Special Protection Systems: Challenges in the Chilean Market in the Face of the Massive Integration of Solar Energy

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Special Protection Systems: Challenges in the Chilean Market in the Face of the Massive Integration of Solar Energy

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Abstract -- Special protection schemes (SPSs) are an efficient alternative to increase the flexibility in the operation of power systems. The implementation of SPSs is often motivated by technical rather than economic reasons. The aim of this paper is, from the Chilean experience, to propose a novel framework for the analysis and development of SPSs in a context that comprises both technical and economic incentives to enable a high penetration of solar energy. With this purpose, this paper explores the new capabilities of SPSs based on maximizing the cost-effective integration of solar power into a power system, given a set of technical challenges (congestion and dynamic response in case of contingencies) that must be considered in their design. In this framework, three main drivers were identified and discussed. The discussion includes the mechanisms associated with each driver that promote the massive integration of solar power. Moreover, within the proposed technical-economic framework, a methodology for both driver selection and SPS design is proposed. The methodology and the drivers identified are evaluated in the Chilean power system.

Index Terms— power system operation, special protection schemes, solar energy.

I. INTRODUCTION

SPECIAL protection schemes (SPSs) have received much attention in recent years due to their ability to extend the transmission system capabilities because they introduce more flexibility into the operation of power systems. An SPS is an automatic protection system designed to detect abnormal or predetermined system conditions and take corrective action (other than and/or in addition to the traditional isolation of faulted components) to maintain system security [2]. Commonly, SPS actions are associated with changes in demand, generation (MW and MVAR), or system configuration to maintain the stability of the system, acceptable voltage levels, or the power flows within predefined levels. Thus, a better use of the currently installed infrastructure is achieved [3,4]. SPSs do not include under-frequency or under voltage (non-voluntary) load shedding actions, fault isolation or out-of-step relaying [2]. Although they are varied, the control resources for SPSs are often classified according to the place in the system where they act [2,3]. For instance, from the supply side, SPSs include generator rejection, turbine valve control, power system stabilization, discrete excitation, dynamic braking generator runback, and automatic generation control. In some specialized literature, SPSs are considered a synonym for remedial action schemes (RAS) [30].

From the demand perspective, SPSs are associated mainly with voluntary load curtailment, which is often implemented through the demand response strategies that are in charge of connecting/displacing demand blocks if the security of the system is threatened (this is an alternative to extend the concept of the SPS that is traditionally considered in the specialized literature). On the network side, advanced warning schemes for angular instability, overload mitigation, congestion mitigation, and flexible alternate current transmission systems (FACTS) are considered SPSs.

SPSs were initially designed to strengthen the bulk power system, to improve system dynamic response following a contingency, to provide rapid corrective actions for system instability avoidance, and to enhance system security under stressed conditions [5]—[10]. In [12], a literature review on SPSs was presented. In this review, frequency and voltage stability as well as transient and small signal stability were addressed by means of SPSs. Following the same approach, the authors in [13] proposed a phasor-measurement-unit-based SPS for the Taiwan power system. In this case, the aim of the SPS was to avoid transient instabilities caused by the operation of an extra-high voltage transmission line. In [14], the authors proposed the use of an SPS to improve the reliability of the electrical energy supply in the central Zagreb area. Although the SPS in this case was implemented in a distribution system, the motivation for its implementation was to fulfill some specific technical criteria. In [15]-[18], the authors provided technical recommendations for the design of an SPS when considering power systems with non-conventional energy sources. Along this line, the authors in [19] stated that the current models of non-conventional energy sources are not adequate for analytical studies of SPSs. In that manuscript, the authors also discussed how the lack of sufficient transmission infrastructure affects the integration of non-conventional energy sources and the role that SPSs may play to facilitate such integration.

Most of the SPSs reported in the literature have been motivated to comply with technical standards and regulatory frameworks. In contrast, in Chile, the installation of an SPS has been motivated by economic criteria, aiming to guarantee an economical operation of the system while fulfilling the security requirements imposed by the grid codes [11]. Fig. 1 illustrates the general economic motivation to implement an SPS in Chile. Implementing an SPS increases the generation that is available to supply the demand. Consequently, the equilibrium point of the market moves to a lower level. Then, there is an enlargement of both demand and generation surpluses, providing additional profits to customers and generation agents. In addition, voluntary load-shedding strategies (flexible demand in Fig. 1) allow an even larger increase of the surplus for both customers and generation agents.

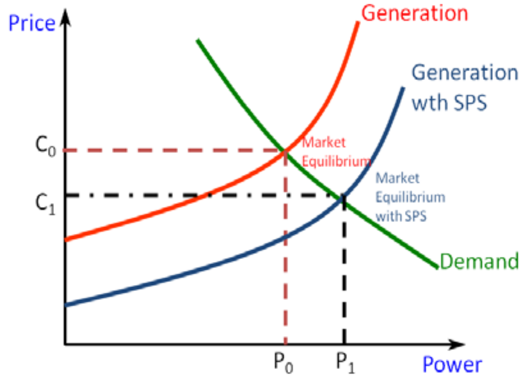

Fig. 1. Economic motivation for the implementation of SPS in Chile

Based on the aforementioned motivations, the authors presented a different perspective to implement SPS in the Chilean power system in a previous work [11]. From this perspective, a general case analysis was conducted without a deeper development of the concepts. From such analysis, the drivers triggering the implementation of an SPS in the Chilean system are purely economic and are focused on achieving the power system operation at minimum cost. These drivers are i) release of congestion for an economical dispatch, ii) time shifting between generation/transmission, iii) maximizing availability of generation assets, and iv) avoiding the risk of rationing by relieving congestion.

