INTEGRATION AND OPERATION STRATEGIES FOR INVERTER-INTERFACED DISTRIBUTED GENERATION SYSTEM

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Abstract: This paper describes an inverter-interfaced distributed generation system that is interconnected with the electric power system. This system has two main goals: to serve customers with reliable electric power and to improve power quality. This system is interfaced through inverters because they are effective to control output voltage and current. Because DGs are interconnected with the electric power system, DGs should have countermeasures against disturbances from the electric power system. This paper proposes the operating strategy of DG in consideration for protection, islanding, and power quality. Using this operating strategy, site loads can be served high-quality power.

Keywords: Distributed Generation (DG), Interconnection, Inverters, Power Quality, Premium Power Supply (PPS), PSCAD/EMTDC.

1. INTRODUCTION

In recent years, much has been studied about *Distributed Generation* (DG) because it can solve many problems that vertically organized conventional power system has (Davis, 2002; Barker, and Mello, 2000; Ackerman, *et al.*, 2000). For example, DGs can improve power system reliability; relieve the capacity limit of the transmission and distribution system; reduce losses; and improve power quality. They can also preserve environment by using renewable energy such as wind, solar power, and biomass heat, not fossil fuel. In addition, if inverter interface is adjusted to DGs, the DGs can efficiently improve power quality because the inverter interface is useful to control output voltage and current waveform compared to rotating machines (Marei, *et al*., 2002; Barsali, *et al.*, 2002).

Most of DGs are interconnected with the electric power system (EPS) in order to overcome their limited capacity. The DGs interconnected with the EPS can serve more reliable electric power with stable frequency and voltage than those separated from the EPS. However, when a fault happens in the EPS or the local EPS, DG interconnection may affect the relay coordination, the safety of utility personnel, and the general public (IEEE Working Group, 1990; Rifaat, 1995).

This paper describes the configuration of the inverter-interfaced DG system called as the *Premium Power Supply* (PPS) with a series and a shunt connection to the EPS. In addition, this paper proposes overall operating strategy of the PPS including inverter control, protection, and islanding detection. The performance of the proposed operating strategy is simulated and evaluated by using PSCAD/EMTDC.

2. PPS CONFIGURATION

The PPS is designed to serve customers with reliable and high-quality electric power regardless of power system abnormalities (Chung, *et al*., 2003; Chung, *et al.*, 2004). Therefore, the customers of the PPS can be served with reliable power and sinusoidal voltage.

Fig. 1 depicts the configuration of the proposed PPS that consists of an energy source, an ac to dc rectifier, dc-link, an inter-tie *Solid-State Breaker* (SSB), a series and a shunt inverter, and a bypass switch of the series inverter.

The electric power generated by the energy source is stored in the dc-link that has large capacitance. The dc-link acts as an energy buffer between the energy source and the inverters.

The whole versatile functions of the PPS are achieved by controlling the inverters. The series inverter can compensate voltage events such as voltage sag and interruption. Because the PPS contains the energy source, the series inverter can effectively restore voltage event while other series compensators like *Dynamic Voltage Restorer* (DVR) have limitation in voltage and power rating. Therefore, the PPS can maintain the voltage of point of the shunt inverter connection. The shunt inverter can supply the electric power to the customer and compensate harmonic currents.

The PPS has two switches: the inter-tie SSB and the series-inverter-bypass-switch. The inter-tie SSB is installed between the two-inverter connections. If a severe fault happens in the EPS, the SSB opens in order to prevent any degradation of power and unintended power-island.

The bypass-switch of the series inverter detaches the series inverter during normal condition by closing the bypass circuit in order to reduce losses of the series inverter and the injection transformer. The bypass-switch opens only when voltage event happens in the EPS.

3. OPERATING STRATEGY OF THE PPS

To set up operation strategy, this paper assumes some conditions as follows. First, DGs can supply reverse power to the EPS in normal state. Second, the EPS must not experience any degradation of service from DGs being added to the line. Lastly, DGs should not energize the line of power-island that suffers loss of mains. Under those conditions, the PPS should have three operation modes and the operating strategy of the PPS is illustrated in Fig. 2 (Chung, *et al.*, 2004).

Parallel operation mode: While no fault takes place in the EPS, the PPS is interconnected with the EPS in parallel and shares load demand power with the EPS. In this mode, the PPS can provide surplus power to the EPS after energizing site loads. In addition, the PPS can improve power quality such as voltage unbalance and harmonics.

Independent operation mode: When some severe permanent faults or inadvertent island happen in the EPS, the PPS should not charge the EPS for the sake of protection and safety. In this mode, the PPS should be separated from the EPS and protect its site load.

