Implementing a Dual Triple Modular Redundant Country-Wide Special Protection System

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Presented at the
13th International Conference on Developments in Power System Protection
Edinburgh, United Kingdom
March 7–10, 2016

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Keywords: power system protection, automation.

Abstract

In order to maintain power system stability in Taiwan, a centralized series of dual triple modular redundant special protection systems (SPSs) have been implemented to prevent blackouts. The redundancy and two-out-of-three voting scheme ensures operational decision-making integrity to minimize false tripping of key system assets while minimizing disturbances. Decisions are made based on action tables which are preconfigured for system peak or off-peak operation. Each SPS has unique arming conditions and arms for the predefined actions as defined within the action tables. This paper discusses details of the Taiwanese SPS, and the requirements and challenges associated with developing the system.

1 Introduction

In order to improve the resiliency and reliability of the Taiwanese power grid, a country-wide special protection system (SPS) has been implemented because recent power contingencies related to system instability have caused significant economic loss [1]. The primary function of the SPS is to initiate fast special protection actions while minimizing generator dropping and load dropping in response to power system disturbances, thereby maximizing power transfers while ensuring power system stability. The amount of generation or load to be dropped is calculated based on system configuration, fault type, and severity. The actions taken by the SPS are selected from a set of predetermined action tables based on system owner input. The complete Taiwanese SPS is comprised of three smaller systems. However, only two are reviewed in this paper, as follows:

- Taiwan East SPS: discussed
- Datan SPS: discussed
- Dongshan SPS: not discussed

Each SPS operates as a triple modular system where three independent controllers perform calculations based on the exact same set of input data to make independent decisions for tripping generation or loads. These three controllers share certain information to create a common set of outputs. Each system is comprised of two triple modular systems providing redundancy to the SPS system. This is why the terms triple modular (three subsystems in each SPS) and redundant (two SPSs) are used. To give redundancy to the comparator system, the secondary unit relies on MIRRORED BITS® communications rather than the ethernet network, as illustrated in Fig. 1.

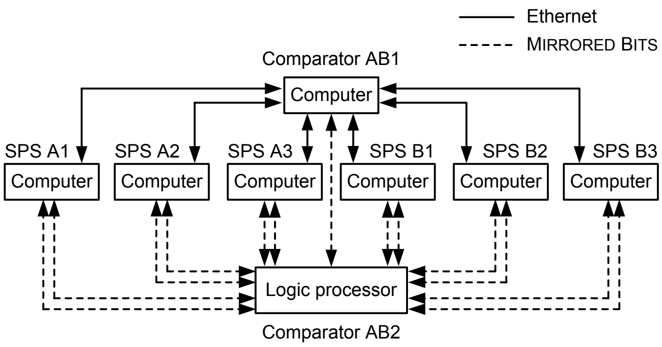

Fig. 1. Triple modular redundant supervisory architecture.

A run-time engine operates within each controller. This is where all logical decision-making is completed. The SPS is designed to detect inputs that act as contingencies. A single contingency is the beginning of an event that triggers an abrupt change in the power system and requires special protections in the form of generation or load shedding. Each system reacts differently, depending on which region it is located in. See Fig. 2 for regional coverage.

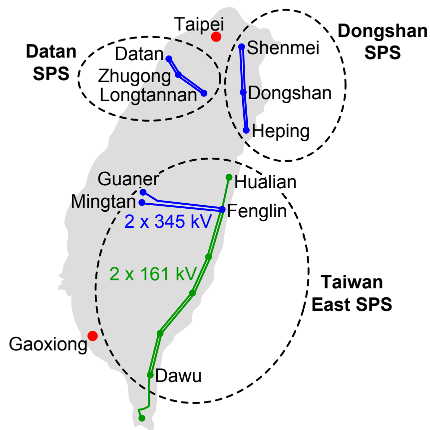

Fig. 2. Geographic coverage of SPSs.

