DESIGN OF A SPECIAL PROTECTION SCHEME AND SUPPLEMENTARY CONTROLS REGARDING HVDC BACK TO BACK INTERCONNECTION BETWEEN TURKEY AND GEORGIA

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submitted by **ÖZGÜR TANIDIR** in partial fulfillment of the requirements for the degree of **Master of Science in Electrical and Electronics Engineering Department, Middle East Technical University** by,

Prof. Dr. Canan Özgen _______________
Dean, Graduate School of **Natural and Applied Sciences**

Prof. Dr. Gönül Sayan _______________
Head of Department, **Electrical and Electronics Engineering**

Prof. Dr. Ali Nezih Güven _______________
Supervisor, **Electrical and Electronics Engineering Dept., METU**

Dr. Osman Bülent TÖR _______________
Co-Supervisor, **EPRA**

Examining Committee Members:

Prof. Dr. Nevzat Özay _______________
Electrical and Electronics Engineering Dept., METU

Prof. Dr. Ali Nezih Güven _______________
Electrical and Electronics Engineering Dept., METU

Dr. Osman Bülent Tör _______________
EPRA

Prof. Dr. Muammer Ermiş _______________
Electrical and Electronics Engineering Dept., METU

M.Sc. Erkut Cebeci _______________
Tübitak MAM Energy Institute

Date: _______________

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last name: Özgür Tanıdır

Signature:

ABSTRACT

DESIGN OF A SPECIAL PROTECTION SCHEME AND SUPPLEMENTARY CONTROLS REGARDING HVDC BACK TO BACK INTERCONNECTION BETWEEN TURKEY AND GEORGIA

Tanıdır, Özgür
MS, Department of Electrical and Electronics Engineering
Supervisor : Prof. Dr. Ali Nezih Güven
Co-Supervisor : Dr. Osman Bülent Tör

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HVDC Back-to-Back interconnection between Turkey and Georgia is operational since November 2013. Previous feasibility analysis regarding to this project has shown that depending on the amount of power transfer between parties and loading conditions, there might be transmission bottlenecks and problems observed in Turkish Power System. In this respect, special protection coordination is required to maintain reliable and sustainable operation. In this thesis, design of a special protection scheme that coordinates outages in the region along with some countermeasures is introduced. The design study starts with analyzing critical scenarios and instabilities endangering the normal operation of Turkish Power System in order to define requirements of the special protection scheme. In this regard, static and dynamic analyses are carried out to identify instability patterns and solution spaces for critical instability conditions. The results have shown that regional system is highly vulnerable to the contingencies and may face regional collapse even without interconnection. Hence, several scenarios and several loading conditions have been analyzed in detail in order to give insight to special protection

logic design and calculate countermeasures required for critical instability conditions.

As a result of these studies, requirements for stable and sustainable operation of the region are specifically determined and a wide area measurement based special protection scheme is designed. In addition, modelling of the designed scheme in a power system simulation environment and simulation results of the proposed scheme are presented. Finally, coordination and compliance between existing protection measures with the proposed protection scheme are also investigated.

Keywords: Special Protection Scheme, Remedial Action Scheme, Wide Area Measurements, Power System Stability, Power System Interconnection

ÖZ

TÜRKİYE VE GÜRCİSTAN ARASINDAKİ HVDC BACK TO BACK ENTERKONNEKSİYONUNA İLİŞKİN KORUMA SİSTEMİNİN TASARIMI VE BAĞLANTI FONKSİYONLARININ GELİŞTİRİLMESİ

Tanıdır, Özgür
Yüksek Lisans, Elektrik ve Elektronik Mühendisliği Bölümü
Tez Yöneticisi : Prof. Dr. Ali Nezih Güven
Ortak Tez Yöneticisi : Dr. Osman Bülent Tör