Regardless of whether the motivation for installing an SPS is technical [15]-[18] or economic [11], the current approaches do not guarantee that the use of variable generation technologies (VGTs) such as solar is maximized to achieve a minimal operation cost. Hence, with the increased growth of photovoltaic (PV) generation in Chile [22], the drivers proposed in [11] must be further analyzed from a solar perspective to guarantee achieving a minimal cost operation given the new operating conditions imposed by this generation technology. The aforementioned factors motivate investigating the economic drivers underlying the implementation of SPS in systems with large penetration levels of VGT in the near future (e.g., the Chilean power system).

The present paper presents a novel framework for the integration of SPS into a power system. This framework is based on the Chilean experience and proposes to combine both traditional technical motivations with economic incentives in a context of high penetration levels of VGT, specifically solar power. This paper thus explores new capabilities of the SPS to guarantee the maximally cost-effective use of VGTs, considering aspects such as congestion and the dynamic response of the system in case of contingencies. Within this framework, a methodology for driver selection, SPS design and placing in service is also proposed. This paper extends the economic drivers presented in [11] to cover power systems with large penetration levels of solar generation. In this context, mechanisms for the massive integration of VGT arising from the proposed extension are discussed. These mechanisms include not completely fulfilling the traditional N — *1* security criteria, allowing the connection of PV generation in congested areas, and using PV generation to reduce the use of strategic resources such as water. To evaluate the proposed methodology, the Central Interconnected System (CIS) of Chile is used as a test case. The remainder of this paper is organized as follows: Section II presents the current Chilean economic context for installing SPS. Section III analyzes the economic drivers that motivate the installation of SPS in Chile and the mechanisms that allow the massive integration of VGT, particularly solar generation. Section IV introduces the proposed methodology for the design of SPS in an economic context. Section V presents the study case used to assess the proposed drivers and their associated SPS. Section VI presents the concluding remarks.

II. CHILEAN BACKGROUND FOR INSTALLING SPS

A. *General overview*

Throughout its history, the Chilean electric system has been characterized by high rates of growth in energy demand [1]. In addition, over the last several years, generation projects based on VGTs such as PV generation have been connected to the grid without a suitable update of the transmission infrastructure. Accordingly, the amount of congestion has increased, causing a detriment to the robustness of the system. As a consequence, transmission system operators have experienced new operational challenges regarding the security of the system.

In the north of Chile, there are several areas characterized by an outstanding solar potential for large-scale PV projects. Therefore, solar generation is expected to play a significant role in the energy matrix of the country in the near future. Indeed, there are currently approximately 850 MW of PV power plants in operation, another 2,300 MW under construction, and 10,500 MW of approved projects [23]. Fig. 2 presents the impressive evolution of the penetration of solar generation into the Chilean power system.

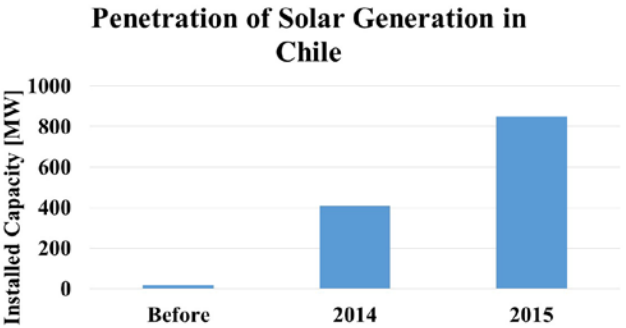

Fig. 2. Penetration of solar generation into the Chilean power system.

Within this context, different opportunities arise to introduce additional flexibility levels into the system either by using original operating strategies or through the introduction of additional equipment such as SPS [21]. Indeed, the Chilean regulatory framework allows developing SPSs for specific contingencies [20, Title VI-10], even if the N — *1* criterion is not strictly fulfilled. According to the technical regulations of Chile [29], the N — *1* criterion is a safety criterion for the planning and operation of the interconnected system that ensures that the negative effects of a single contingency do not spread throughout the system. The motivation for relaxing the N — *1* criterion to foster the implementation of an SPS is to decrease the system operating costs and/or prices (see Fig. 1). Such an initiative was supported by the Chilean Experts Panel for the Electricity Law [21], whose members supported the installation of SPS in the northern interconnected system for economic purposes.