1.1 Input voting

Within each controller there are two types of inputs used for decision-making: digital and analog. These digital inputs arrive at each SPS subsystem independently and are immediately voted among the three systems. This method of voting utilizes a two-out-of-three voting scheme, which means that two of the three systems must agree for an input to be on or off [2]. This logic is shown in Fig. 3. The voted value is then used throughout each of the SPS subsystems. If a disagreement occurs, a voting alarm is annunciated.

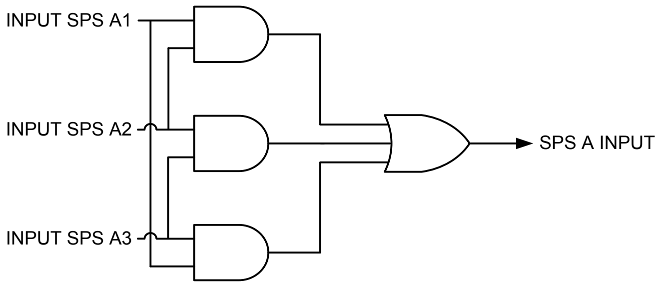

Fig. 3. Digital input voting logic.

The other inputs that arrive at each of the SPS subsystems are analog inputs. The comparison between the analog inputs is similar to the digital voting, but instead, an average of the three subsystems is calculated and then used in each subsystem. This ensures that each system is using the correct value and that the three are also identical. If a value exists outside of the allowable range, a nonsevere comparison alarm is declared and only the values that are within the range are used to calculate the average. If no values are within the allowable threshold, a severe comparison alarm is declared and the SPS logic is suspended.

1.2 Cross-point switch and logic flow

The deciding factor in each SPS for the output actions lies within the cross-point switch. This is a virtual array of values relating each contingency to a combination of the actions and is precalculated in each of the SPS subsystems. This cross-point switch can be viewed at any moment on the human-machine interface (HMI) screen to tell the operator which actions are expected to trip if a particular contingency occurs. This cross-point switch is also voted between each of the three subsystems in each SPS so that a consistent cross-point switch is decided for each. The voting algorithm is exactly the same as the digital input voting shown in Fig. 3.

Fig. 4 shows the general logic flow within the SPS. This process repeats to constantly evaluate the present state of the system and create a cross-point that reflects what the SPS outputs for each potential contingency.

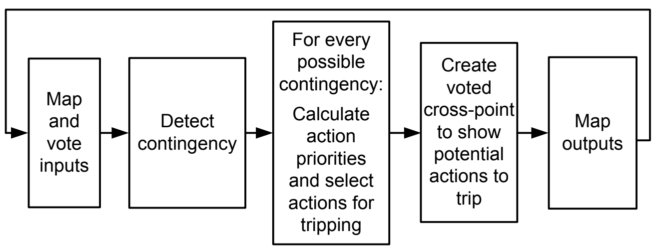

Fig. 4. Core logic diagram.

2 Taiwan East SPS

The Taiwan East SPS has the following control actions:

- Load shedding
- Reactor switching
- Capacitor switching

Taiwan's Hualian area is a major load center in the Taiwan East region. Due to the lack of local generation, most regional loads are supplied through two 345 kV and two 161 kV transmission lines. The two 345 kV lines are from the Mingtan and Guaner substations in the west. The two 161 kV lines are long transmission lines originating from the Dawu substation in the south. The transmission network is shown in Fig. 5.

The Guaner-Fenglin line utilizes three-phase trip and three-phase reclosing for any type of fault. The Mingtan-Fenglin line uses three-phase trip and does not reclose for any type of fault. The power system of the Taiwan East region may experience instability during heavy load periods when both 345 kV transmission lines are tripped open due to system disturbances.

The Taiwan East SPS measures the load flows on the 345 kV and 161 kV lines into the Taiwan East load center. It monitors the in-service and out-of-service status of the 345 kV lines, the fault types from the 345 kV line protective relays, and the breaker status of system capacitors and reactors.