Şubat 2014, 120 pages

Türkiye ve Gürcistan elektrik sistemleri arasındaki HVDC enterkonneksiyon, 2013 yılı Kasım ayı itibariyle gerçekleşmiştir. Bu bağlantı kapsamında daha önce yapılan fizibilite çalışmaları, ülkeler arası elektrik transferinin seviyesine ve sistem yüklenmesine bağlı olarak, Türkiye elektrik iletim sisteminde kısıtlar ve problemler yaşanabileceğini göstermektedir. Bu bağlamda, Türkiye elektrik sistemi işletmesinin kesintisiz ve güvenli olması amacıyla, bağlantı bölgesi ve çevresini kapsayan bir özel koruma sisteminin tasarlanması ve uygulanması gerekliliği ortaya çıkmaktadır. Bu tez çalışmasında, bölgesel şebekedeki anormal durumları gözlemleyen ve karşı önlemlerle olası bölgesel çökmelerin önüne geçen bir özel koruma sistemi tasarımı anlatılmaktadır. Özel koruma uygulanacak sistemin anlaşılması ve koruma sisteminin tasarımı için gerekli kriterlerin belirlenmesi amacıyla, bölgesel şebeke için kritik senaryolar, statik ve dinamik kararlılık analizleri ile incelenmiştir.

Yapılan çalışmalarda, bölgesel elektrik şebekesinde yüklenme seviyesine bağlı olarak bölgesel sistemin oturması problemi ile karşı karşıya kalınabileceği, sistemin bu duruma karşı savunmasız olduğu ve sistem kararsızlığının Gürcistan ile elektrik ticareti olmasa dahi oluşabileceği gözlemlenmiştir. Bu nedenle çalışmada, farklı senaryolar ve yüklenme koşullarında yaşanılabilecek olası şebeke çökmelerinin analizi yapılmıştır. Bu analizlerin sonuçları, özel koruma sistemi dizaynında ve karşı önlemlerin oluşturulmasında kullanılmıştır.

Yapılan çalışmaların sonucunda, bölgeye tesis edilmesi planlanan özel koruma sistemi için gereksinimler belirlenmiş ve geniş alan ölçümlerine dayanan bir özel koruma sistemi tasarımı gerçekleştirilmiştir. Bu çalışmada, bahse konu koruma sisteminin tasarımı, öngörülen sistemin güç sistemleri analiz programında modellenmesi ve sistemin çalışmasına dair simülasyon sonuçları anlatılmıştır. Ayrıca tasarlanan sistemin, mevcut koruma düzeni ile koordinasyonu ve uyumluluğu incelenmiştir.

Anahtar kelimeler: Özel Koruma Sistemi, Acil Eylem Şeması, Geniş Alan Ölçümleri, Güç Sistemi Kararlılığı, Güç Sistemleri Enterkonneksiyonu

To My Parents

My Sister

And My Cutie

x

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CHAPTER 1

INTRODUCTION

As being one of the most significant energy type, electricity is todays driving source in all around the world. Exponential development in technology forces electricity to be supplied in higher amounts and increased quality. Consequently, electric power systems should be improved constantly to maintain secure and continuous operation. This requires a reasonable demand forecast and cost effective grid planning. However, grid planning is a complex problem as it includes several important concerns such as environmental issues, economical issues, technological issues, etc. In that respect, grid plans aim the maximization of both utilization of existing system infrastructure and marginal benefit from grid investments while satisfying certain degree of quality with a continuous service. This will force grids to operate closer to their loadability limits. In that case, system security and integrity become a significant concern for grid operation which requires a special attention.

In addition to the technical electricity quality issues, the electricity service should be provided in a reasonable price in order to satisfy both producers and customers. Therefore electricity grid should also be planned in a way that it provides a competitive environment for producers and customers. In today's vertically unbundled systems, generation expansion is handled by non-utility companies, however; transmission plan should aim to increase the number of players in electricity market such that the competition among players is increased. One example way of doing it is the interconnection of power networks. Along with the increase in competition, interconnection of power networks provides several benefits for countries such as reserve sharing, reliability enhancement, etc. Today most of the power networks become interconnected to utilize benefits introduced by interconnection.

