown. The blue line is torque waveform with initial phase consideration while the red line is the result without phase consideration.

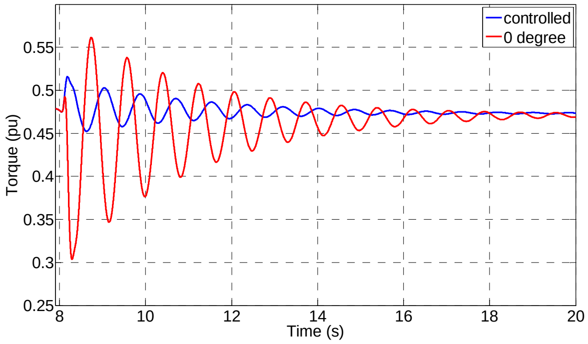
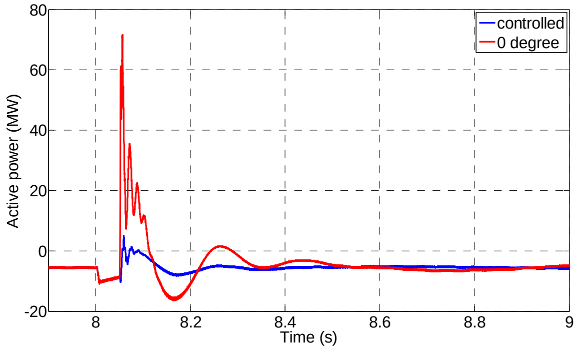


Fig. 6. Induction machine torque waveform.

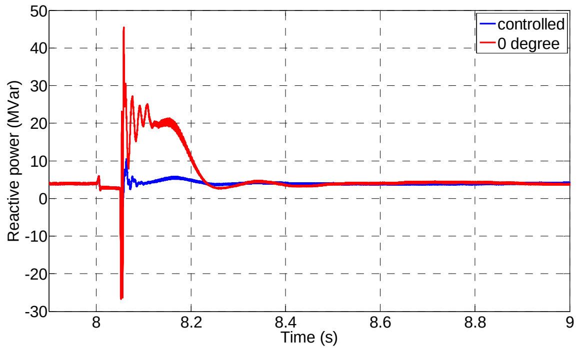
Such high torque oscillation shown in Fig. 6 takes a long time to be damped throughout and after the control mode switch process. It should be pointed out that, under several worst situations, the system may become unstable.

It could be expected that the active power output of induction machine will experience similar behavior as torque responses. Fig. 7 demonstrates the active and reactive power outputs of induction machine with two initial phases. Negative number means generating power to the microgrid from the induction machine. It is obvious that there are several high spikes on active and reactive power output from the induction machine if initial phase is 0 degree, which is harmful and not desired for machine operation. Nevertheless, the spikes are mitigated effectively if initial phase is considered carefully.

Figure 8 demonstrates the performance of VSC system under two initial phase selections. In which, the blue lines are the corresponding waveforms with initial phase tracking, while the red lines are with 0 degree initial phase. Figure 8(a) shows the PCC RMS voltage waveforms, the response with initial phase consideration is much faster than the other one. Moreover, the PCC RMS voltage sag is around 18% if the initial phase is set to 0 degree, while the sag is 12% in the other case, and that 12% sag is mainly due to the control mode switch time interval. The differences are more obvious on active and reactive power output at grid-side converter of VSC system as shown in fig. 8(b) and (c), in which negative number means generating power to the microgrid. With careful initial phase selection, both active and reactive power responses are fast and smooth. However, the responses with 0 degree initial phase are much worse. Such high overshoots on powers are very harmful to IGBT switches, which should be prohibited as much as possible. Fig. 8(d) shows DC-link voltage responses, in which oscillations are higher and takes longer time to be damped with 0 degree initial phase. The DC capacitor is critical for overall VSC system, since it supports

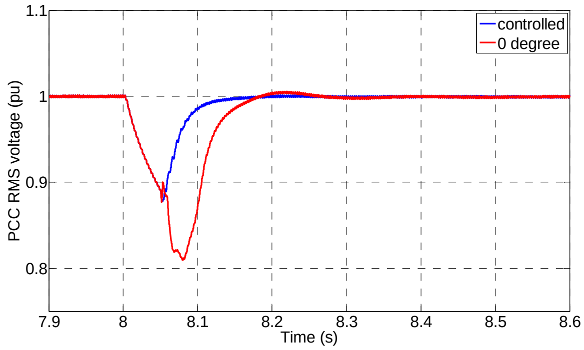


(a)



(b)

Fig. 7. Active and reactive power outputs of induction machine.