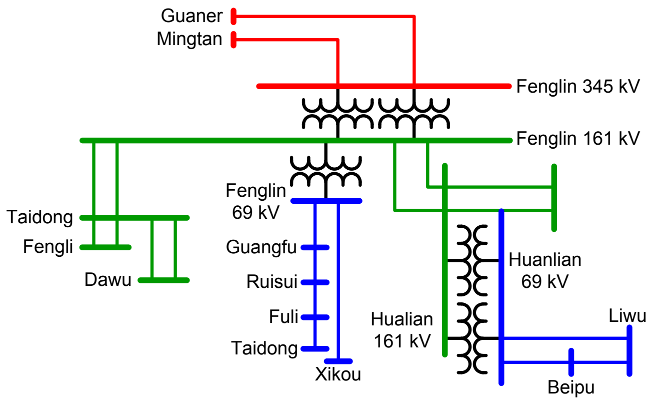

Fig. 5. Taiwan East power system.

2.1 Action table selection and arming

The Taiwan East SPS utilizes a series of action tables to determine system correction in case of an N-2 event. An N-2 event for the Taiwan East SPS would be the opening of both of the Fenglin-Mingtan line and the Fenglin-Guaner line. This can happen by tripping both lines at the same time or by tripping one of the lines while the other line is out of service.

When an N-2 contingency occurs on the 345 kV lines, the SPS sheds loads to ensure the stability of the system, based on the actions detailed in Table 1. The amount of loads to shed depends on the load flow and whether load shedding is enabled within the action table. The action tables shown in this paper are excerpts from much larger tables. After the N-2 event, the SPS measures the 161 kV bus voltage at Hualian and Taidong substations and controls the system voltage by switching predefined capacitors and reactors accordingly.

Received Fault Type		SPS Fast Load Shed	SPS Voltage Control
Fenglin-Mingtan	Fenglin-Guaner		
Line open	Line open	SPS action	SPS action
Line open	Line closed	No SPS action	No SPS action
Line closed	Line open	No SPS action	No SPS action

Table 1: General overview of Taiwan East SPS actions.

The Taiwan East SPS utilizes two action tables—peak and off-peak—to select the proper arming levels, as shown in Table 2 and Table 3. The selection of these two tables is accomplished by monitoring the power levels of ten critical generators/motors throughout the system. When one or more of the units is motoring, the SPS uses the off-peak action table. Otherwise, it uses the peak action table.

Arming Threshold (Taiwan East net MW)	(1 = Enabled, 0 = Disabled)	
	Load Shedding	Trip 80 MVAR of Reactor
380	1	0

Table 2: Taiwan East SPS N-2 peak actions.

Arming Threshold (Taiwan East net MW)	(1 = Enabled, 0 = Disabled)	
	Load Shedding	Trip 80 MVAR of Reactor
430	1	1
220	0	1

Table 3: Taiwan East SPS N-2 off-peak actions.

The SPS arms for a given row within these tables if the Taiwan East net MW is above the arming threshold. If the value is below the arming value, the action is disabled. When the N-2 event occurs, the SPS performs the desired action as defined in the two right columns. If the action is set to 1, that action is enabled for that arming level. If it is set to 0, the action is disabled.

Equation (1) is used to calculate the Taiwan East net MW.

$$\begin{aligned}&\text{Mingtan-Fenglin line MW} + \text{Guaner-Fenglin line MW}\\&+ \text{Dawu-Fenggang line 1 MW} + \\&\text{Dawu-Fenggang line 2 MW} = \text{Taiwan East net MW}\end{aligned} \tag{1}$$

When the system meets the required system states, the SPS control outputs are enabled. The two following conditions will arm the Taiwan East SPS:

1. Either of the Fenglin-Mingtan lines or the Fenglin-Guaner lines is in an N-1 state, which occurs when one of the parallel lines is open.
2. The Taiwan East net MW is greater than or equal to the lowest arming threshold in the active action table.