Being already connected to ENTSO\E (European Network of Transmission System Operators for Electricity), Turkey is now planning to interconnect with Georgia via asynchronous HVDC Back-to-back link (B2B) from northeastern region of Turkey. According to the information obtained from TEİAŞ (Turkish TSO), the interconnection has been planned to be realized in 2013 with 350 MW capacity and will be increased to 1050 MW until 2017. The previous feasibility study regarding to this interconnection has shown that, due to the transmission bottlenecks in the region, even 350 MWs of power import is infeasible especially in the spring season [1]. According to that study, significant hydraulic potential in the region is expected to create transmission bottlenecks in the spring season due to the water regime. Consequently, power import from Georgia will be limited in magnitude in order to preserve secure operation of Turkish grid.

This limitation creates an economic burden not only for the investors of this interconnection but also reduces the economic benefits for countries planning to enjoy this interconnection. Hence, additional transmission investments are required in Turkish grid to increase efficiency of this interconnection. However, geographical difficulties in the region are delaying the transmission investments. Under these circumstances, a technical solution based on special protection scheme (SPS) is sought in order to coordinate the outages around the region; hence, reducing the risk of regional brown-out.

Special protection schemes are designed to detect abnormal system conditions and to initiate preplanned corrective actions to mitigate consequences of abnormal system conditions [2]. As the existing transmission system infrastructure is challenged to support loads beyond original design limits, SPS applications are required to maintain power system security and reliability. Hence, in this study, an SPS that is required to resolve transmission bottlenecks in the region is designed.

As a special application for the network, SPS requires to be tailored according to the grid requirements. Therefore, starting point should be the analysis and understanding of weak points in the grid. Nevertheless, this study requires detailed grid modelling in terms of static and dynamic models. As the model under investigation is a relatively larger one, several engineering assumptions are required to ease the modeling process.

As indicated, SPS design requires several grid analysis studies that include static security, power quality, transient stability, etc. All of the analysis have critical importance in the design process and are utilized to form correct scheme for the region. Starting from static security analysis which monitors system weak points in detail, studies continue with examining transitions between system states via transient stability analysis. In addition, continuous operation of HVDC link is checked utilizing power quality analysis conducted for the region.

Similar to any protective device, SPS should also be highly reliable and dependable as it ensures the stability and security of the network. This task necessitates investigation of several scenarios and grid loading conditions. Hence, in this study, 2 main scenarios namely, summer scenario and spring scenario are utilized. In addition, several generation dispatch alternatives are simulated in both analysis and design verification process.

Taking the requirements defined for SPS into consideration, design study is conducted utilizing a step-by-step development approach. Starting from the determination of grid condition, every state of the grid is detected and required actions are determined in the SPS design.

In order to model and analyze the Turkish grid in detail, two power system analysis programs, namely Digsilent PF and PSS/E, are utilized. These simulation programs provide a wide range of power system analysis functions and proven their reliabilities; hence, they are commonly used by most of the power system analysis studies. In addition, for evaluation of the results, MATLAB is also utilized as it offers more flexible and easy environment for combining and arranging several analysis results.

This thesis is organized as follows. In the second chapter, results of the previous feasibility study regarding the interconnection between Georgia and Turkey is introduced. The SPS requirement and implementation examples are also given in this chapter. Third chapter mainly focuses on grid analyses that are required to design SPS to the regional network. This chapter starts with grid modelling and scenario building for analysis. Later, analyses conducted for defining SPS requirements are given. In addition, step by step SPS design is explained in this chapter. In the fourth chapter, simulation results for proposed SPS for the region are introduced. Additionally design evaluation is included in this chapter. Finally this study ends with conclusive remarks which are given in fifth chapter.

CHAPTER 2

SPECIAL PROTECTION DEMAND IN NORTHEASTERN REGION OF TURKISH POWER SYSTEM

In this chapter, brief information regarding the HVDC interconnection between Turkey and Georgia is introduced. The importance of this interconnection project among Caucasus region countries is explained. In addition, results of the previous study which is conducted for analyzing the feasibility of this interconnection are given along with the interconnection requirements. Previous study has shown that the energy trade between the countries should be limited especially during spring season due to the transmission bottlenecks existing in Turkish Power System [1]. It is emphasized that due to insecure transmission conditions exist under some circumstances, a special protection system should be installed in the region against the risk of a regional system collapse. Hence, this chapter focuses on necessities and expectations regarding to the special protection scheme implementation. In addition, several SPS practices around the world are also presented for a better understanding of SPS applications.