B. Mathematical overview

Let P_{gi}^{t} and c_i, respectively, denote the power assigned to the i^{th} generation unit at hour t and its corresponding generation cost, $i = 1, \ldots, M_t$, with M_t as the number of committed generation units at hour t. Then, the minimum cost operation at hour t is obtained by solving the following minimization problem:

$$\begin{aligned} &\min_{P_g} \sum_{t=1}^{24} \sum_{i=1}^{M_t} c_i P_{gi}^{t} \\ &\text{subject to:} \\ &\text{Transmission constraints} \\ &\text{Generation units constraints} \end{aligned} \tag{1}$$

Let $P_g^* = \left[P_{g1}^{*T}, P_{g2}^{*T}, \ldots P_{gN}^{*T}\right]$ denote the optimal solution of (1)with N being the number of total generation units available in the system. Assume that the transmission constraints in (1) are relaxed, e.g., it is allowed for the solution of (1) not to exactly satisfy the $N - 1$ security criterion. Then, a new vector of minimal operating cost $\bar{P}_g$ is obtained such that $C_m(\bar{P}_g) < C_m(P_g^*)$, with $C_m(\cdot)$ as the marginal cost. The reduction in the operating costs is explained by relaxing the transmission constraints to enlarge the feasible region of (1). Therefore, less expensive options appear for the dispatch of the generation units. However, $\bar{P}_g$ does not necessarily satisfy the N — *1* security criterion. Then, in the case of a contingency, the costs associated with the complementary actions taken to maintain the system integrity must be considered. These costs include the re-dispatch of generation units and perhaps load shedding. Accordingly, only in case of contingency are the operating costs with SPS equal to or higher than the operating costs without SPS.

III. ECONOMIC DRIVERS FOR IMPLEMENTING AN SPS IN THE CHILEAN POWER SYSTEM

Given the new conditions identified in Chile and considering that Chile is not the only country experiencing a significant increase in the penetration of solar generation into the transmission network (see the cases of Germany, United States, China, Japan, and Italy, for instance [24]), in this paper the framework proposed in [11] for the integration of an SPS is updated. The new framework includes both the economic drivers and corresponding mechanisms that allow the massive integration of such generation technology into the current power systems. Specifically, three main economic drivers are analyzed: release of congestion for an economic dispatch, time shifting between generation/transmission, and avoiding rationing by relieving congestion.

Commonly, solar generation is concentrated in specific locations. To avoid solar curtailment actions that might threaten the achievement of minimal cost operation, the drivers “Release of congestion” and “Time shifting between generation/transmission” have been proposed. Furthermore, because water resources are scarce and are often used for irrigation, transportation, and power generation purposes, making strategic use of the water stored in reservoirs is crucial, especially during drought periods. Hence, the use of solar energy resources arises as an alternative to reduce the water consumption in power generation. This situation motivated the driver “Avoid rationing by relieving congestion”. These three drivers correspond to the economic reasons identified from the Chilean context for the implementation of SPS in power systems with major penetration of solar generation. Next, details about each aforementioned driver are provided.

A. Release of congestion for an economical dispatch

This driver is related to the use of economically convenient energy sources to supply the system demand, even if this implies relaxing the N — *1* security criterion. From the solar perspective, the use of economically convenient energy sources implies the use of solar generation as a base resource to supply the demand. Fig. 3 illustrates how this driver works. In subplot a), we assume that the system operates without fulfilling the N — *1* criterion. Therefore, the tripping of any line that connects buses B1 and B2 produces an overload of the remaining line, the tripping of that remaining line, and a further partial system blackout. To overcome this situation, SPS strategies are designed to coordinate the supporting actions performed locally by the conventional power plants and to prevent a system collapse. The reasoning behind this driver is the following: The system operation (without fulfilling the N — *1* criterion) is scheduled in such a way that the use of the energy provided by the "Solar Power Plant" is maximized, i.e., the energy provided by the "Solar Power Plant" is ideally used to supply the load centers "Local Demand 1" and "Local Demand 2". In this sense, a minimum cost operation is achieved because the generation costs of "Solar Power Plant" are less than those of the "Conventional Energy Source". If the circuit connecting buses B1 and B2 experience a short-circuit (see Fig. 3, b), one of the following two situations arises: *i*) the "Conventional Energy Source" is available for applying counteracting measures, or *ii*) the "Conventional Energy Source" is not available for applying counteracting measures. The actions taken by the SPS in each situation are described below.

1. “Conventional Energy Source” is available: in this situation, the SPS performs the following actions:
    - Increases the power provided by the "Conventional

Energy Source".
    - Performs solar curtailment actions in the “Solar Power Plant” to prevent overloading the line L2 that connects buses B1 and B2.
    - Supplies the load center “Local Demand 2” by “Solar Power Plant”.
2. “Conventional Energy Source” is not available: in this situation, the SPS performs the following actions.
    - Performs solar curtailment actions in “Solar Power Plant” to prevent overloading the line L2 that connects buses B1 and B2.
    - Supplies the load center “Local Demand 2” by “Solar Power Plant”.
    - Activates demand response actions and volunteer demand shedding/displacement.

Moreover, if a sudden decrease in the power produced by "Solar Power Plant" at bus B3 occurs, the same two situations described above also arise. The actions taken by the SPS on each situation are described below.

1. "Conventional Energy Source" is available: in this situation, and assuming that there is a sufficient reserve in "Rest of the System", the SPS performs the following actions:
    - Increase the power provided by "Conventional Energy Source" to quickly supply the missing power at "Local Demand 2" and avoid major events.
    - Slowly decrease the power provided by "Conventional Energy Source", trying to reach a new minimal cost operation. This action is performed once the droop control of power plants at "Rest of the System" starts to react.
2. "Conventional Energy Source" is not available: in this situation and assuming that there is a sufficient reserve in "Rest of the System", the SPS does not react, and "Rest of the System" provides the missing power at bus B3. If necessary, volunteer load shedding/displacement is activated by the SPS.

