

## Impact of Network Protection in the prevention of Major Events in the Power System

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### KEYWORDS

System Integrity Wide Area Monitoring Systems (WAMS), System Integrity Protection Schemes (SIPS), Remedial Action Schemes (RAS).

### 1 INTRODUCTION

The electric grid is a key piece of critical infrastructure upon whose operation the economy depends. The size and complexity of the power grid, however, makes the electrical system vulnerable and subject to collapse under situations such as congestion, over/under frequency, over/under voltage, system load adjustment, power swings, etc. Penetration of renewable in the grid is increasing at a fast pace. System operators demand that the existing lines / corridors are to be loaded to their limits. It is the responsibility of the system operators to meet the market requirements and at the same time maintaining grid security, safety quality and reliable power supply. Hence power system operator needs to be provided with the necessary tools to meet such complex, multi-dimensional requirements. The overall impact is achieving newer dimension in power flow quantum and direction. As the existing transmission system infrastructure is challenged to support loads beyond original design limits.

The implementation of “wide area” System Integrity Protection Schemes (SIPS) are often needed to detect and take preventive/protective actions to maintain transmission system integrity. SIPS is a concept of using system information from local as well as relevant remote sites and sending this information to a processing location to counteract propagation of the major disturbances in the power system, during un-planned contingency conditions or when system or operating constraints could not allow meeting the power demand.

SIPS encompass Special Protection Schemes (SPS), Remedial Action Schemes (RAS) as well as additional schemes such as, but not limited to, Underfrequency (UF), Undervoltage (UV), Out-of-Step (OOS), etc. These schemes provide reasonable countermeasures to slow and/or stop cascading outages caused by extreme contingencies

Implementation of such schemes involve many factors including: Comprehensive knowledge of the wide area system to which the scheme will be applied, well-developed system planning criteria defining all possible contingencies, Detailed design and implementation for operation and restoration, reliable telecommunication system, levels and types of redundancy, detailed test plans for scheduled system wide testing, etc.

SIPS classifications have been defined through a collective global industry effort by members of the IEEE and CIGRE [6]. Below is a summary.

- a) **Local (Distribution System)** – SIPS equipment is usually simple, with a dedicated function. all sensing, decision-making and control devices are typically located within one distribution substation. Operation of this type of SIPS generally affects only a very limited portion of the distribution system such as a radial feeder or small network.
- b) **Local (Transmission System)** - all sensing, decision-making and control devices are typically located within one transmission substation. Operation of this type of SIPS generally affects only a single small power company, or portion of a larger utility, with limited impact on

neighboring interconnected systems. This category includes SIPS with impact on generating facilities.

- c) **Subsystem** - The operation of this type of SIPS has a significant impact on a large geographic area consisting of more than one utility, transmission system owner or generating facility. SIPS of this type are more complex, involving sensing of multiple power system parameters and states. Information can be collected both locally and from remote locations. Decision-making and logic functions are typically performed at one location. Telecommunications facilities are generally needed both to collect information and to initiate remote corrective actions.
- d) **System wide** - SIPS of this type are the most complex and involve multiple levels of arming and decision making and communications. these types of schemes collect local and telemetry data from multiple locations and can initiate multilevel corrective actions consistent with real-time power system requirements. These schemes typically have multi-level logic for different types and layers of power system contingencies or outage scenarios. Operation of a SIPS of this type has a significant impact on an entire interconnected system [5].

The mitigation measure to maintain grid integrity are described in [4] and the list of types are as follows: Generator Rejection, Load Rejection, Under-Frequency Load Shedding, Under-Voltage Load Shedding, Adaptive Load Mitigation, Out-of-Step Tripping, Voltage Instability Advance Warning Scheme, Angular Stability Advance Warning Scheme, Overload Mitigation, Congestion Mitigation, System Separation, Shunt Capacitor Switching, Tap-Changer Control, SVC/STATCOM Control, Turbine Valve Control, HVDC Controls, Power System Stabilizer Control, Discrete Excitation, Dynamic Braking, Generator Runback, Bypassing Series Capacitor, Black-Start or Gas-Turbine Start-Up, Automatic Gain Control (AGC) Actions, Busbar Splitting.