2.1. HVDC Interconnection between Turkey and Georgia

Electric power utilities are responsible for ensuring continuity and reliability of supply which is indeed a difficult job in today’s developing world. As the need for the electric energy is constantly increasing, operation and planning of grid is becoming even harder. Cost effective grid planning is the key for the success. From short term unit dispatch problem to long term capacity expansion problem, power system planning should aim to minimize the cost of delivering energy while satisfying the reliability criteria. Therefore, power utilities should pay highest attention to the planning issue in order to ensure secure operation of their current and future grids.

On the other hand, power system planning task includes several complex problems that needs to be solved simultaneously. This fact also indicates the importance of the planning issue. The overall picture illustrated in Figure 2-1 shows the interactions and related time horizons of these problems.

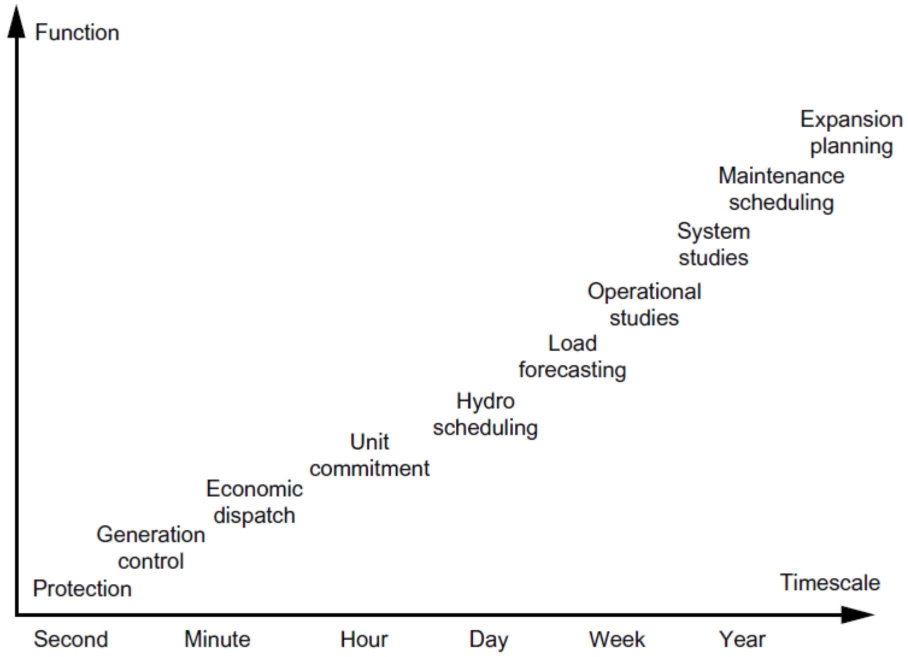


Figure 2-1. Power system planning chart [3].

On the top of the grid planning issues, transmission and generation expansion problem holds crucial importance. Since this problem constitutes the first level in the planning process, it directly affects whole grid plan. Capacity expansion decisions are dependent on many subjects such as environmental and social effects, government policies, technological developments, electricity demand growth rate, costs etc. However, as the traditional way, most important considerations are demand growth rate, i.e. supply-demand balance, and costs. In vertically unbundled power systems, these considerations can further be narrowed to transmission investment problem as generation investments are not handled by transmission companies. Then the question becomes `*What is the most valuable and cost effective investment to fulfill continuity and reliability of supply objectives*? `.

Power system interconnection is one of the most promising answer to this question. Today, most of the electric utilities decide to interconnect power systems as it introduces economical and technical benefits such as;

- Reliability enhancement
- Reserve sharing
- Peak load sharing
- Electricity cost reduction.