Transition mode: If an EPS voltage event occurs, the PPS switches directly to this mode, not to the independent operation mode. In this mode, the series inverter starts to compensate for the missing voltage, so that the voltage at the point of the shunt inverter connection will be kept the same as the voltage of the normal state. The shunt inverter controls its output to prevent reverse power from flowing to the EPS without opening the inter-tie SSB. In addition, the voltage at the Point of Common Coupling (PCC) will be unaffected by the transition mode operation.

Theoretically, the inverters can control the voltage and current of the point of the shunt inverter connection in order to prevent the fault current from flowing into EPS. Thus, during the transition mode, the PPS can keep the inverters from giving bad effect on the EPS. If faults last long, it is safer to separate the PPS from the EPS. IEEE Std. 1547 has specified the clearing time (T_{clr}), in that DGs should be separated from the EPS, as listed in Table 1 (IEEE Standard, 2003).

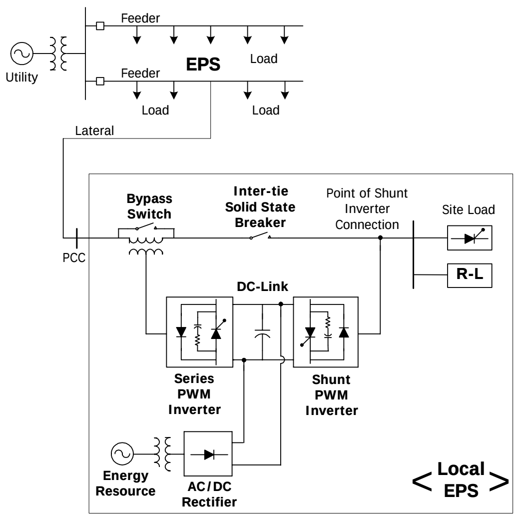

Fig. 1. Configuration of the PPS

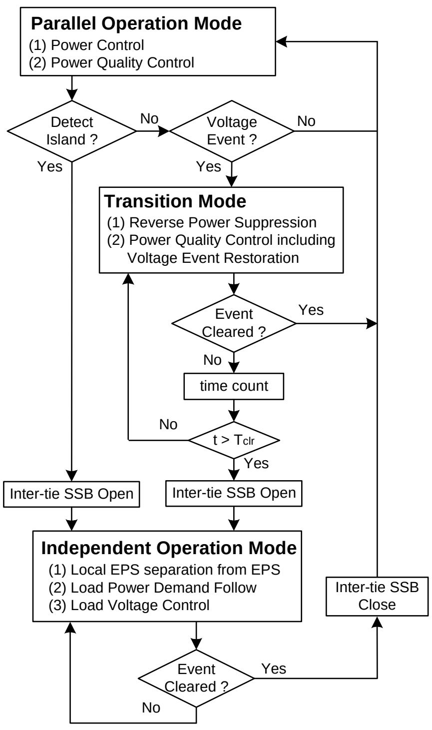

Fig.2. Flow chart of the operating strategy of PPS

There is a particular case, inadvertent islanding. In this case, the PPS should directly change the parallel operation mode to the independent operation mode. There have been several researches about how to detect islanding case (Mattison, 1995; Redfern, *et al.*, 1995; Pai, and Huang, 2001). This paper uses the window-relaying method that will be described in the next chapter (Mattison, 1995).

Table 1 Interconnection system response to abnormal voltages

Voltage range (% of base voltage)	Clearing time (sec)
V < 50	0.16
50 < V < 88	2.00
110 < V < 120	1.00
V >120	0.16

4. CONTROL SCHEME OF PPS

The dc-link voltage goes down while two inverters use the stored energy in the dc-link to accomplish the functions of the PPS. The major role of the energy source is to supply electric power to the dc-link.

The main function of the series inverter is to compensate the load voltage when the voltage of PCC varies suddenly. Fig. 3 depicts the configuration of equivalent circuits of the inverters and the inter-tie SSB. Specifically, the series inverter injects the voltage difference between the load reference voltage and the fault voltage. Therefore, the load voltage can be maintained as balanced sinusoidal waveform.