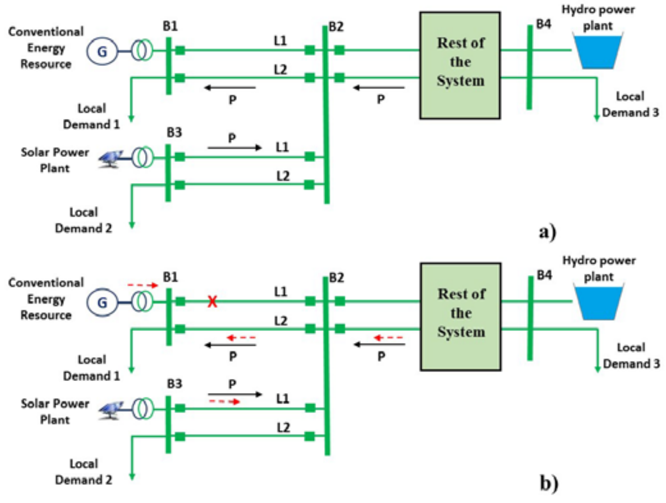

Fig. 3. Driver “Release of congestion for an economic dispatch”. a) Operation without fulfilling $N-1$ security criteria. b) Actions taken by the SPS to prevent system collapse under contingency.

Note that maximizing the use of solar generation to supply the demand constitutes an interesting mechanism to promote the massive integration of VGTs such as solar generation. Despite the further measures that might be necessary to maintain system integrity, this mechanism makes the solar energy projects more attractive for investors (from the economic viewpoint).

B. Time shifting between generation/transmission

This driver regards the allowance of connecting generation projects to the transmission system, even if their dispatch requires relaxing the N — *1* security criterion. In power systems, it is widely known that as the demand grows, new investments in infrastructure are required. However, the time elapsed from the beginning to the commissioning of each project is different. In general, transmission projects take longer to be placed in service than generation projects. Furthermore, solar generation plants are easier to place in service than conventional power plants are. Given this context, the solar perspective of this driver implies allowing an early connection of new solar power plants, even if transmission projects are planned but are delayed for any reason. With this measure, the use of available solar generation resources is maximized, whereas a minimal cost operation is achieved and solar curtailment is avoided.

Fig. 4 depicts this driver. In subplot a), the system operates without fulfilling the N — *1* security criterion because the reinforcement project of line L1 that connects buses B3 and B2 is delayed. Hence, the tripping of line L2 in the same circuit produces an overloading of line L1 and its subsequent disconnection. To tackle this situation, SPSs are used to coordinate the actions taken by the solar and conventional energy sources and to keep the security and quality standards of the system. The reasoning behind this driver is the following: the connection of the solar generation project "Solar Power Plant" is allowed even though the N — *1* security criterion is not fulfilled in the circuit connecting the buses B3 and B2. In this sense, the energy provided by "Solar Power Plant" is used to supply the load center "Local Demand 2", and the excess is exported to "Rest of the System" and/or is used to partially supply the load center "Local Demand 1". Therefore, the operating costs are reduced because, for instance, the power provided by "Conventional Energy Resource" is decreased. If a short circuit occurs in the circuit that connects the buses B2 and B3 (see Fig. 4, b), the SPS reacts, taking the following actions:

- Performs solar curtailment actions at “Solar Power Plant” to prevent the overloading of line L1.
- Increases (if necessary) the amount of power provided by “Conventional Energy Source” to eventually supply the missing energy in the load center “Local Demand 1”.

Unlike in driver A, load shedding is not required to guarantee the integrity of the system. Furthermore, in case of a sudden reduction in the power provided by the "Solar Power Plant", both the "Conventional Power Plant" and the "Rest of the System" react to supply the missing power at "Local

Demand 2". Such a reaction could be coordinated by means of droop controllers and/or using an SPS similar to the one described in driver A to compensate for the intermittent behavior of solar generation. Maximizing the use of solar generation by relaxing the N — *1* security criterion while transmission projects are commissioned constitutes a mechanism that promotes the massive integration of VGTs such as solar. From an economic perspective, this mechanism also makes the solar projects more attractive for investors because an increase in their profitability is promoted.

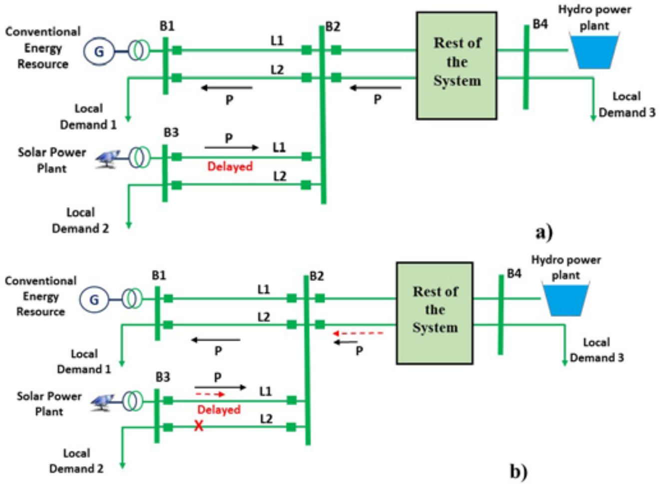

Fig. 4. Driver “Time shifting between generation/ transmission”. a) Operating conditions above $N-1$ security criterion. b) Actions taken by the SPS to prevent the total disconnection of the solar power plant.