As a result, huge interconnected networks (ENTSO/E, IPS/UPS (Unified power system of CIS countries)) are formed to enjoy these benefits. As being an associate member of ENTSO/E, Turkey also benefits from the interconnection and working on other interconnection projects with its neighbors as well.

One of the ongoing projects is the connection of Turkish and Georgian power systems via HVDC link. As agreed by both Turkish and Georgian parties, asynchronous interconnection between Georgia and Turkey is planned to be established via line commutated back to back (B2B) HVDC Substations (SS) located in Akhaltsikhe and Batumi regions of Georgia. Details of these substations are:

- 3x350 MW HVDC B2B converters are planned to be installed at Akhaltsikhe SS by the Georgian party until 2017.
    - This interconnection between Akhaltsikhe region of Georgia and Borçka region of Turkey is planned to be established between Akhaltsikhe (in Georgia) and Borçka (in Turkey) (see Figure 2-2).

- The second line in that region is planned to be between Akhaltsikhe and Tortum which is under investment planning program of Turkey (see Figure 2-2).

- 2x175 MW HVDC B2B converters are planned to be installed at the Batumi region by the Georgian party until 2015.
    - The interconnection between Batumi region of Georgia will be between Batumi and Muratli in Turkey (see Figure 2-2).

The realization of B2B installations is as follows;

- 2013: 2x350 MW Akhaltsikhe
- 2015: 2x350 MW Akhaltsikhe; 2x175 MW Batumi
- 2017: 3x350 MW Akhaltsikhe; 2x175 MW Batumi

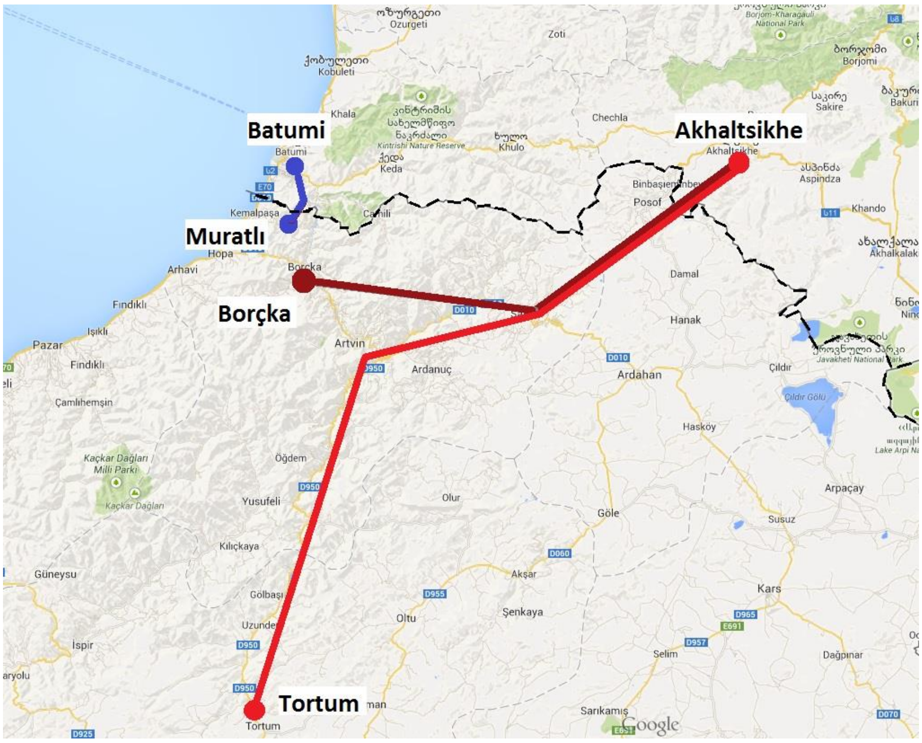


Figure 2-2: The basic transmission routes (blue line: Muratli – Batumi line representation; dark red line: Borçka – Akhaltsikhe line representation, light red line: Y. Tortum-Akhaltsikhe line representation).