In the scenario of an N-2 event, the Taiwan East SPS initiates all required actions. The SPS monitors the Taiwan East net MW to determine how to arm for the N-2 event. When the Taiwan East net MW value goes above the arming level, the SPS arms for that row in the action table. The Taiwan East SPS also has an action table for the post-N-2 event overvoltage/undervoltage system correction.

The SPS uses Equation (2) when the armed row of the action table has load shedding enabled.

$$\begin{aligned}&\text{Taiwan East net MW} - \text{Current arming threshold}\\&= \text{required-to-shed MW}\end{aligned} \tag{2}$$

The SPS uses the load shed priorities shown in Table 4 to select enough loads to cover the required-to-shed MW. The SPS adds all present power values for each load and each priority to determine the amount of load that will be reduced by a particular action. It starts at Priority 1. It continues on, including groups of loads based on priority until the amount of load selected to shed is equal to or greater than the required-to-shed MW.

Priority	Substation	Sheddable Loads	Load (MW)
1	Beipu	750, 760, 770, 810, 820	15.74
2	Guangfu Ruisui Fuli	Guangfu 750, 760 Ruisui 750, 760, 810 Fuli 750, 760, 810, 820	18.8
3	Chuying Xikou	Chuying 750 Xikou 690	17.33
4	Liwu	690	19.85
—	—	—	—
0	Taidong	1780	15.00

Table 4: Taiwan East SPS load shed priorities.

2.2 Reactor and capacitor switching

After the N-2 event action is complete, the SPS initiates two overvoltage and undervoltage timers to ensure that voltage has stabilized and no further action is required. The premonitor delay (PMD) and monitor delay (MD) were determined based on system operational values. Table 5 shows timers and voltage limits for the Taiwan East SPS.

Description	Timer 1 Setting	Timer 2 Setting
PMD	5 seconds	15 seconds
MD	2 seconds	2 seconds
Hualian voltage limit	1.05 pu	1.045 pu
Taidong voltage limit	0.90 pu	0.905 pu

Table 5: Taiwan East SPS overvoltage/undervoltage timers and limits.

Once the premonitory timers are complete, the SPS starts monitoring the overvoltage and undervoltage conditions. If these conditions remain for the entire monitoring time delay, the SPS performs one action as defined in Table 6. Both the

Hualian overvoltage and Taidong undervoltage conditions can occur at the same time.

Sequence Number	Taidong 161 kV Below the Limited Voltage	Hualian 161 kV Above the Limited Voltage
1	Open Taidong 40 MVAR reactor	Close Fenglin #1 40 MVAR reactor
2	Open Fenglin #1 40 MVAR reactor	Close Fenglin #2 40 MVAR reactor
3	Open Fenglin #2 40 MVAR reactor	Close Taidong 40 MVAR reactor
4	Close Taidong #1 42 MVAR capacitor	Open Hualian 14.4 MVAR capacitor

Table 6: Taiwan East SPS overvoltage/undervoltage actions.

There is a 1.15 pu check in the overvoltage logic for Hualian and a 0.8 pu check in the undervoltage logic for Taidong to prevent outside limit values due to communications or other errors before attempting voltage correction logic, as shown in Fig. 6.

A block reactive device time setting can be adjusted to set how long the SPS blocks the switching of a reactive device after a switching action.

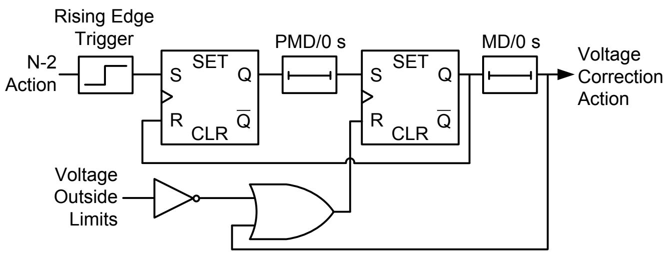

Fig. 6. Voltage correction logic.