C. *Avoid rationing risk by relieving congestion*

This driver comprises the strategic use of water resources in congested areas to avoid rationing during drought periods. This strategic use of water resources requires reducing as much of the water consumption for power generation purposes as possible, though the N — *1* security criterion is not strictly fulfilled and/or more expensive generation resources are used to supply the demand. From the solar perspective, this driver promotes the use of solar generation to totally/partially supply the demand at locations of the system where the generation resources are mainly hydraulic. As in the previous drivers, this measure allows maximizing the use of solar generation, reducing the use of water for generation purposes, and decreasing the use of expensive generation resources to supply the demand. Consequently, a minimal cost operation is achieved wherein the use of solar generation is maximized.

Fig. 5 exemplifies this driver. In subplot a), the system operates without fulfilling the N — *1* security criterion because any line tripping in the circuit that connects the bus B2 with “Rest of the System” produces an overloading of the remaining line. Under such operating conditions, the amount of power produced by “Solar Power Plant” is injected into “Rest of the System”. “Rest of the System” is in charge of supplying the load center “Local Demand 3” in such a way that the use of water resources of “Hydro Power Plant” is minimized. In addition, a programmable load, in this particular case, a pump-storage system, is also assumed to be connected to bus B4. In case of a failure in the circuit that connects the bus B2 with “Rest of the System”, SPS actions are required to mitigate the negative effects associated with the failure. The reasoning behind this driver is the following: Despite not fulfilling the N — *1* criterion, it is possible to take advantage of the energy provided by “Solar Power Plant” to make strategic use of the hydraulic resources at “Hydro Power Plant” while keeping a minimal cost operation. Indeed, in case of having a surplus of energy, pumping-storage systems could be connected to increase the available water resources. If a short-circuit occurs in line L2 of the circuit that connects bus B2 with “Rest of the System” (see Fig. 5, b)), the SPS reacts by taking the following actions:

- Decreases the amount of power produced by “Conventional Energy Resource” to decrease the overload of line L1.
- Performs load shedding actions at bus B4, i.e., programmable loads such as pumping-storage systems are gradually disconnected, to reduce the power requirements from “Rest of the System”.
- Performs solar curtailment actions (if necessary) at “Solar Power Plant” to prevent the tripping of line L2.

As in driver B, load shedding is not required in this driver. In fact, “Hydro Power Plant” could be used to provide the missing energy (if needed). In addition, maximizing the use of solar generation to promote the strategic use of water resources is an additional mechanism for the massive integration of VGT into the Chilean power system. Indeed, this driver enforces using all available VGTs, thus making them more profitable and therefore more attractive from the economic viewpoint.

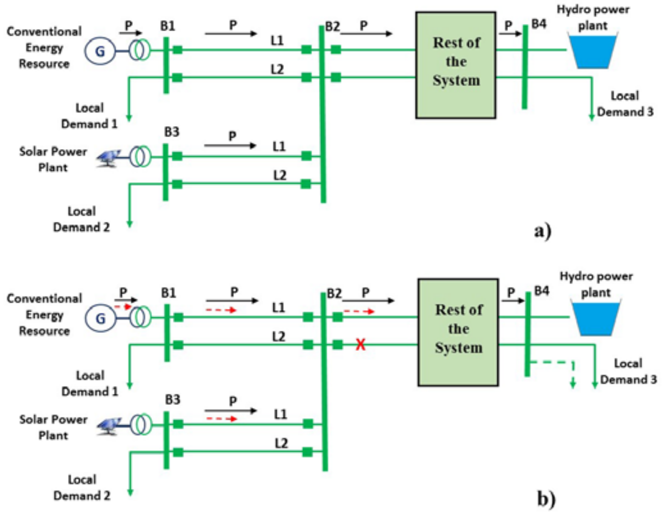

Fig. 5. Driver “Avoid rationing risk by relieving congestion”. a) Operating conditions above $N-1$ security criteria. b) Actions taken by the SPS to prevent the collapse of the system

IV. GENERAL PROCEDURE FOR THE DESIGN OF THE SPS

This section presents the proposed methodology for the design of the SPS from an economic viewpoint. The methodology is composed of five steps: driver selection, identification of contingency situations, steady state simulations, dynamic study, and economic analysis and business model. Fig. 6 shows these steps and their interactions.