This interconnection project introduces a power bridge between not only Turkish and Georgian parties but also includes power trade opportunities between Azerbaijan, Georgia, Russia, Turkey and ENTSO\E.

The benefits are much clear when countries among the Caucasus region are examined. Brief outlook to Georgian Power System has shown that [4];

- Installed capacity is around 3300 MW which is composed of hydro and thermal power plants.
- Electricity demand is highly seasonal in Georgia, with peak demand in winter and lower demand in summer. This is the inverse of the seasonal hydropower generation pattern: hydropower generators tend to produce at their peak during summer months and at their lowest levels during winter. This situation enables Georgia to export energy during the summer, but also requires hydropower generators to spill large amounts of water.
- While Georgia has interconnections with Russia, Turkey, Azerbaijan and Armenia, the vast majority of its trade is with the first two countries. Trade with these countries comprises imports in winter to meet Georgian demand with exports in summer months when Georgia has excess hydro output.
- Electricity price is around 1.25 $cent/kWh during spring season while ~5.6 $cent/kWh during other months [5].

On the other hand, brief outlook to the Azerbaijan Power System has shown that [6];

- Installed capacity is around 6500 MW where majority of electric power is produced by thermal power plants as a result of rich natural gas resources in Azerbaijan.
- Peak demand of the country occurs in winter season and is about 5000 MW at 2013.
- Due to new generation investments, Azerbaijan is expecting excess energy which is planned to be exported over the interconnections through Georgia and Russia.
- Electricity price is around 7.5 $cent/kWh.

Finally, consideration of Turkish System will lead to following conclusions [7] [8];

- Installed capacity of Turkish Power system is around 60000 MW and the primary source of the generation is almost equally distributed between coal, hydraulic and natural gas sourced plants.
- Peak demand of the country occurs in the summer season and corresponds to ~38000 MW in 2013.
- Average price for electricity is around 15 $cent/KWh. However, as the natural gas combined cycle power plants (NGCCPP) has a significant share in the electricity generation, prices can go up to 30 $cent/KWh ,especially when system loading reaches to winter peak loading conditions, due to the shortages in natural gas supply.
- Electricity demand forecasts have reported that about 7% increase in electricity demand per year is expected. Therefore, electricity sector in Turkey is attractive for players who are willing to invest on generation.

Consideration of Caucasus region power networks essentially shows that the interconnection project is a win-win situation for all power utilities around the region. On the economical bases, high electricity prices in Turkey provide a rock solid reason for this interconnection investment. Furthermore, as having high hydro potential, Georgia expects to import electric power not only to Turkey but also to other Balkan countries via utilizing Turkey's ENTSO/E interconnection. Same reasoning can be applied for the case of Azerbaijan due to the natural gas supplies in the country. On the technical bases, security and reliability of supply clearly increase in the region with the implementation of this project. Both Georgian and Azerbaijani power systems are small and relatively weak compared to Turkish one. In case of a major disturbance, Turkey can be utilized as a hot reserve in order to ensure continuity of supply. Here, it should be noted that the type of interconnection is asynchronous which means that no stability enhancement should be expected by this interconnection project unless auxiliary controls are embedded and tuned in HVDC controls for this typical situation. However, if such controls are implemented, there will be other technical benefits, such as reserve sharing and oscillation damping, can also be utilized. As the HVDC technology is capable of increasing and decreasing power exchange in milliseconds, it can be utilized for such oscillation damping purposes in case of any need in the power system.

In conclusion, both technical and economic considerations indicate that the interconnection based on a HVDC B2B scheme between Georgia and Turkey is beneficial and valuable for Southern Caucasus countries. This project is now in the realization phase and expected to serve as a power bridge between Caucasus countries in the following years.

