A PMU based special protection scheme: a case study of Taiwan power system

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Received 4 December 2001; revised 5 August 2004; accepted 24 September 2004

Abstract

This paper proposes a special protection scheme to prevent power system blackout due to a sequence of relay trip events based on phasor measurement units (PMUs). In a control center, we use PMU's to monitor the generators and the major EHV transmission lines of a power system, and apply an instability prediction algorithm for initiating a special protection schemes (SPS) to avoid a sequence of relay trip events whenever necessary. When a fault happens, we group the generators swinging coherently and reduce the system to One-Machine-Infinite-Bus (OMIB) system. The remedial control actions consist of load shedding and generation tripping. The strategy for determining the amount of remedial control actions is a proposed relay setting limited equal-area criterion for OMIB. A case study of Taiwan power system assumed to be equipped with proposed special protection scheme is conducted. Encouraging results are obtained.

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Keywords: PMU; Blackout; Special protection schemes (SPS); Remedial action schemes (RAS); Transient stability

1. Introduction

Electric power systems in Taiwan are undergoing significant change. Due to ever-increasing environmental and economical pressures, it becomes extremely difficult to construct new transmission or generation facilities. As a result of the limited power supply and steady growth of load demand, Taiwan Power System (Taipower system) has a severe area generation–load imbalance and a heavy power transfer between northern area and southern area over two 345 kV transmission line. Therefore the operating point is pushed closer to the stability boundary and the system is increasing susceptible to transient instability condition following a severe disturbance such as three-phases short circuits of EHV transmission lines. In fact, on July 29, 1999, Taipower system experienced an outage (call 729 event) due to a collapse of a 345 kV transmission tower, which results in about 80% power interruption of total energy lasting

several hours [1]. Thus, the issue of maneuvering a system to a more secure operating condition by on-line stability monitoring and control becomes a critical task for Taipower system.

Traditionally, special protection schemes (SPS) [2] (also called remedial action schemes or RAS) are designed to detect abnormal system condition, typically contingency-related, and initiate pre-planned, remedial control action such as generation tripping, load shedding and system separation, etc. to mitigate the consequence of the abnormal condition and provide acceptable system performance. SPS can provide remedial control actions and are often used to increase the transfer capability of the transmission system. Compared with constructing new transmission facilities, SPS can be installed relatively quickly and inexpensively. However, conventional SPS may result in risk to system reliability by failure to operate when required and nuisance tripping when unintended. To increase meaningful decisions of SPS, the precise knowledge of the current state of the power system must be acquired in real-time. Fortunately, the recent advent of synchronized Phasor measurement unit (PMU) using the global positioning

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system (GPS) of satellites for synchronization has made possible a state estimate that is a true snapshot of the power system [3]. Furthermore, the state could be renewed in tens of millisecond; thus, it is possible to track the system dynamic phenomena in real-time and make much more meaningful decision for SPS.

In this paper, we propose a PMU based SPS against transient instabilities caused by EHV transmission line failures. Specifically, the proposed SPS is applied to Taipower systems. Simulation results are shown to demonstrate the effectiveness of the proposed method in the last section.

2. Configuration and algorithms

2.1. Configuration

Due to the most power system load centers and generators are not in the same area, so EHV tie lines are needed to transfer large power between areas. If one or more than one tie line are tripped due to faults, the power that transfers in the faulted line before faults may transfer by the other tie lines between the areas. If the transfer power is very large, it may cause the other tie lines overloaded. This will cause a successive relay trips resulting in the system blackout. We propose a method in real-time to predict the system stability, and determine the amount of remedial control actions to stabilize the system whenever necessary.

Fig. 1 shows the PMU based special protection scheme. In a control center, we use PMU's to monitor the generators and the major EHV transmission lines of a power system, and apply an instability prediction algorithm for initiating a SPS to avoid a sequence of relay trip events whenever necessary. When a fault happens, we group the generators swinging coherently and reduce the system to One-Machine-Infinite-Bus (OMIB) system. Then using real-time phasor measurements to estimate the parameters of OMIB system. The remedial control action consists of load shedding and generation tripping. The algorithm for determining the timing and amount of the remedial control

Fig. 1. The PMU based special protection scheme.

Fig. 2. Two-machine equivalent system.

action is a proposed relay setting limited equal-area criterion. The following steps are the proposed SPS.