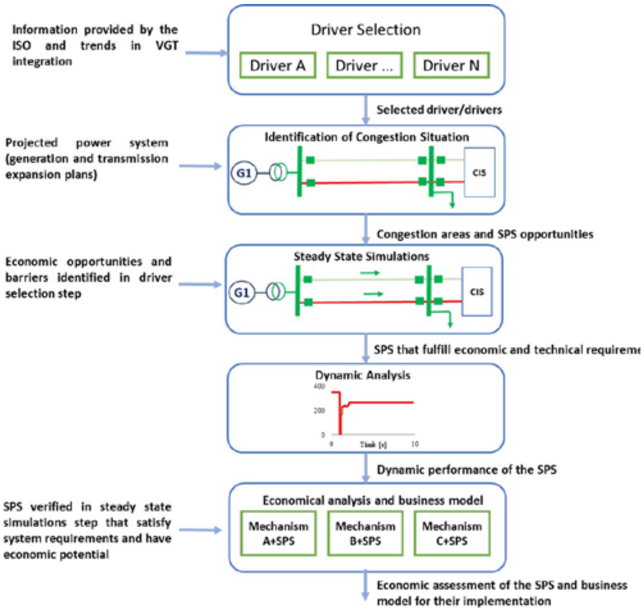

Fig. 6. Block diagram of the general design procedure

In the first step: "*Driver selection*", the information provided by the transmission system operator (TSO) and market agents about observed trends in the integration of VGT and system requirements is used to perform a preliminary selection of drivers that could motivate the installation of the SPS. Such a selection includes the economic opportunities and integration barriers found in each case analyzed. In the second step, "*Identification of congestion situations*", steady state simulations for different operating points of the system are performed, considering a strict fulfillment of the $N — 1$ security criterion. These simulations must be done based on the projected power system according to the generation and transmission expansion plans. From these simulations, congested areas are identified, as are SPS opportunities and technical requirements. In the third step, "*Steady-state simulations*", the SPS opportunities and technical requirements previously identified are assessed considering the economic opportunities and barriers found in the first step. Then, the most suitable SPSs are selected such that the system requirements and economic opportunities are matched. The technical viability of these SPSs is first tested using steady-state simulations where the $N — 1$ security criterion is not strictly fulfilled. This step is done to verify whether the selected SPSs are sufficient to satisfy system requirements in normal operation (e.g., congestion alleviation) and to assess their economic potential for the system and market agents. If the selected SPSs are attractive from an economic viewpoint and satisfy the system requirements, the fourth step consists of evaluating the dynamic performance of the system. This step ("*Dynamic study")* is performed for critical contingencies and operating points. As is usual in this type of system studies, detailed dynamic models must be built using different simulation platforms. The idea behind this evaluation is to show the dynamic system performance under contingencies when the N — 1 criterion is not strictly fulfilled but is supported by an SPS. Finally, in the fifth step: "*Economic analysis and business model"*, a detailed SPS design and business model is performed using the information from the steady state assessment.

V. CASE STUDY

A. Power system under study

The simulations performed in this work are based on the main CIS of Chile [25]. The CIS, which is the main power system of Chile and supplies the central zone of the country, represents 79% of the total installed capacity of Chile, catering to more than 90% of the population of the country. The CIS is a good example of a 50 Hz extreme longitudinal power system characterized by long distances among major load centers and generation areas. As a consequence, long transmission lines are also a distinctive feature of the system, covering a total length of 2100 km. The CIS supplies a peak load of 7550 MW, with the major load located in Santiago, Chile's capital, which his located in the central part of the system and encompasses approximately one third of the population of the country. The voltages in the bulk network are from 110 to 500 kV with nearly 750 buses. The system is composed mainly of hydroelectric and thermal power stations, with a total installed capacity of approximately 15450 MW. Hydroelectric power plants are concentrated in the south of the country, comprising approximately 31% of the total installed capacity. Among the hydro plants, there are a few with large reservoirs, which enable them to deliver full capacity for a long period of time. Thermal units are located mainly in the central and northern areas of the system.

The frequency control of the system is characterized by a manual secondary regulation and a primary regulation supplied only by a reduced number of hydraulic machines. The CIS also includes under-frequency load shedding schemes (UFLSSs) that are activated if the system frequency drops below 49 Hz. To illustrate the network structure, a simplified diagram is shown in Fig. 7. The zoom highlighted in the figure aims to better illustrate the dynamic simulations performed in this case study.

As shown in Fig. 7, the conventional power plant Taltal is located on the north of the CIS and is composed of two generators that can run based on gas or diesel fuel with a total installed capacity of 240 MW. The generated electrical energy is carried through a 220 kV double circuit transmission line (Paposo-Diego de Almagro) that has a nominal capacity of 280 MW per circuit and is 180 km long. The PV power plant is connected to the circuit L1 of the line. Currently, this PV power plant has an installed capacity of 50 MW, but in the short term, its installed capacity will be 156 MW. The wind farm WT has an installed capacity of 99 MW, and it is connected through a tap-off substation to the circuit L2 of the transmission line.

Today, depending on the operating conditions of the system, the switches 52J2 or 52J1 open in occasionally unexpected ways, which often leads to an overload of the remaining circuit of the transmission line if the conventional unit Taltal is dispatched. To avoid these undesirable situations, an SPS was installed in December 2014 to reduce the overloads in the transmission line under those circumstances.

For the dynamic assessment, two simulations were performed: a real-time simulation (RTS) and an off-line simulation. The RTS was performed using an OPAL-RT simulator [26], and the off-line RMS simulations were done using the power system simulation tool DigSILENT Power Factory [27].

For the RMS simulations, a simplified model of the CIS with 1740-buses and 610 demand points distributed throughout the network was implemented in DigSILENT. To study a worst case scenario from a system stability perspective, constant PQ models were used for the loads. The PV power plant and the wind farm were modeled using validated models available in the library of DigSILENT.

Regarding the Real Time simulation, a simplification of the CIS was implemented in the Simulink-Matlab software to upload the data in the Real-Time Digital Simulator (OPAL platform). The model includes synchronous generators, representative static loads, simplified models of PV power plants and SVCs. These models are available from Simulink SimPowerSystem, the transmission lines were modeled using distributed parameters, and the models are available from Artemis library (OPAL-RT). The parameters of all elements used in the models were obtained from database CDEC-SIC [28] to analyze the system responses to different scenario simulations.