## **2 OPERATING CONSTRAINTS**

Main constraints of the power system include: [7], [8].

**Thermal limit** : The thermal limit of an overhead transmission line is determined by maximum permissible sag, auxiliary components such as breakers, voltage transformer, current transformer, etc.

**Voltage limit** : The main symptoms of voltage collapse are – low voltage profiles, heavy reactive power flows, inadequate reactive support, and heavily loaded systems. The collapse is often precipitated by low-probability single or multiple contingencies.

**Frequency limit** : During dynamic state, the frequency derivation should regain the range if the frequency derivation exceeding the range. Too large frequency derivation will lead system collapse [9]. The maximal admissible frequency derivation is issued by the power system operator.

**Rotor angle limit** : The maximal permissible value of rotor angle ensures the generator will not lose synchronism if it is operated below this value. An important quantity to be studied here is Critical Clearing Time (CCT). The concept of CCT is: A contingency, which may lead oscillation, is injected by the power system. If the contingency is cleared without exceeding the time duration, the generator is able to not lose synchronism [9].

**Oscillation damping ratio** : Damping ratio is used to decay the oscillation during dynamic state. The oscillation is caused by the internal electromagnetic and mechanical of generator. If the demanded electric power suddenly changed, those inherent characters of generator leading generator cannot adjust the difference immediately [2]. Oscillation is introduced into power system. In interconnected power system, even a small oscillation can be a system wide problem [9]. Insufficient damping ratio may lead instability of the power system.

### **3 SIPS REQUIREMENTS**

It is not realistically possible to completely eliminate blackouts (unless very large investments are made that would make the price of electricity unreasonable for end users), for that, the use of SIPS combined with the traditional criteria of N-1 and a reasonable maximum number of time of power availability, shows that by taking some reasonably cost-effective measures, occurrence of the blackouts could be reduced among a optimization of the investment in infrastructure to reinforce the grid (new lines, generators, etc.).

Starting from the above criteria, the total operation time (time between the initiation of the phenomenon that trigger operands or functions in the SIPS and breaker's opening) depends on the Power System Transient performance under the most critical events that could happen. For that, required operating time can range from 100 ms, up to 4 seconds. Lower values are more typical of RAS systems that are installed in relative weak power systems or with a high dependability of its transmission system. Grids or areas of the power system that cannot operate during multiple contingencies usually require also short times (100 to 200 ms), while other portions, particularly the ones that interconnect two large areas with power flow between them representing a few percentage of the total load in both areas require longer times, because the capability usually is limited by thermal constrains that by stability ones. In summary, we can say that overall requirements for SIPS are as follows :

- Fast enough (linked with the power system needs)
- Reliable (with a balance between dependability and security)
- Available
- Deterministic

### **4 SIPS ARCHITECTURE**

#### **4.1 Centralized SIPS vs. Distributed SIPS**

SIPS have traditionally been designed as centralized automated protection systems. These SIPS may rely on local inputs (e.g. breaker statuses) and initiate local control actions (e.g. trip generator). In addition to local data, SIPS may require additional inputs from remote stations or initiate additional control actions at other remote stations; these signals are transferred via the communications systems, but the decision-making may still be done by the centralized logic processor.

As transmission systems are operated closer to their stability margins and approach other operating limits, automated control actions may be required at various stations in an area, in response to various contingencies in the area. For instance, SIPS may be required to trip remote wind farms in addition to local conventional generators. The availability of high speed, reliable communications allows for the deployment of these wide area SIPS.

Most schemes deployed today are centralized SIPS. In centralized SIPS, all logic processing and arming is done at a central site, and only input/output (I/O) interface devices are deployed at the remote sites. These input interface devices typically have limited intelligence and are only required to monitor breaker statuses and other inputs at remote stations, and transfer all data to the central logic processor. Based on the arming signals, this central processor will then send trip commands to the output interface devices. In some cases where improved security is required, the I/O devices may employ polling and supervision schemes.

