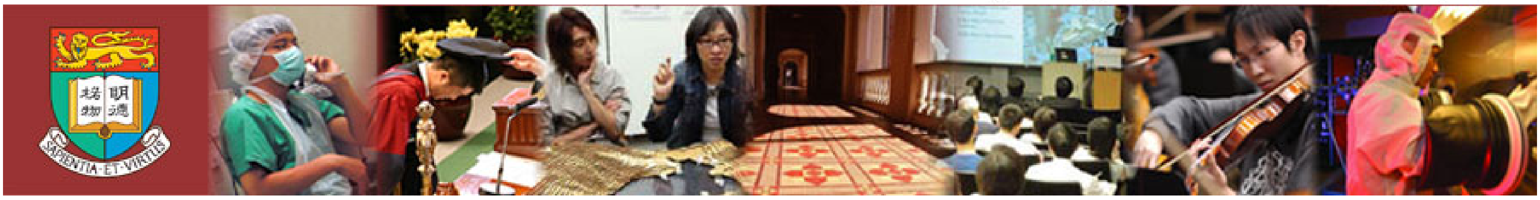

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Virtual Synchroscope: a novel application of PMU for system restoration

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Abstract：Power system restoration is well recognized as one of the key technologies to improve the reliability of power systems. Generally, the restoration process is divided into several stages as preparation, system restoration, load restoration, synchronization and inter-connection. Currently, re-closure of breakers is done by field crews with synchroscope. A novel methodology, entitled as “virtual synchroscope”, is proposed in this paper. By utilizing Phasor Measurement Units (PMUs), the proposed methodology compares phasors of voltages at connection points from the two islands with the accurately time-stamped measurements. By adjusting voltage magnitude, frequency, and phase angle in the control center, all the requirements for synchronization are satisfied and the synchronization can be implemented. A case study on a power system is presented to validate the feasibility of the proposed method. It is proved that the proposed method can meet the requirements of all standards and resulting in smooth synchronization.

Keywords：**system restoration, synchronization of islands, phasor measurement unit, optimal power flow**

1 Introduction

Power system restoration is well recognized as one of the key technologies to improve the reliability of power systems. As a complex problem involving a large number of generation, transmission, distribution and load constraints, the restoration process is generally divided into several stages, such as preparation, system restoration, load restoration, synchronization and connection stages.

During implementation of these stages, synchronization of small islands to establish a strong system is one major task. Traditionally, synchronization must be conducted within the substation equipped with synchroscope, i.e., the synchronization can only be conducted through some predetermined path. However, it is difficult to specify such substations and paths that cover all possible scenarios of system restoration. This fact significantly limits the flexibility to establish and implement system restoration strategies. Furthermore, the synchronization is monitored and operated in the substation. The re-closure occasion is mainly decided by substation crews with synchroscope. Since the substations have no control effect on the island’s frequency and voltage, the time for synchronization could be long. The impact after re-closure is not unpredictable or controllable in substation’s point of view.

The restoration strategy establishment, modification, and implementation are all based on a good understanding of the system status. As a state-of-the-art technology for measurement, PMUs (phasor measurement units) at various measuring sites are synchronized on a common time base. It provides a direct measurement of system states, which has the potential to benefit power system restoration.

During the process of system restoration, PMUs can provide information for both steady state and dynamic conditions. Recent reports have shown that, installed PMUs have already made significant contributions on information acquisition during system blackout and system restoration [1, 2]. The deployment of PMUs has been strongly recommended by authorities after the Northeast US and Italian blackouts in 2003 [3]. It is believed that the PMUs have a wide range of potential applications for system restoration.

With PMU measurements, a novel methodology entitled as “virtual synchroscope” for islands-synchronization is proposed in this paper. This application in the control center reads data from installed PMUs at different locations through the power grid. A re-dispatch is conducted to adjust frequencies, voltages of both sides to meet the requirement of synchronization. A case study on a power system is presented to validate the feasibility of the proposed methodology.

2 Current industry practice in synchronization

During a system restoration, after two islands are strong enough and tie-lines are available, synchronization of two electric islands might be carried out based on some restoration strategy.

According to NERC’s Standard EOP-005-1, the islands can be synchronized with the surrounding island(s) when the following conditions are met: voltage, frequency, and phase angle permits. The size of the area being reconnected and the capacity of the transmission lines effecting the reconnection and the number of synchronizing points across the system are considered. Reliability

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Coordinator(s) and adjacent areas are notified and Reliability Coordinator approval is given. And load is shed in neighboring areas, if required, to permit successful interconnected system restoration.