2.2. Utility Requirements, Expectations and Need for SPS Application

As being one of the most significant energy source, electricity is todays driving source in all around the world. Exponential development in technology forces electricity to be supplied in higher amounts and increased quality. In order to compete with this challenge, electricity grids should be improved to achieve constant supply quality. As being one of the developing countries, Turkish electricity system has been improved significantly during last decades. Average annual increase rate in the electricity demand in Turkey is 7% which means that the need for electricity is expected to be doubled in a 10 years period. However, it is not easy to maintain both security of supply and quality of service as expected. Since demand and generation centers have substantial distance due to primary power source location, grids have to face with several challenges in maintaining the service. These challenges such as right of way, geographical conditions, economics, etc. introduce complex problems which require optimal solutions.

An example of this situation exists in Northeastern region of Turkey. As indicated in Section 2.1, electricity import is planned via HVDC Interconnection between Georgia and Turkey through one of the most congested transmission corridors in Turkey. A brief outlook to the region has shown that;

- North Black Sea and Eastern Anatolian region are among the power exporter regions in Turkey with a net consumption of 2490 MW whereas installed generation capacity is 7721 MW [9].
- Even by a deductive approach, there are two basic transmission routes connecting the generation in the region of interest to the load centers in Turkey, as illustrated in single line diagram given in Appendix A. The total thermal capacity of those two transmission paths is about 3000 MW, whereas the generating capacity (installed capacity, planned for 2013) in the region is 7721 MW.
- Almost all the generators around the region are hydraulic type (many are run-of-river type). Although dispatch of the generating units in Turkey is subjected to system security and electricity market conditions, it is reasonable to assume that a considerable amount of generation is to be dispatched from that region, particularly during spring and initial summer periods, given the hydrological conditions and competitiveness of those generating units.

Considering these facts, it is essential that the planned HVDC B2B interconnection between Turkey and Georgia should be carefully investigated in order to ensure secure operation of the power system. In order to determine secure transfer limits rather than physical capacities of these B2Bs, a detailed feasibility study is conducted to analyze the effects of different levels of power import from Georgia to Turkey on the possible transmission bottlenecks in Turkish network [1]. Results of this study are presented in Table 2-1 where color coding in the table indicates the effect of contingencies on electricity transmission system security in the region. In this presentation, examined cases are classified as follows;

- Cases colored with minor re-dispatch mark indicate situations where generation rearrangements smaller than 100 MW are required to maintain safe operation.
- Cases colored with major re-dispatch mark indicate situations where generation rearrangements larger than 100 MW are required to maintain safe operation.

- Cases colored with unsecure mark indicate situations where base case itself requires generation rearrangements larger than 100 MW and further consideration in the grid is required to manage such level of import.

Results of this study clearly indicate that even 350 MW of import from Georgia to Turkey is insecure for the year 2013. Hence, this report suggests that the initial power export should not exceed 350 MW even under best transmission system conditions and re-dispatching might be necessary in this region as a short term measure to resolve the transmission bottleneck.

Results also imply that the net transfer capacity (NTC) between Georgia and Turkey is zero during the spring season and it may be the case for other seasons due to n-1 security criterion in NTC calculation. From an economical point of view, zero exchange for certain months will be a huge burden for both investors and electricity traders who desire to benefit from this investment. Considering the price difference between Georgian and Turkish electricity markets, zero exchange is the worst scenario for both countries as well.

Table 2-1. Results of the Contingency Analysis for 2013 [1]

	2013 Expected Peak Load Conditions			2013 Expected Spring Load Conditions		
	350 MW Import	700 MW Import	1050 MW Import	350 MW Import	700 MW Import	1050 MW Import
N Case (Base Case, i.e., no outage)						
The Outage of Borçka-Deriner 400 kV Line						
The Outage of Deriner-Artvin 400 kV Line						
The Outage of Y. Tortum-Erzurum 400 kV Line						
The Outage of Erzurum-Ozluce 400 kV Line						
The Outage of Ozluce-Keban 400 kV Line						
The Outage of Borçka-Kalkandere 400 kV Line						
The Outage of Kalkandere-Tirebolu 400 kV Line						
The Outage of Tirebolu-Borasco 400 kV Line						
The Outage of Borasco-Kayabaşı 400 kV Line						
The Outage of Borasco-Çarşamba 400 kV Line						
The Outage of Çarşamba-Kayabaşı 400 kV Line						
The Outage of Boyabat-Kursunlu 400 kV Line						
The Outage of Borçka-Artvin Double Circuit 154 kV Line						
The Outage of Muratli-Borçka Double Circuit 154 kV Line						