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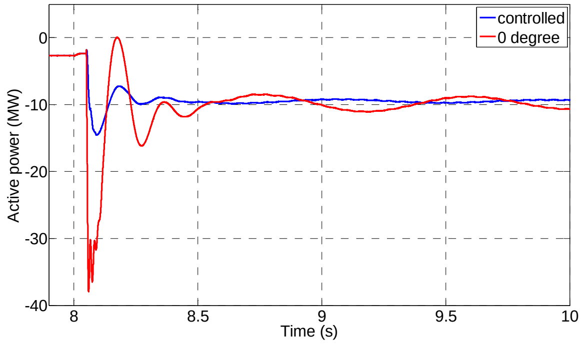

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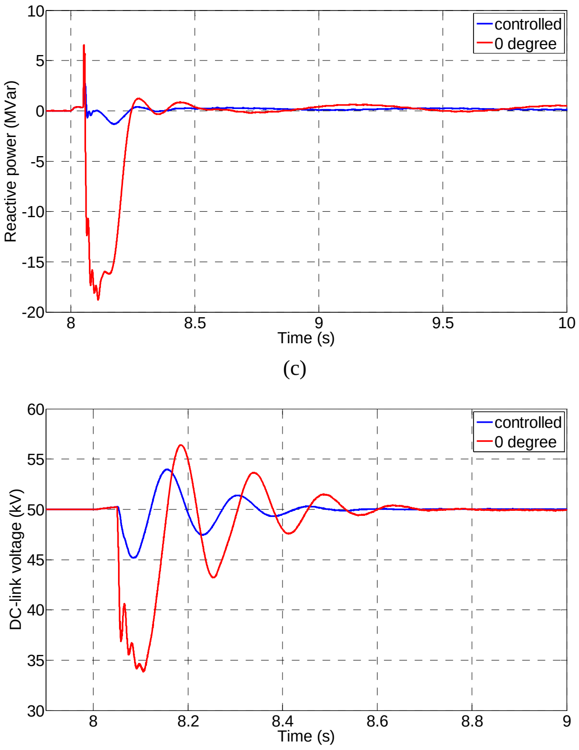


(c)

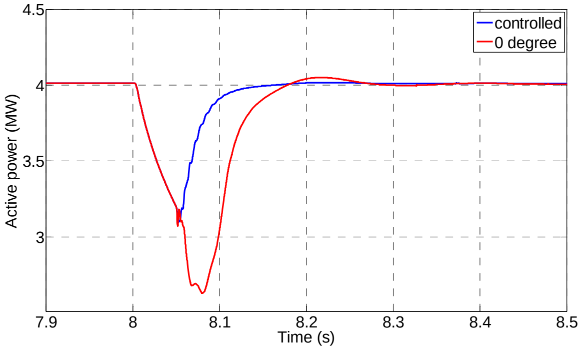
(d)

Fig. 8. Performance of VSC system under two initial phase selections

the DC-link voltage for power delivery. High DC-link overvoltage may damage insulation and cause fatal faults within VSC system.

From the load's point of view, customers always expect uninterrupted power supply with high power quality even a serious fault occurs. Although the VSC system could provide such services, the transient performances are sensitive to initial phase selection if induction machine involved. Fig. 9 depicts active and reactive power consumption of load 1 during the control mode switch of VSC system. It points out that a well controlled initial phase could significantly improve the power supply to loads, which is much more beneficial and necessary if the loads are critical.

The initial phase selection not only affects the performance on the induction machine, but also affects the VSC system and the loads.



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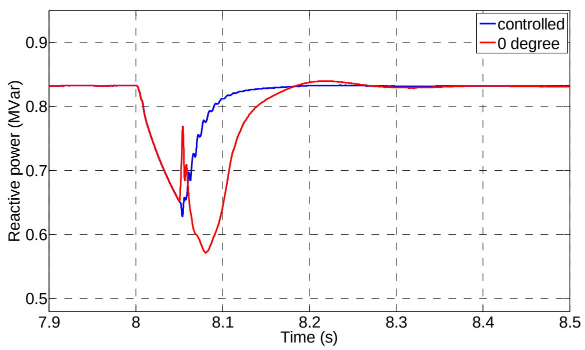

(b)

Fig. 9. Active and reactive power consumptions of load 1.

V. CONCLUSION

This paper investigates the initial phase of VSC output voltages on microgrid dynamic performance during operating mode switching periods. PSCAD/EMTDC simulations demonstrate a proper selected initial phase significantly improves the performance both on induction machine and the VSC system.

VI. APPENDIX

TABLE II INDUCTION MACHINE PARAMETERS

Quantity	Value
Rated RMS phase voltage	8kV
Rated RMS phase current	0.5kA
Base angular frequency	60Hz
Stator resistance	0.066pu
First cage resistance	0.298pu
Second cage resistance	0.018pu
Stator unsaturated leakage reactance	0.046pu
Unsaturated magnetizing reactance	3.86pu
Rotor unsaturated mutual reactance	0.122pu
Second cage unsaturated reactance	0.105pu
Polar moment of inertia	1.0s
Mechanical damping	0.0001pu

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