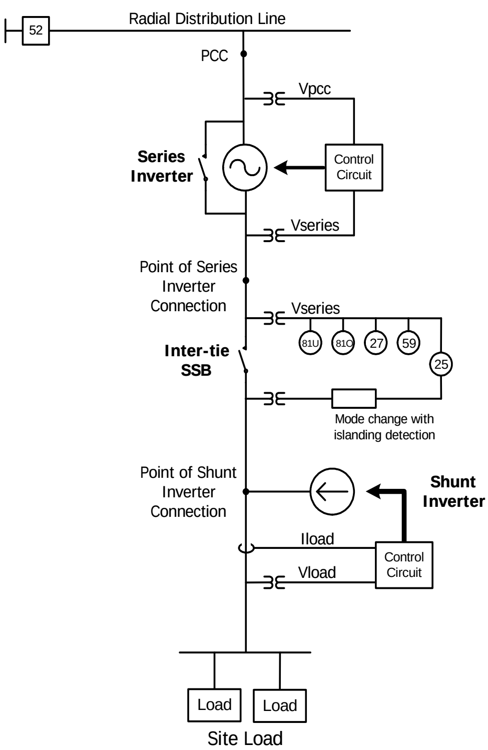

Fig. 3. Configuration of control circuits of the inverters and the inter-tie SSB

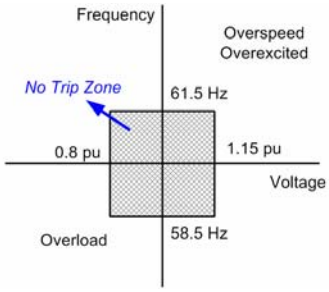

Fig. 4. Window-relaying method

The inter-tie SSB has basic protection functions like undervoltage (27), overvoltage (59), under-frequency (81/U), and over-frequency (81/O) relay functions as illustrated in Fig. 3. Using those basic functions, the SSB can easily detect inadvertent islanding. Fig. 4 shows the window-relaying method (Mattison, 1995). If voltage and frequency would go out of no-trip zone, the PPS could judge the condition as islanding. This method, however, could not detect islanding when the power mismatch between normal condition and islanding condition is too small to give an impact to the voltage and frequency of the PCC. Therefore, more delicate method should be adjusted to the PPS later.

5. SIMULATIONS

The test distribution system for simulation is illustrated in Fig. 5 that is modeled by using PSCAD /EMTDC. The parameters of the test system are listed in Table 2.

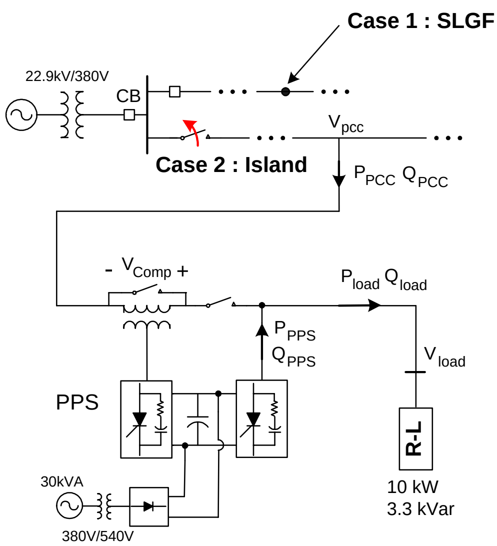

Fig. 5. Distribution system for simulation

The test distribution system for simulation is illustrated in Fig. 5 that is modeled by using PSCAD /EMTDC. The parameters of the test system are listed in Table 2.

Table 2. Parameters of the distribution system

Components	Parameters
Transformer	Winding Ratio: 22.9kV/380V Rated Capacity: 1MVA Impedance: 10%
Line (ACSR)	Positive Seq.: 3.86+j7.42 %Z/km Zero Seq.: 9.87+j22.68 %Z/km (Base: 100MVA)
DC-link	Capacitance: 3300uF Rated Voltage: 700V
Diesel generator	Rated Capacity: 30kW Rated Voltage: 380V
Site load	Linear Load: 10kW, 3.3kVar Non-linear Load: 5kVA (only case III)

5.1 Case 1: Single-line-to-ground-fault (SLGF)

5.0 ~ 5.5 sec: the PPS starts in the parallel operation mode and supplies 20kW. Because the demand power of site load is 10kW, the reverse power flows into the EPS to the amount of 10 kW.

5.5 sec: SLGF occurs in the EPS. Then, the PPS will suffer the voltage sag and change its operation mode to the transition mode.
5.5 ~ 6.0 sec: during the transition mode, the PPS compensates the missing voltage to constantly maintain load voltage, and supplies only 10kW demanded by local load.

6.0 sec: the SLGF is cleared and the voltage of the PCC gets back to the normal voltage. Therefore, the PPS switches operation mode to the parallel operation mode and supplies 20kW.