1. Group generators swinging coherently and reduce the system to an OMIB system (This step is conducted off-line based on large simulation results. For a longitudinal system, like Taipower system, it is not hard to group the generators after faults).
2. Estimate the parameters of an OMIB system using real-time phasor measurements.
3. Determine the timing and amount of the remedial control action by relay setting limited equal-area criterion (EAC) method.

2.2. Real-time parameter estimation

In a power system consisting of two synchronous machines and a tie line over which synchronizing power can flow, the problem of instability detection can be solved in real-time [4]. A modified equal-area criterion (called relay setting limited EAC method) is applicable in this case, and if the machine rotor angles and speeds can be measured in real-time a prediction algorithm can be developed for the detection of instability. When ac power imported over relatively long distances for example Taipower system, so that both the sending system and receiving system consist of groups of coherent generators, one of the modes of oscillations of such a power system is that of a two-machine system.

In the two-machine equivalent of a power system, it is assumed that for an assigned fault, the power system is decomposed into two subsets: (1) the critical cluster of machine(s) B, and (2) the remaining machines A (Fig. 2). The former is responsible for system separation when it arises. Then the two subset are transformed into two equivalent machines, modeled within their corresponding frame of partial center of angle (COA), and with the assumption of strong coherency of machines in each cluster, the two-machine equivalent system is further reduced to an OMIB system (Fig. 3). The dynamics of OMIB system is

Fig. 3. One-machine-Infinite-bus (OMIB) system.

Fig. 5. Structure of the Taiwan 345 kV system including the proposed scheme.

transient conditions without solving the swing equation. Power angle curves are used to analyze the physical conditions before, during and after a fault. We obtain the postfault system power angle curve by using estimated system parameters P , B , and C . The EAC method can decide the stability of the systems. Our method is to prevent the EHV tie lines far from cascade tripping, so we use the smallest relay setting limited area power flow, to modify the EAC methods. We transform the tie line relay setting to the equivalent relay setting limited area power flow, and choose the smallest relay setting limited area power flow to determine the stability. For example, the current setting of the i th tie line relay can be transformed to an relay setting power, $P_{set,i}$, by the equation:

$$P_{set,i} = \sqrt{3} \times (\text{rated line voltage}) \times (\text{current setting}) \quad (8)$$

We transform the relay setting power to the equivalent relay setting limited area power flow by the following equation

$$P_{R,i} = P_{area} + \frac{P_{area}}{P_{line,i}} \times (P_{set,i} - P_{line,i}) \quad (9)$$

$$P_{Rmin} = \min(P_{R,i}), \quad i = 1, 2, \dots, \text{all tie-lines} \quad (10)$$

Table 1
Summary for Taipower system facility

	Peak load	Off-peak load
No. of buses	467	467
No. of plants	84	84
No. of machines	80	52
No. of loads	166	166
No. of branches	716	716
No. of transformers	395	395

Table 2
Area generations and load (MW)

Peak load	North	Center	South
Generation	6310	8941	9317
Load+loss	11,314	7487	5767
Surplus power	−5004	1454	3550
Off-peak load	North	Center	South
Generation	3838	5666	7321
Load+loss	6496	4178 (+2500)	3651
Surplus power	−2658	−1012	3670

The number in the parenthesis is the pump-storage pump power.

Table 3
Transfer power between areas (MW)

	Center to north	South to center
Peak load	5004	3550
Off-peak load	2658	3670

where

P_{Rmin} is the smallest relay setting limited area power flow.

$P_{R,i}$ is the i th tie line equivalent relay setting limited area power flow due to the i th tie line relay setting.

P_{area} is the measured area power flow between the areas.

$P_{line,i}$ is the measured power on the i th tie line.

$P_{set,i}$ is the i th tie line relay setting power.

Fig. 6. One-line diagram of main 345 kV transmission systems.

Table 4
Summaries of models

Machine	Model name (Number)
Generators	GENROU(62), GENSAL(22)
Stabilizers	STAB1(1), IEEEEST(5), PTIST1(8)
Exciter systems	IEEEET1(30), IEEEET3(13), IEEEET5(1), SCRX(23), IEEX2A(2), EXAC1(2), EXAC3(12)
Governors	GAST(20), HYGOV(21), IIESGO(41)

The principle of the relay setting limited EAC is described as follows. In Fig. 4, the computed P_{Rmin} is the smallest relay setting limited area power flow, and P_{area} is the measured area power flow. If the accelerating area A_a is greater than the decelerating area A_d , shown in Fig. 4, then the system swing will enter other tie line relay protective zones and may cause a cascade trips to deteriorate the stability condition. By adjusting P_{area} to the dot line in Fig. 4, which means the load shedding and generation tripping is activated simultaneously, such that $A_a \leq A_d + \Delta A_d$, then the system

swing will not cause a second trip and the system will be stabilized. The amount of remedial actions is the value of the reduced P_{area} . The load shedding sequence is predetermined by the contract with the customers and the load survey. The generation tripping sequence is in the order of accelerating kinetic energy except base generators, that is, the generator with maximum accelerating kinetic energy will be tripped first.