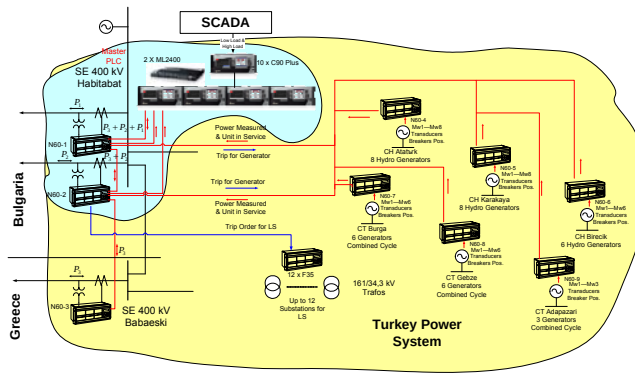


Figure 1: Example of a Centralized Architecture

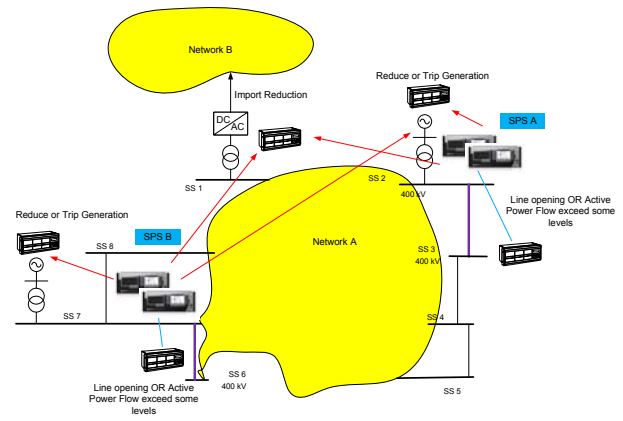


Figure 2: Example of Distributed architecture. Lines in Violet are the supervised ones.

In distributed SIPS, the logic processing and arming functionality is distributed across the various stations. The logic processor at each station can independently initiate control actions. Once contingencies are detected, the interface I/O devices can transmit the signals to the local logic processor, which can initiate local control actions, as well as transmit remote trip signals over the communications systems. In such a distributed approach, all remote sites do not need to communicate with one central site, and local tripping for locally detected contingencies do not rely on the communications systems [4].

#### 4.2 Redundancy Considerations

Failure of the SIPS to operate when required, or its undesired or unintentional operation may have adverse impact on the power system. Therefore, design of the SIPS often involves redundancy or some backup functions. Although simple redundancy or backup systems will improve the dependability of the system it will reduce the security of the overall system. To maintain the security level of a single system and achieve the dependability of a redundant system a two out of three voting system may be needed. Redundant systems also improve operations and maintenance efficiency by minimizing downtime, and the overall life cycle support [4].

Figure 3 is an overview. SIPS Systems A and B are identical, triple redundant systems with full two-out-of-three voting. In this example, PMU's are being used (this is the recommended option for fast operating SIPS (under 100 ms as total time). Analog Gooses also can be used instead of PMUs, but because the latency of the measurements (up to 250 ms in some cases), and the need to be "pseudo-synchronized" where they are processed, their use is normally employed in Centralized SIPS where critical times are higher than 1 second.

### 5 ARMING AND TRIGGER METHODOLOGY

#### 5.1 Type 1

These type of SIPS specifically respond to events based on the steady-state situation in the power system before the disturbing event. These SIPS make its mitigating actions for an event based on the pre-disturbance state of the power system, as reflected in measurements taken in the seconds well before the disturbance. As the different power unbalances has been pre-established before the event occurrence, to activate any trip, they require only the occurrence of any of the pre-defined conditions. In that way, its operation is very fast (in some cases, total times lower than 100 ms) and they are frequently used in RAS schemes where speed is critical to maintain the integrity of the power system