To maintain the stability of synchronization, the reserve capability is required in order to enable an area to restore its tie-lines as soon as possible after synchronization that causes an imbalance between load and generation. During normal operation, these reserves must be provided by increasing energy output on electrically synchronized equipment. However, during restoration, customer load may also be classified as Synchronous Reserve. Each area/subsystem must carry enough Synchronous Reserve to cover its largest energy contingency. The guidelines for synchronous reserve are specified based on the different characteristics of systems.

Prior to synchronizing two islands, usually, the smaller island adjusts the frequency to match the frequency of the larger islands. In addition, the voltages of the two areas are as close as possible prior to synchronization. Several substations are selected as candidates for synchronization. Generally, these substations must be equipped with a synchroscope that can be used for synchronizing the two areas. Also, it must have reliable communication with the system operator who will direct the tie-in. In no case should synchronization between two areas be attempted without either a synchroscope or synchro-check relay due to the high probability of equipment damage and possible shutdown of one or both areas. The shortest path will be found for synchronization between the candidate substations.

To meet the constraints, the stronger island, i.e., the system with better adjustment capability, will be used to crank the path for synchronization until the last breaker. The outputs of generating units in each island will be adjusted. To minimize the impact, the voltages of two buses within two islands for synchronization are adjusted to the same value.

According to NERC standards, substations that are equipped with synchroscopes can be employed for synchronization. Actually, from NERC's criteria [4] of partitioning system into islands, only the preset substations can be used. As a result, all these islands or tie-lines should be identified in advance before they can be used during system restoration. Several difficulties might be met during system restoration according to these requirements.

On one hand, it is very difficult to specify substations for synchronization, which cover all possible scenarios of system restoration. During system restoration, outages and system characteristics are diverse. For tie-lines between regional power grids, the substations for synchronization may be specified and synchroscopes can be installed. However, following a partial outage, system might have multiple black-start units or remaining energy resources that can be used to energize the outage components. After some islands are strong and close enough, synchronization is needed. The path for synchronization is determined by characteristics of outage, locations of energy resources and restoration strategies. It is impractical to design paths for synchronization, which cover all the scenarios during the planning stage. On the other hand, traditional synchroscopes require field operation to monitor the differences of phase angles between two sides of the breaker. However, no voluntary control means are provided in substation. Lack of global information and control tends to make synchronization fail.

3 Virtual synchroscope methodology

3.1 Data acquisition with PMUs

The difficulty with the conventional synchronization practice lies in that the substations have inadequate observe and control means to make synchronization conditions satisfied.

State-of-the-art PMU technology can acquire data with 30-60 samples per second. With this fast rate, the magnitude and angle of voltage and current are measured with time tags. As a result, the following steady-state data can be provided by PMUs: 1) bus voltage magnitude and standing phase angle; 2) current magnitude and phase angle; 3) real power and reactive power calculated from voltage and current; 4) standing angles identification for the purpose of stability assessment; 5) system frequency.

In the restoration process, system monitoring is critical. An accurate assessment of the system state is critical for advanced applications such as system security evaluation and control. Raw measurements of the system states are not directly usable; they are filtered by state estimation. Traditional state estimation provides steady-state voltage phasors (including voltage magnitude and phase angle) by processing redundant data collected at substations (real power, reactive power and voltage magnitude). With the development of PMUs, phasor data are used in building advanced state estimators by providing direct measurements. For example, phasor measurements and data visualization provide the dispatchers with a useful view of the power grid, including real-time values of node voltages and branch currents. Their variation and rapid changes of components are indications of the possible problems [5]. This information is critical for all stages of system restoration.

3.2 Observability and Controllability with PMUs

Phasor measurement leads the progression form a nonlinear state estimation to a complete linear state estimation of the system. A 20%-30% ratio of the number of PMUs to the number of buses is adequate for a direct linear measurement algorithm in most networks [6]. It is necessary to consider that system observability is subject to change due to the topology changes [7] in restoration stage. The patent US 7069159 introduces a hybrid state estimator that uses the observed phasor measurement location data to estimate parameters at unobserved locations [8], which can be utilized in the virtual synchroscope methodology.

In the control center, applications as Dispatcher Power Flow or Optimal Power Flow can be used to perform centralized adjustment to change the steady voltage magnitude and phase angle to some appropriate value. With PMUs, the frequency of each island can also be adjusted in the control center, as conventional generator paralleling in power plant.