3. Case study

3.1. System description

The system under study is the Taipower system in the year 1999. The Taipower system structure is a longitudinal one with three major areas on the island, namely, North, Center, and South, connected together by a number of 345 kV transmission lines. Its structure is illustrated in Fig. 5.

Fig. 7. Simulation results of 729-event: (a) generator angle, (b) system frequency, (c) areas transfer power.

Since major load centers are located in the north and most generating plants are in the central and southern areas, significant power transfers from central area and southern area to the northern area have been experienced in the past few years.

Table 1 summarizes the Taipower system. System planners at Taiwan Power Company establish two representative power flows, one for peak load and the other for off-peak load. Table 2 summarizes area generation and load for the peak and off-peak load patterns under study. It is observed from Table 2 that the deficit power in the northern area must be supplied from the generators in the central and southern areas through the 345 and 161 kV tie lines between areas. Table 3 shows the transfer power between the areas. Since most of the inter-area power flows are transmitted through 345 kV lines, how to protect these EHV tie lines far from the cascade events will be of major concern in this work.

3.2. Protective systems

Fig. 6 depicts an one-line diagram of the main 345 kV transmission systems connecting the North, the Center and the South areas. The surplus power in the central and southern areas is transmitted to the North through two parallel circuits. Every circuit has two parallel three-phase transmission lines, which are built on the same iron tower. For protecting the 345 kV transmission systems we simulate Mho distance relays and overcurrent relays on every 345 kV tie line between areas. The Mho distance relay protective zones are set to be 92, 150 and 220% of line impedance for zones 1, 2 and 3, whose pickup times are 1.5, 10 and 60 cycles, respectively. All opening time of circuit breakers is 1.5 cycles and re-close time is 36 cycles. The operating currents of overcurrent relays are set to be $1.5 \times (\text{line thermal rating})$ and delay time is 0.6 s.

3.3. Simulation results

On July 29, 1999, a severe fault occurred on the major 345 kV tie line circuit between the southern area and the center area, which carried more than 1500 MW and caused a successive relay trips resulting in system north and center area blackout (729-event). Almost total 80% consumers had an interruption lasting several hours in 729-event, and affected more people and extended over a wider geographic area than any previous outages.

To verify the proposed method, simulations are performed using the Power Technologies Incorporated (PTI) PSS/E-24 simulator program on the Taipower system. The automation process was achieved using FORTRAN program, which was written into the PSS/E-24 simulator program by the author. The Taipower system has a total of 467 buses, 80 machines, which were modeled in details including exciter systems, stabilizers, and governors. The system has 166 load buses with nonlinear

composite load models. Table 4 summarizes the complete power system models names and numbers. We simulate the 729 events which has two three phase short circuit faults at $t=0$ and 1.632 s on the same iron tower's circuit between the southern area and the center area. The simulation results are in the Fig. 7. The simulation results agree well with the measurement records of 729-event [1]. From Fig. 7, at $t=0$ the first fault occurs due to the collapse of iron tower and trips the faulted line after three cycles by the Mho distance relay. After 36 cycles later, $t=0.65$ s, the breaker recloses and fails because the fault is not cleared. At $t=1.632$ s, the fault 2 happens due to the same iron tower collapse and tripps the fault line after three cycles by the Mho distance relay. After 36 cycles later, $t=2.282$ s, the breaker recloses and fails because the fault is not cleared. Because the two lines trip due to the iron tower collapse, the other circuits have an overloading condition between southern area and center area and a successive relay trippings occur. A transient instability condition occurs.

Now, we assume that the Taipower system was armed with PMU based SPS. Then 729 event is simulated again. The estimated parameter results of OMIB system using real-time phasor measurements are showed in Fig. 8. The remedial action is taken after the second faults fails. The amount of remedial action is 1332 MW. That is, the rejection of southern generators is 1332 MW, and the shedding of northern load is 1332 MW. The results are shown in Fig. 9.