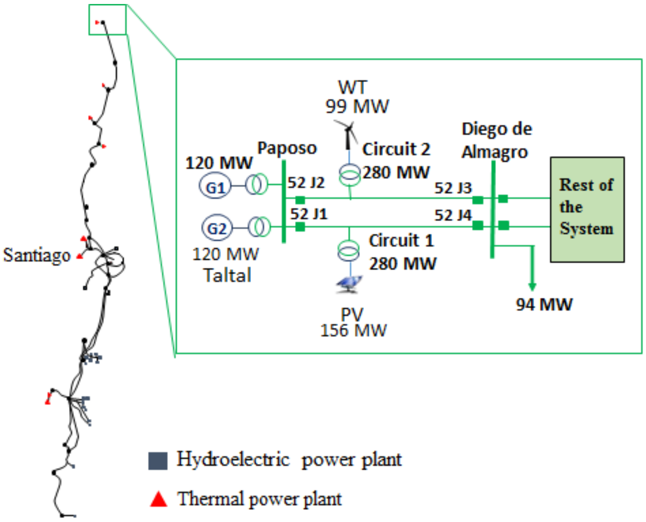

Fig. 7. Simplified diagram of the Chilean Interconnected System (CIS) including a zoom of the area involved in the case study.

B. Dynamic simulations

The simulated contingency is a three-phase short circuit applied at circuit L2 of the transmission line Paposo-Diego de Almagro, between the tap-off in the substation of the WT and the busbar Diego de Almagro. The short circuit is applied at t = 5 seconds of the simulation. The fault is cleared 120 ms after the short circuit appliance by opening the interrupters 52J2 and 52J3 (reconnection of circuit L2 is not considered). The pre-fault conditions of the system are presented in Table 1. In this table, it is evident that for the pre-fault condition, the $N - 1$ criterion is not strictly fulfilled in the line Paposo-Diego de Almagro.

Table 1. Operation points

	Pre-Fault		**During the Fault**		**After SPS Actions**	
Devices	P [MW]	Loading [%]	P [MW]	Loading [%]	P [MW]	Loading [%]
Taltal U1	81	67.5	81	67.5	61	50.8
Taltal U2	81	67.5	81	67.5	61	50.8
WT	0	0	0	0	0	0
PV	156	100	156	100	156	100
Circuit L1	159	56.8	318	**113.6**	278	97
Circuit L2	159	56.8	-	-	--	--

Fig. 8 shows the sequence of events that were implemented in DigSILENT and OPAL to simulate the contingency. The time axis is not scaled.

The power system is in normal operating condition until t = 5 seconds. Once the short circuit in L2 occurs, the circuit L1 is overloaded (see Table 1, column "During the fault"). The SPS system detects the fault conditions, and 130 ms after the fault clearance, it is able to take corrective actions to fulfill the $N - 1$ criterion under contingency. The corrective measure in this case is to decrease the active power injection from the conventional power plant Taltal until the overloading condition of the remaining circuit L1 disappears, i.e., until the load level is less than or equal to 100% (see Table 1). The power reduction of the conventional generators aims to keep the power injected by the PV power plant. The active power reduction from the conventional power plant Taltal is presented in Fig. 9. In this figure, subplots a) and b) correspond to the RTS (OPAL) and off-line simulation (DigSILENT) results, respectively. Both responses are quite similar in terms of both damping and the final steady state operating point.

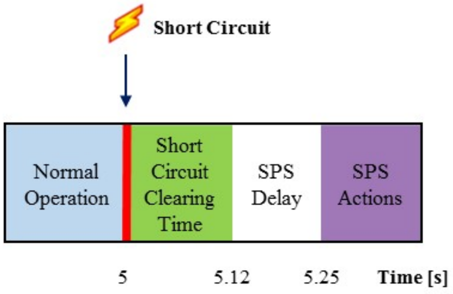

Fig. 8. Sequence of events implemented in DigSILENT and OPAL.

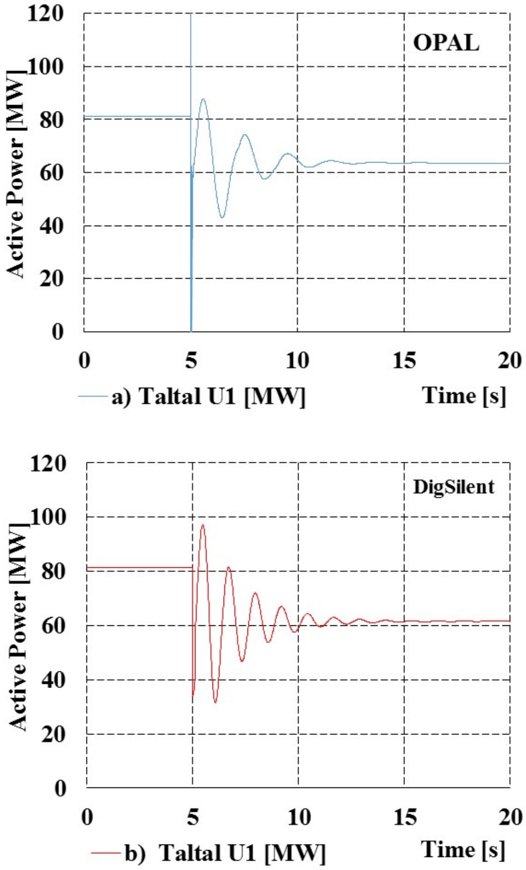

Fig. 9. Active power injection of the conventional power plant Taltal (unit 1), a) RTS; b) off-line simulation.