3.3 Work flow of virtual synchroscope

We assume that the observability and controllability has been checked during the synchronization stage in the control center. For a system illustrated as Figure 1, the proposed virtual synchroscope methodology is described as follows.

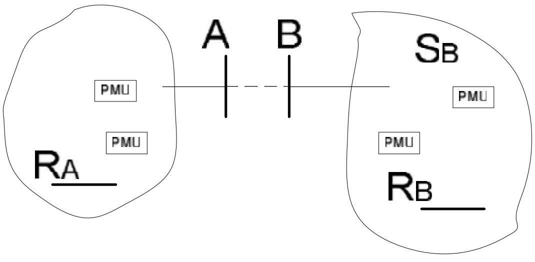

Figure 1 Islands synchronization by virtual synchroscope methodology

For two energized islands, SA and SB, bus RA and RB are selected as swing buses, respectively. Bus A and Bus B are selected for synchronization of the two systems. Assume sufficient PMUs have been installed on the two systems to ensure the observability of Bus A, Bus B, Bus SA, and Bus SB of two islands.

Step 1. Frequency (phase angle) adjustments are performed to swing buses in different electric islands based on PMUs. This step makes voltage angles of swing buses are close enough. By PMUs, the phase angles of buses in different islands have the same reference. As a result, system dispatchers can compare the all phasors in all islands in the control center.

Step 2. Re-dispatch are performed to meet closure requirements for terminal buses of the transmission line. The re-dispatch is based on steady power flow, the target being that the voltages (magnitude and phase angle) in the closure point are close enough.

Step 3. Power flow simulation on the closure of the breaker to validate the steady power flow impact on the transmission line.

Step 4. Check the phase angles of swing buses. Frequency adjustment is performed to make swing buses have the same phase angle.

Step 5. Close the breaker.

Mathematically, the system dispatcher can adjust voltage phase angle of a bus by adjusting the generator output, i.e., using an OPF algorithm to adjust the bus voltage and phasor angle to a given value. However, the transient process is involved during implementation of this adjustment. Comparing with the other system, the phasor angle of the swing bus in this system may be changed after adjustment. As a result, two bus voltage phasor angles can be very close mathematically, but cannot be ensured in the physical system. Hence, step 4 is needed after re-dispatch to guarantee the phase angles of buses in different islands still have the same reference.

4 Case study

A case study using IEEE-4 buses and IEEE-14 buses as test system is utilized to demonstrate the synchronization process of virtual synchroscope. SA is a 14 buses island with bus 1-14. SB is a 4 buses system with bus A, B, C and D, as in Figure 2. Bus B and bus 10 are selected as closure points to connect two islands. The topology after synchronization is shown in Figure 3.

Power flow calculation is performed in both SA and SB, respectively. Notice that the slack bus of SA is bus 1, the slack bus of SB is bus D. The phase angles of slack buses are set as 0 degree. It means that the buses of these two islands are referred to the same absolute 0 degree. It is reasonable with PMUs, for PMUs can measure voltages of buses in a geographically long distance and frequency (phase angle) adjustment can be performed to generators. The power flow result is shown in Table 1 and Table 2.

Voltage magnitudes and phase angles of bus B and bus 10 are investigated to check whether these two buses can be connected by tie-line or not. If not, re-dispatch of each island is performed respectively based on OPF algorithm (minimize the adjustment of output of generators) to adjust the voltages of bus B and bus 10 to an assigned value, as shown in Table 3 and Table 4.

After re-dispatch, the dispatchers have to check whether the swing buses still have the same values using PMU data. Adjustment will be implemented if necessary.