If an action is needed, the SPS selects the corrective action based on the action availability and in order of the sequence number. Availability is determined by the present state of the reactive device, the control selector position, and the SPS internal blocking timers.

The SPS monitors the breaker status for each controlled reactive device and determines when to block the reactive device from switching. When the reactive device opens or closes, a block timer starts and runs for the predetermined block time. This particular device is unavailable for SPS control until this timer has completed.

The SPS controllers monitor the requested device for the overvoltage and undervoltage corrective action. If this device fails to indicate that it has switched to the requested state, the SPS switches the next available device in Table 6. The SPS repeats this for a total of three switching requests for the first voltage control stage and repeats until reaching the end of the table for the second voltage control stage. After the predetermined request is sent, the SPS controllers stop attempting to switch reactive devices.

If the reactive device fails to switch, it is blocked for a period of time before it becomes available to be switched again. This prevents the device from being switched on the second overvoltage and undervoltage condition. After the blocking time is complete, this device switches back to available.

2.3 Timing and supervision

The Taiwan East SPS uses one timing sequence, as shown in Fig. 7. When the SPS detects an N-2 fault, it delays for the reclosing delay if the delay timer is set. After the delay, the SPS checks to verify whether both of the lines are still open. If they are not, it resets. It does not initiate any corrective action or start the voltage premonitoring timers. If the lines are open, it takes the required action as selected from the action table.

Once the required corrective action is sent, the SPS starts the two premonitor overvoltage and undervoltage delay timers. If the decision is that no initial corrective action is required, the SPS still starts the premonitor timers. After these timers are complete, the SPS monitors for an overvoltage and/or undervoltage condition. If these conditions are present for the entire monitoring delay, the SPS takes corrective action.

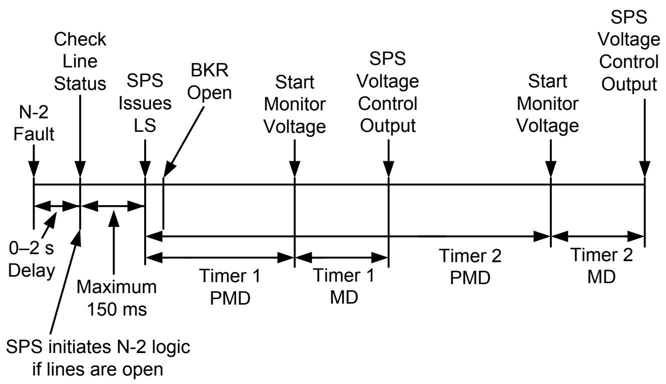

Fig. 7. Taiwan East SPS timing.

3 Datan and Dongshan SPS

The Datan and Dongshan SPSs have a different function than Taiwan East because synchronous machines are part of their topology. Therefore, they have to be able to control those generation resources, and they do not have any reactors or capacitors within the network to switch.

In the steady-state condition, all synchronous machines connected to the power system are operating very close to their normal speed. When there is a power system disturbance, the rotors of the synchronous machines may accelerate or decelerate, resulting in an angular difference between them. Power system instability may result from lasting torque imbalance and angular separation of the connected synchronous machines [3].

Both the Datan-Zhugong parallel lines and the Zhugong-Longtannan parallel lines utilize a single-phase trip and single-phase reclose for a single-phase-to-ground fault.

They trip all three phases and do not reclose for multiphase faults.

The Datan SPS measures the load flows of all four transmission lines from Datan to Zhugong and from Zhugong to Longtannan. It also measures the power outputs of all six generator groups. The SPS monitors the in-service and out-of-service status of the 345 kV lines and six generator groups, the fault types from the 345 kV line protective relays, and the closing sequence of protection systems, as shown in Fig. 8.