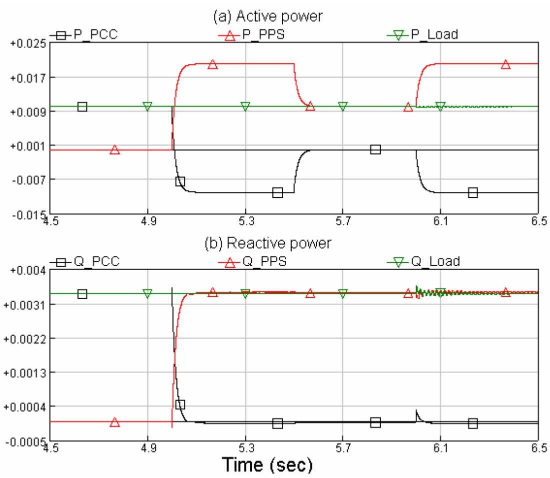

Fig. 6. Simulation result: active and reactive power
P_PCC, Q_PCC – the active and the reactive power measured at the PCC; P_PPS, Q_PPS – the active and the reactive power supplied by the PPS; P_Load, Q_Load – the active power absorbed in local loads

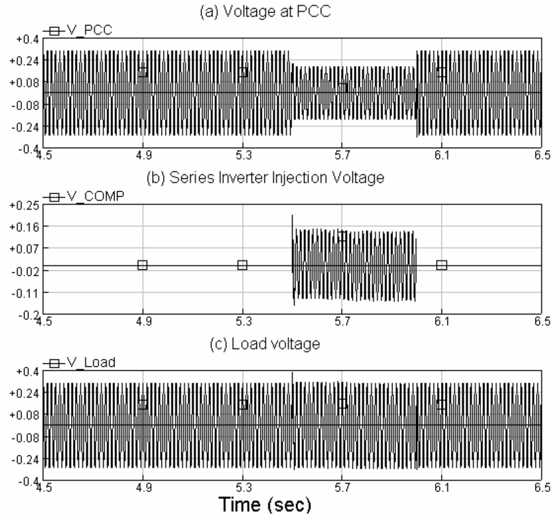

Fig. 7. Simulation result: voltages
V_PCC – the PCC voltage; V_COMP – the compensation voltage of the series inverter of the PPS; V_Load – the local load voltage

5.2 Case 2: Inadvertent Island

5.0 ~ 5.5 sec: the PPS starts in the parallel operation mode and supplies 20kW. Because the demand power of site load is 10kW, the reverse power flows into the EPS to the amount of 10 kW.

5.5 sec: the upper circuit breaker opens so that the local area turns to inadvertent island. The frequency of the island area varies from the normal value, 60Hz.

5.5042 sec: The frequency of the island area goes out to the window-relaying range from 58.5 to 61.5Hz. Therefore, the PPS makes switch to the independent operation mode. Then, the voltage and frequency are kept in the normal operation area that is inside of the window-relaying region.

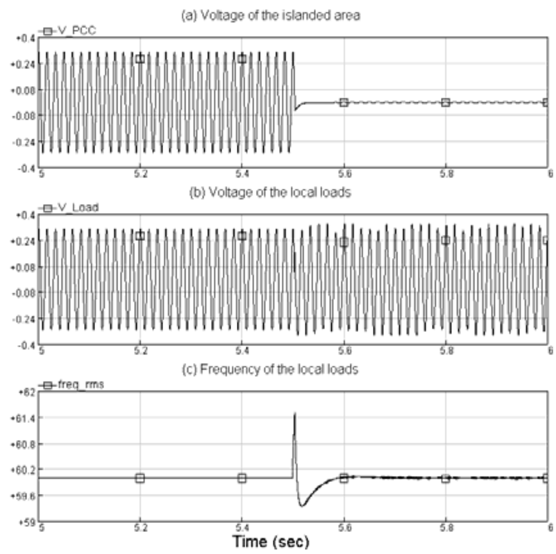

Fig. 8. Simulation result: voltage and frequency
V_PCC – the PCC voltage; V_Load – the local load voltage; freq_rms – the frequency of the local load voltage

6. CONCLUSION

To preserve power quality and provide alternative power source, this paper proposed the inverter interface DG called the PPS. The combination of components of the PPS like the inverters and the energy source is so complementary to each other that the entire system is effective to control the local EPS.

This paper proposed the operating strategy of the PPS. Under this operating strategy, the PPS can supply high-quality electric power to the customer and deal with power system abnormalities such as power system faults and inadvertent island. The operating strategy and major functions of the PPS were validated by simulation.

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BIOGRAPHIES

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