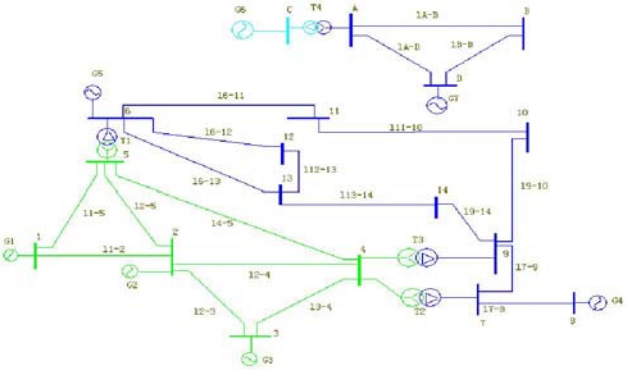

Figure 2 Topology of test system before synchronization

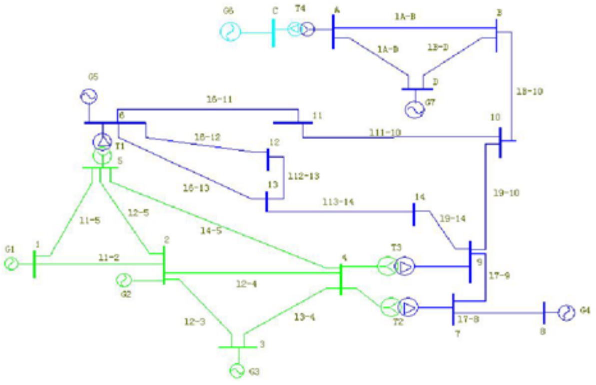

Figure 3 Topology of test system after synchronization

Table 1 Power flow of SA

Bus	Type	Voltage (pu)	Angle (degree)	PG (pu)	QG (pu)
1	Swing	1.060	0	1.162	-0.003
2	PV	1.045	-2.37	0.650	0.053
3	PV	1.010	-9.00	0	0.168
4	PQ	1.033	-5.93		
5	PQ	1.038	-4.32		
6	PV	1.070	-3.12	0.850	0.112
7	PQ	1.055	-6.64		
8	PV	1.090	-6.64	0	0.214
9	PQ	1.046	-7.40		
10	PQ	1.041	-6.93		
11	PQ	1.051	-5.17		
12	PQ	1.055	-4.22		
13	PQ	1.048	-4.55		
14	PQ	1.028	-7.17		

Table 2 Power flow of SB

Bus	Type	Voltage (pu)	Angle (degree)	PG (pu)	QG (pu)
A	PQ	0.985	-0.50		
B	PQ	0.964	-6.45		
C	PV	1.10	6.73	0.500	0.093
D	Swing	1.05	0	0.368	0.265

Table 3 Power flow of SA after re-dispatch

Bus	Voltage (pu)	Angle (degree)	PG (pu)	QG (pu)
1	1.055	0	0.660	0.067
2	1.047	-1.22	1.000	0.298
3	1.012	-7.84	0	0.298
4	1.013	-4.22		
5	1.020	-2.77		
6	1.044	0.23	1.000	-0.018
7	1.006	-5.23		
8	0.989	-5.23	0	-0.099
9	1.002	-5.77		
10	1.000	-5.00		
11	1.016	-2.52		
12	1.028	-0.67		
13	1.018	-1.36		
14	0.989	-4.93		

Table 4 Power flow of SB after re-dispatch

Bus	Voltage (pu)	Angle (degree)	PG (pu)	QG (pu)
A	1.001	1.731		
B	1.000	-5.00		
C	1.10	10.35	0.609	0.262
D	1.094	0	0.019	0.369

When PMU monitors (or estimates) that the difference of voltages of bus 1 and bus D is close enough, the tie-line B-10 is energized to synchronize SA and SB. Theoretically, the power flow of tie-line B-10 is close to 0. A power flow calculation supporting multiple slack buses is used to figure out the power flow distribution of the synchronized island. Numerical result confirms that, after re-dispatch, the power flow of the synchronized island is nearly the same as island I and island II before synchronization. Also, the power flow of tie-line B-10 is very close to 0 (<1E-3 pu), as shown Table 5.

Table 5 Power flow after synchronization

Bus	Type	Voltage (pu)	Angle (degree)	PG (pu)	QG (pu)
1	Swing	1.055	0	0.653	0.051
2	PV	1.047	-1.209	1.000	0.264
3	PV	1.012	-7.849	0	0.288
4	PQ	1.015	-4.294		
5	PQ	1.024	-2.746		
6	PV	1.044	-0.739	1.000	0.048
7	PQ	1.011	-4.948		
8	PV	0.989	-4.948	0	-0.124
9	PQ	1.009	-5.647		
10	PQ	1.007	-5.083		
11	PQ	1.020	-3.053		
12	PQ	1.028	-1.936		
13	PQ	1.020	-2.296		
14	PQ	0.994	-5.260		
A	PQ	1.008	1.707		
B	PQ	1.005	-5.038		
C	PV	1.10	10.32	0.609	0.013
D	Swing	1.094	0	0.261	0.352

5 Conclusion

A new methodology entitled “virtual synchroscope” for island synchronization in power system restoration is proposed. With PMU data, the states of islands can be observed and controlled in the control center. It is shown that the proposed method can help the dispatchers meet the requirements of all standards of synchronization. Since voluntary observation and control is practical with

PMU, the impact on closure tie-line is controllable and predictable, which results in smooth synchronization.

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