To further verify the proposed SPS on the Taipower system, we used the Eight cases like 729-event but at different places listed in Table 5. The simulation results are shown in Table 6. Fig. 10 shows the response of

Fig. 8. The estimation curves of OMIB system.

Fig. 9. Simulation results of 729-event with PMU based SPS: (a) generator angle, (b) system frequency, (c) areas transfer power.

Table 5
Summaries of study cases

Case	Load	Description
1	Peak	3PSC between Lunch-S and Chamin at $t=0.0(s)$ 3PSC between Lunch-S and Chnliao-S at $t=1.632(s)$
2	Peak	3PSC between Lunch-N and Chamin circuit 1 at $t=0.0(s)$ 3PSC between Lunch-N and Chamin circuit 2 at $t=1.632(s)$
3	Peak	3PSC between Chnliao-S and Tienln at $t=0.0(s)$ 3PSC between Chnliao-S and Luntan-N at $t=1.632(s)$
4	Peak	3PSC t between Chnliao-S and Omei at $t=0.0(s)$ 3PSC between Chnliao-N and Omei at $t=1.632(s)$
5	Off- peak	3PSC between Lunch-S and Chamin at $t=0.0(s)$ 3PSC between Lunch-S and Chnliao-S at $t=1.632(s)$
6	Off-peak	3PSC between Lunch-N and Chamin circuit 1 at $t=0.0(s)$ 3PSC between Lunch-N and Chamin circuit 2 at $t=1.632(s)$
7	Off-peak	3PSC between Chnliao-S and Tienln at $t=0.0(s)$ 3PSC between Chnliao-S and Luntan-N at $t=1.632(s)$
8	Off-peak	3PSC between Chnliao-S and Omei at $t=0.0(s)$ 3PSC between Chnliao-N and Omei at $t=1.632(s)$

3PSC, three phase short circuit fault.

Table 6
Summaries of simulation results

Condition	Algorithms	Case 1	Case 2	Case 3	Case 4
Peak load	No action	Unstable	Unstable	Stable	Unstable
	The proposed SPS	The system is stabilized with 1332 (MW) remedial action	The system is stabilized with 2550 (MW) remedial action	The system is stabilized with 0 (MW) remedial action	The system is stabilized with 2500 (MW) remedial action.
Condition	Algorithms	Case 5	Case 6	Case 7	Case 8
Off-peak load	No action	Unstable	Unstable	Stable	Stable
	The proposed SPS	The system is stabilized with 1350 (MW) remedial action	The system is stabilized with 2271 (MW) remedial action	The system is stabilized with 0 (MW) remedial action	The system is stabilized with 0 (MW) remedial action

case 3. We can see that no remedy control action is needed in case 3. In cases 1, 2, 4, 5, and 6, the remedial control action is taken only at after second fault fails. From Table 6, it demonstrates that the proposed PMU

based SPS can stabilize the unstable situations, ex. Case 1, Case 2, Case 4, Case 5, and Case 6. Also the proposed SPS will not cause a false action, ex. Case 3, Case 7, and Case 8.

Fig. 10. Simulation results of Case 3 with PMU based SPS: (a) generator angle, (b) system frequency, (c) areas transfer power.

4. Conclusion

Some power systems are stability limited (like Taipower system), and desired operating conditions may require avoiding blackout that SPS be provided in order to operate the system in a secure manner. To meet these requirements, this paper proposes PMU based SPS to prevent power system blackout due to a sequence of relay trip events. We use PMU's to monitor the generators and the major EHV transmission lines of a power system. Real-time phasor measurements are used to estimate the parameters of OMIB. The remedial control actions consist of load shedding and generation tripping. The strategy for determining the amount of remedial control actions is a proposed relay setting limited equal-area criterion for OMIB. We used global measured data to predict the system stability, and used the remedial control actions to avoid system blackout. The proposed method has been verified on Taipower system. Encouraging results are obtained.

References

- [1] Department of Economic Affairs, Investigation Report of 729 event of Taiwan Power Company; September 1999 (in Chinese).
- [2] Anderson PM, LeReverend BK. Industry experience with special protection schemes. *IEEE Trans Power Syst* 1996;11(3): 1166–79.
- [3] Phadke AG, et al. Synchronized sampling and phasor measurements for relaying and control. *IEEE Trans power Deliv* 1994; 9(1):442–52.
- [4] Thorp JS, Phadke AG, Horowitz SH, Begovic MM. Some applications of phasor measurements to adaptive protection. *IEEE Trans Power Syst* 1988;3(2):791–8.

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