Fig. 10 shows the loading of the remaining circuit L1 of the transmission line, and Fig. 11 shows the frequency of the system, measured at the bus bar Diego de Almagro. Fig. 10 shows that immediately after the fault clearing (at t = 5.12 seconds), circuit L1 is overloaded. Then, after 5 seconds, the SPS actions are able to lead the system to a new operating condition in which the transmission line operates within its thermal limits (considering the post contingency situation). The steady state operating points achieved in DigSILENT and OPAL show load levels of the circuit L1 of 95% and 91%, respectively. Thus, the SPS actions proved to be a key factor to avoid undesirable operating conditions in the transmission line related to its thermal limits. In this way, the SPS allows the PV injections to be maximized by relaxing the N — *1* security criterion without threatening the system security under contingencies.

From the dynamic simulations, we can conclude that the results obtained with the RTS and the off-line simulations are quite similar. The previously described results show a preliminary validation of the SPS proposal.

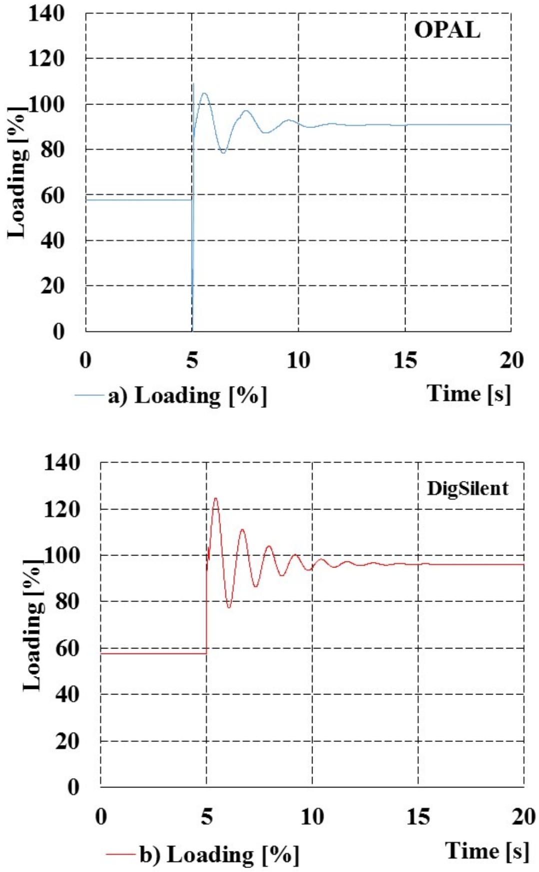

Fig. 10. Loading of the transmission line: a) RTS, b) off-line simulation

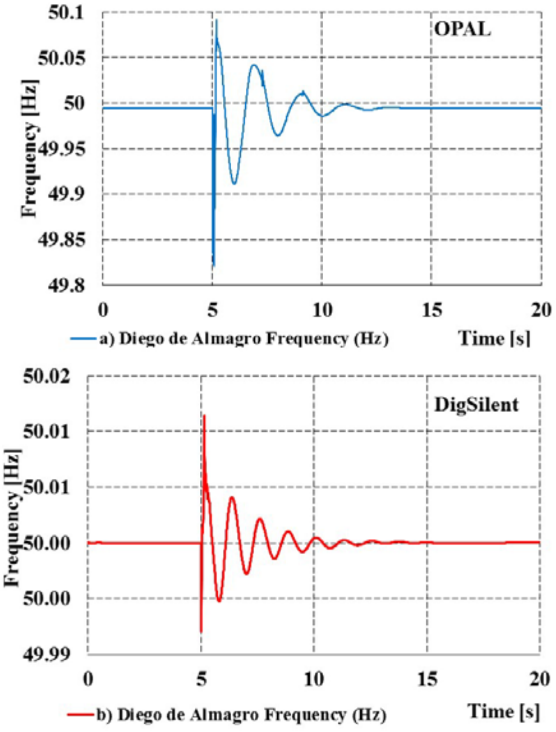

Fig. 11. System frequency: a) RTS, b) off-line simulation

VI. CONCLUSIONS

In this paper, considering the Chilean experience, a novel framework for the integration of an SPS into a power system was proposed. This framework combined traditional technical motivations and economic incentives within a context of high penetration levels of VGT, specifically solar power. Inside this framework, a methodology for the selection of the drivers, the design of the SPS and their place in service was also proposed. The proposed framework was found to enable the massive integration of solar power projects and the maximum use of the power supplied by these resources keeping the security and integrity of the system. These results confirm the feasibility of a high penetration of solar power into the presence of transmission congestion, while satisfying regulatory and market requirements. In addition, the results obtained in this paper could be extended to other countries with integration conditions similar to Chile, such as South Africa and Morocco, and to the integration of other non-conventional resources such as wind generation. In the case of wind generation, the impact of less predictable behavior characteristics should be carefully analyzed.

Future work in this field involves the automated identification of SPSs by means of specialized algorithms and optimization tools, the assessment of the interaction among different special protection schemes, and a more detailed analysis of the business model design.

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