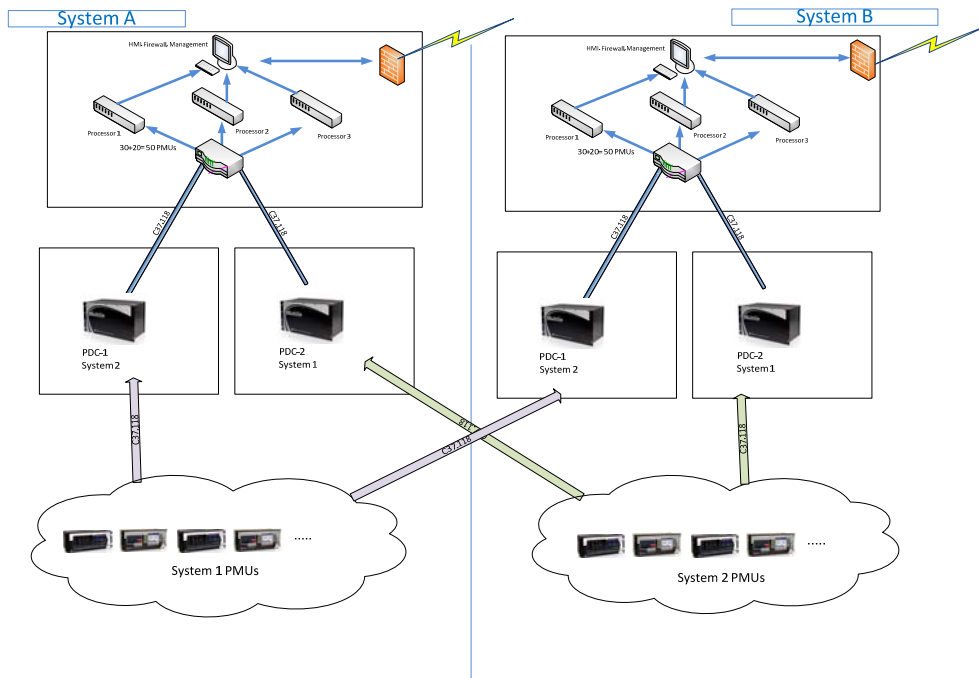


Figure 3: SIPS Redundant System Architecture Overview

The following is an example of a generation-to-shed calculation equation:

$$G = K + Af(X) \quad (1)$$

Where:

$G$  = MW of generation to be tripped

$K, A$  = coefficients for the particular event that initiate the trip

$X$  = Pre-disturbance MW measurements in specific points (in general this is an average in the last 5 or 10 seconds)

## 5.2 Type 2

These type of SIPS responds to events based on the dynamic performance in the power system during the disturbing event. Planning studies usually are done to determine the trigger methodology and amounts of generation and load to shed, associated with critical times. Because the real-time process of analog signals, most of them remote ones, these SIPS responds in times in the order of seconds (1 to 4 seconds) and they are usually used to maintain interconnections between two relative big blocks of the grid.

As examples of arming and trigger methodology we can mention some of them:

### Angular Stability Techniques

Angular instability has been a concern to utilities since the early days of the electric power industry. The research on this subject is extensive and many approaches have been thoroughly investigated in order to predict it. In the power-angle estimation method, the deviation in the phase angle is estimated from the difference in power between a group of generators and the reference generator before and after inception of a fault. Using the estimated phase angle along with the phase angle before the fault, the relative phase angle is predicted for the following 0.2-0.3 seconds. If this value exceeds a pre-determined (based on off-line simulations) threshold phase angle, a step-out is predicted [2]

### Active Power as Operand

Here some examples:

Signs of  $\Sigma P$ , of  $|\Sigma \Delta P| 1.5''$  and of  $|d\Sigma P/dt| 1.5''$  (2)

- $\Sigma P$ : positive for export; negative for import.
- $|\Sigma \Delta P| 1.5''$  and  $|d\Sigma P/dt| 1.5''$ : positive in case of increase of export or of reduction of import; negative in case of increase of import or reduction of export