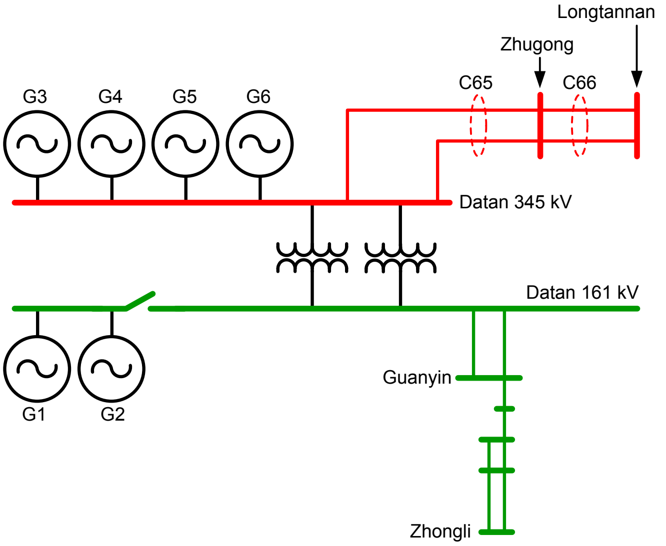

Fig. 8. Datan power system.

When an N-2 contingency occurs to the 345 kV transmission paths, the SPS sheds generation to ensure the stability of the system. The amount of generation to shed depends on the system load flow, the in-service and out-of-service status of transmission lines and generators, and the fault types and reclosing schemes in use. The predefined strategic action tables specify the details of the generation shedding strategy.

After the initial SPS operation, the SPS continues monitoring possible equipment overload conditions of the Datan main transformers, substations, and lines. The SPS further sheds gas turbine (GT) generators in stages if equipment is overloaded.

3.1 Datan SPS action tables

The Datan SPS utilizes its own two action tables (not shown here) to determine the number of 345 kV generator groups to trip, depending on whether an N-2 trip occurs on the Datan-Zhugong lines or the Zhugong-Longtannan lines. The SPS monitors the number of Datan generator groups that are in-service to select the appropriate rows in the action tables. If the system is armed, the SPS trips and/or disables all generation set within the action tables.

The SPS determines generator group status by monitoring all generator breakers and the power output of each individual generator within a group. Each generator group is made up of three sets of individual generators: two GT generators and one steam turbine (ST) generator. The overall generator group is considered in-service if a minimum of one GT breaker is closed and at least one of its individual GT generators is at or above 120 MW.

Overload system monitoring in the Datan SPS is used to monitor devices in the power system for overload conditions. The SPS starts the three overload timers (OLTs) to initiate overload trips when an N-2 event is detected, as shown in the timing diagram in Fig. 9.

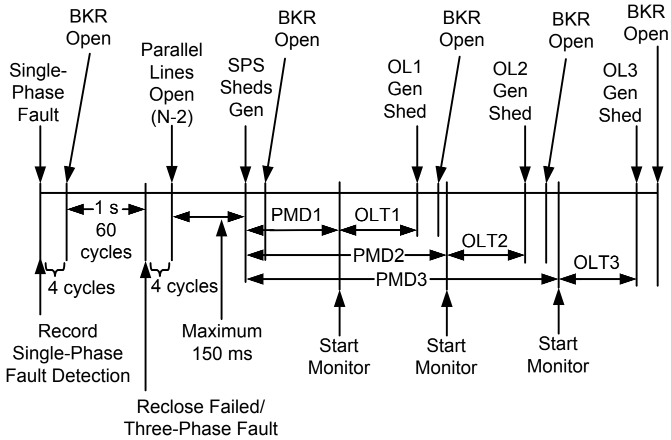

Fig. 9. Timing diagram.