OR

- $P_{av.\Delta t} \geq XXX \text{ MW}$  (3)

- $R_{1sec} = P(t) / P_{av.\Delta t} \geq K$  (4)

### Frequency as Operand

Frequency derivative in a Substation measured higher than a pre-set threshold,  $df/dt'$  (tentatively  $+ 0.75\text{Hz/s}$ ) during a time of 100ms

The SIPS dynamically calculates the generation needed to be shed for each of the and then selects generators or loads to shed,

In general, Generation or Load to be tripped is available only in specific increments dictated by Power Balance at the time of the line loss event the amount of power to be disconnected, usually depends of the amount of the active power unbalance and it is calculated on-line. With this value, SIPS determine the generators or load to be dropped, having in count the availability of generation and loads connected. The combination of units to be dropped may vary depending on the different polynomials or action statements for the different contingencies.

## 6 FACTORY TESTS AND COMMISSIONING

Tests process depends on the type of arming and triggering

SIPS of Type 1, usually requires only regular FAT w/o the need to do real time power system simulations, limiting the test to produce only the conditions needed to activate the different pre-programed events and verify that devices are activating the corresponding outputs to trip the breakers, or to do command actions. In that way, SAT is an extension of FAT, but with the particularities of field testing

SIPS of Type 2 are more complex to tests because, they require creating the network dynamic conditions in order to generate the signals (voltages and currents) to tests in close-loop the different algorithms. In that way, usually for FAT they require the use of Real Time Digital Simulators (RTDS) as the main tool for testing. SAT usually is done, using the data generated during FAT (as Comtrade files) combined with portable test equipment.

The process of commissioning a system of this magnitude is highly critical and involved many groups including: protection and control, and communication engineering; field technicians; system planning; operations; and dispatching. Because of this dynamic, it is key to have a primary individual or small group of individuals responsible for the coordination of each independent group's efforts.

## **7 ALTERNATIVES TO GENERATION AND LOAD REJECTION SCHEMES**

Generator rejection schemes are an effective means of maintaining system stability and avoiding wide area disturbances. Shutdown of large steam turbine generators can be extremely costly, may result in very long restart times, and also subjects the turbogenerator set to significant thermal stresses. On the other hand, most hydroelectric generators can be relatively easily shut down and quickly restarted. There is however some detrimental effect on a hydro generator that may be subjected to severe overspeed if the unit breaker is opened under high load conditions. For that, alternatives as Fast valving to reduce the generator output without removing the unit from service or dynamic braking schemes based on fast temporary connection of resistors produce a minimum impact of generators. If available, HVDC active power support must be prioritized, because it can be achieved in the time scale of seconds, while the gas turbine start up process takes some minutes.

Load rejection is a protection system designed to trip load following the loss of a major supply to the affected power system area. The major supply deficiency may be caused by the loss of generation or key transmission facilities. As this also represents a major impact in the network, it is recommended the application of storage systems that could help in support the system during some seconds and may be minutes, in case of contingencies, and so, reduce the amount of load to shed during deficits or power caused for major contingencies in the network.

Other possible aids are also Automatic shunt reactor tripping or shunt capacitor switching to prevent voltage collapse

## **8 NEW CHALLENGES**

### **8.1 Expanded network**

Very early, power systems were often isolated from each other. The network of one single power system was not complex and the operation was very simple. Now, the network is much expanded. Many power systems, belonged to different regions in the past, are interconnected together. The voltage levels of power system increase higher. The amount of state variables increases. Those state variables include: node voltage magnitudes, rotor angles of generator, frequency, transmitted electric power through transmission lines, etc. Besides, the synchronizing operation for the AC transmission network must be ensured. Losing synchronous operation will lead the power system swing. To keep power system operating synchronously faces spatial extension [9].

### **8.2 Power electronic devices**

There are more power electronic devices being installed into the power system. Those devices will introduce high percent of harmonics into power system, which distort the waveform of current. The harmonics can increase the losses and hence cause abnormal temperature rises to some equipment e.g. transformer. This kind of temperature rising will decrease the lifetime of such equipment [9].

### **8.3 HVDC links operating in parallel with HVAC systems**

HVDC links present a new real challenge for SIPS. If the HVDC joins two isolated areas, there are considerable advantages, because for each area the HVDC link represent a big generator with possibility to supply active and reactive power in milliseconds. In that way a priorized action to increase or decrease the power through the HVDC brings more benefits than disconnect generators or loads.

The major difficulty appears when the HVDC is operating in parallel with the AC network. In this circumstance, control of the HVDC must be done usually in less than 100 ms and this represents a real challenge, particularly when is needed to collect and manage remote analog signals. In that way the use of PMUs is bringing good possibilities if they are incorporated in the SIPS scheme.

#### 8.4 Penetration of renewable energy

More capacity of renewable power is penetrated into the power system. However the electric power supply from either distributed generation (e.g. home used solar panel) or centralized generator (e.g. wind farm) is time-variant [9]. The variation of electric power production from renewable energy may lead the demanded amount of electric power cannot be satisfied some time.

### 9 OPERATIONAL EXPERIENCE

Majority of SIPS actually installed has justified their investment. In general, SIPS rarely operate, because they are designed to take care of extreme contingencies and they rarely happen. For that, always are welcome data on the operation of these systems.

The most recent experience that we have is the one corresponding to the SIPS installed (2010) in the 400 kV interconnection between Turkey/ENTSO-E. SIPS has operated successfully 7 times in least than two years, and none incorrect operation was reported. Two reported non operations were because the system was disabled or locked out. Figure 4 shows the oscillography record of some of these operations that caused a load shed of 400 MW [10].

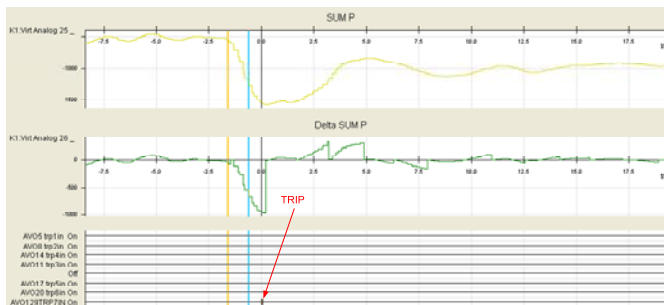


Figure 4: Oscillography of SIPS activation and load Rejection

### 10 FUTURE

SIPS will become part of the Energy Management System (EMS) and probably EMS will be divided in two: Stable Energy Management System (SEMS) and Dynamic Management System (DEMS), being SIPS part of the last one.

Today the action of the SIPS are relative simple (disconnection of loads, generation, switching capacitor banks, etc.), but as these systems evolve and become more reliable it is probably that the optimization dimension will be incorporated, in order to minimize the impact of the different action on the Network, maintaining also the main components of the Power System (generators) ready for operation to contribute more efficient in the Restoration actions after the operation of a SIPS. In this way, the utilization of fast valving or dynamic braking instead of generation dropping could justify its use. Additionally, the possibility of using storage systems that could help in support the system during some seconds and may be minutes, in case of contingencies, could reduce the amount of load to shed during deficits or power caused for major contingencies in the network.

## **11 CONCLUSIONS**

- The introduction of the Phasor Measurement Unit (PMU) has greatly improved the observability of the power system dynamics. Based on PMUs different kinds of wide area protection, emergency control and optimization systems can be designed. A great deal of engineering, such as power system studies, configuration and parameter settings, is required since every wide area protection installation is unique.
- SIPS are demonstrated to be a very useful tool in prevent major disturbances in the Network and also must be considered as part integral of the protection and control system. Also it has demonstrated to be an alternative to immediate network reinforcement, giving Utilities the possibility to postpone major investments. We need to emphasize that this is not a replacement of needs to reinforce the grid when the evidence for that is clear. This is an aid to help Utilities in prevention and optimization.

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