As long as at least one of the items remains overloaded for the entire overload time, the SPS trips one GT generator. At the end of each overload time, if an SPS action is needed, the Datan SPS trips one of the 345 kV GT generators. The SPS selects the in-service GT generator with the lowest power output to trip each time. Each overload trip selects a GT generator to shed from different generator groups. For example, if GT1 of Generator Group 3 was shed in the first stage SPS overload action, the second stage overload action selects a GT generator to shed from Generator Groups 4 to 6.

The SPS monitors the state of each available GT generator, and if one of the two GT generators for a given group is out of service, the remaining GT generator is bypassed for initial selection. After the SPS has utilized all active pairs of GT generators for overload selection, the SPS selects individual active GT generators for tripping, starting with the lowest GT output value.

3.2 Power rate of change supervision

Supervision logic monitors the rate of change of power to verify that the corresponding parallel lines have tripped. To do this, the relays monitor power levels over a period of time, and if the power decreases above a given set point, the relay allows all corresponding control signals to pass from the SPS to the corresponding outputs.

Both Datan and Dongshan utilize this supervision logic. This is done by monitoring the generation power level's rate of change. Datan implements this scheme for each generator. The corresponding relays associated with these generators sum the three individual generators to determine the overall generation power. When the overall generation power value decreases beyond a given rate, the relay enables the SPS control signals. This enables the generation trip outputs and automatic generation control/economic generation control disable signals. These outputs remain enabled for a given time to allow for all SPS actions.

4 Simulator testing

Due to the costs associated with testing each SPS on Taiwan's active power system, a simulator was developed to prove functionality. The test simulator was used at the factory as well as the site to verify SPS control system functionality. It was designed to simulate all external inputs including digital status, control inputs, and analog data. All systems were run autonomously from each SPS. The test simulator had the two following modes:

1. Static simulator. This was used to set various set points, breaker status conditions, and detect generator trips from the SPS. The main benefit was that the static simulator could be used to create any power system scenario to test the controls.
2. Data playback simulator. Two forms of data playback were designed and each operated differently. The first type was from real data based on recorded events, and the second type of data was based on simulated data.

5 Conclusion

The key to any SPS implementation is to be deterministic on the speed of reaction to a system disturbance. Typically, most systems have a maximum allowed time from when the disturbance is detected to the time that the corrective action needs to be taken. To accomplish this, reliable equipment must be used to perform all of the required calculations and make the proper decisions within a given amount of time. This is particularly important because—in various instances of Taiwan's power system networks—some of the key transmission lines have reclosing capabilities, while others do not.

In the Datan and Dongshan SPSs, single-pole tripping can be incorporated into operations to improve system stability by increasing the amount of power that can be transferred. During a single-pole operation, the SPS keeps two phases of the line connected, which can significantly improve stability. Power system angle stability improves because of the transmission of active power over the healthy phases, and voltage stability improves because the transmission of reactive power over the healthy phases reduces the reactive power losses of the system [4].

The controllers used for this project have a processing interval of two milliseconds, making it straightforward to calculate the number of process cycles required for triple modular redundant logic. This leaves the remaining reaction time to communications and control signal processing at the IEDs. It is also desirable to have a communications protocol that is reliable and deterministic in the amount of time it takes to bounce a signal from the remote device to the SPS controllers and back [5]. This is why Generic Object-Oriented Substation Event (GOOSE) protocol was chosen for this application.

During the execution of this project, it was determined that a 3 MW hysteresis should be used for set points to prevent chattering of contacts and ensure smooth operation. The SPS also has the ability to load new action tables to allow for future system adjustments. This is important because the same system can be used even if network power system topologies or configurations change.

Triple modular redundant SPSs are complex systems utilized for applications where availability and safety are the highest priority. While the costs of implementing triple modular redundancy may be high relative to traditional systems, they are still less than the financial impact of falsely tripping a critical component, essential load, or a heavily loaded line.

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