Legend

350 MW Import: Only one block of 2x350 MW Akhaltsikhe converter is in operation

700 MW Import: Two blocks of 2x350 MW Akhaltsikhe converter are in operation

1050 MW Import: Two blocks of 2x350 MW Akhaltsikhe converter and 350 MW Batumi converter are in operation

	No problems related to Georgia Interconnection
	Minor redispatch problems related to Georgia Interconnection (< 100 MW)
	Major redispatch problems related to Georgia Interconnection (> 100 MW)
	Unsecure

Surely, in order to resolve these issues, new transmission system investments (i.e., third 400 kV transmission corridor in the region) are required. However, according to the master plan of Turkish power system [7], third transmission corridor connecting Borçka SS to Keban SS, where some of the high capacity transmission lines connecting Southern Anatolian region to load centers around İstanbul originates, will be realized in 2016. Until then, the transmission bottleneck will exist and get worse as new HVDC B2B blocks and regional generation investments will be realized during upcoming years.

Considering these facts and future developments in the region, expansion in the transmission capacity of the current infrastructure by using an intelligent protective system seems to be the only viable solution. These systems are called special protection schemes (SPS) which are designed to ensure power system security during abnormal conditions and contingencies. The main purpose of SPS is to mitigate the consequence of abnormal conditions via initiating a series of pre-planned corrective actions. The need for such a system has also been emphasized in [1]. Furthermore, the utilization of SPS in the region will enable to monitor system conditions in n and n-1 conditions, hence will provide prevention from cascaded outages that may result in a regional system blackout. As a result, transmission capacity of the system which is dependent to the n-1 security can be increased in a controlled manner.

2.3. SPS Applications around the World and State of Art in SPS Installations

As the existing transmission system infrastructure is challenged to support loads beyond original design limits, SPS applications are required to maintain power system security and reliability. Today, many transmission utilities prefer SPS deployment in order to resolve complex network problems and enhance system integrity. SPS survey studies [10] [11] [12] have shown that the implementation of these schemes has grown significantly as given in Table 2-2.

Table 2-2. SPS survey studies

1989 Survey		1996 Survey		2009 Survey	
Respondents	Schemes	Respondents	Schemes	Respondents	Schemes
18	93	49	111	110	958

SPSs are generally tailored for specific needs of utilities. In Hydro Quebec, remote load shedding system (RLSS) is a decent example. The main aim of this SPS is to preserve system frequency stability. The RLSS is triggered by extreme contingencies detection system which is responsible for monitoring 735 kV grid constantly. In case of a disturbance, amount of load shedding required to ensure system stability is calculated automatically and shed order sent to available distribution substations [13].

Bonneville Power Administration utilizes SPS in order to keep up system integrity in Pacific NW and California. This scheme works based on trip matrix approach in which pre-determined transfer trip signal is sent to substations and plants, namely load shedding, based on the place of the contingency. Moreover, it is supported with wide area measurements from PMU's in several locations. Hence, combination of response based and event based SPS system is implemented [14].

In BC Hydro, SPS deployment improves the system reliability and expands transmission infrastructure limits. In this scheme, transient stability assessment is performed in systematic intervals and suitable control actions such as load/generation shedding, line tripping etc. are orchestrated by SPS controller. This automatic system improves grid security and reliability significantly as it ensures system security in transient, voltage and frequency stability issues [15] [16].

There are several other utilities using SPS for problems ranging from single contingency protection to complete network stability assessment and protection. Figure 2-3 shows the system problems that can be addressed effectively and economically using SPS, and corresponding countermeasure to relief the system stress.

The composition of SPS applications generally includes measurement of some power system variables such as power, voltage, etc., that are related to the infrastructure to be protected. The overall simplified structure is shown in Figure 2-4.

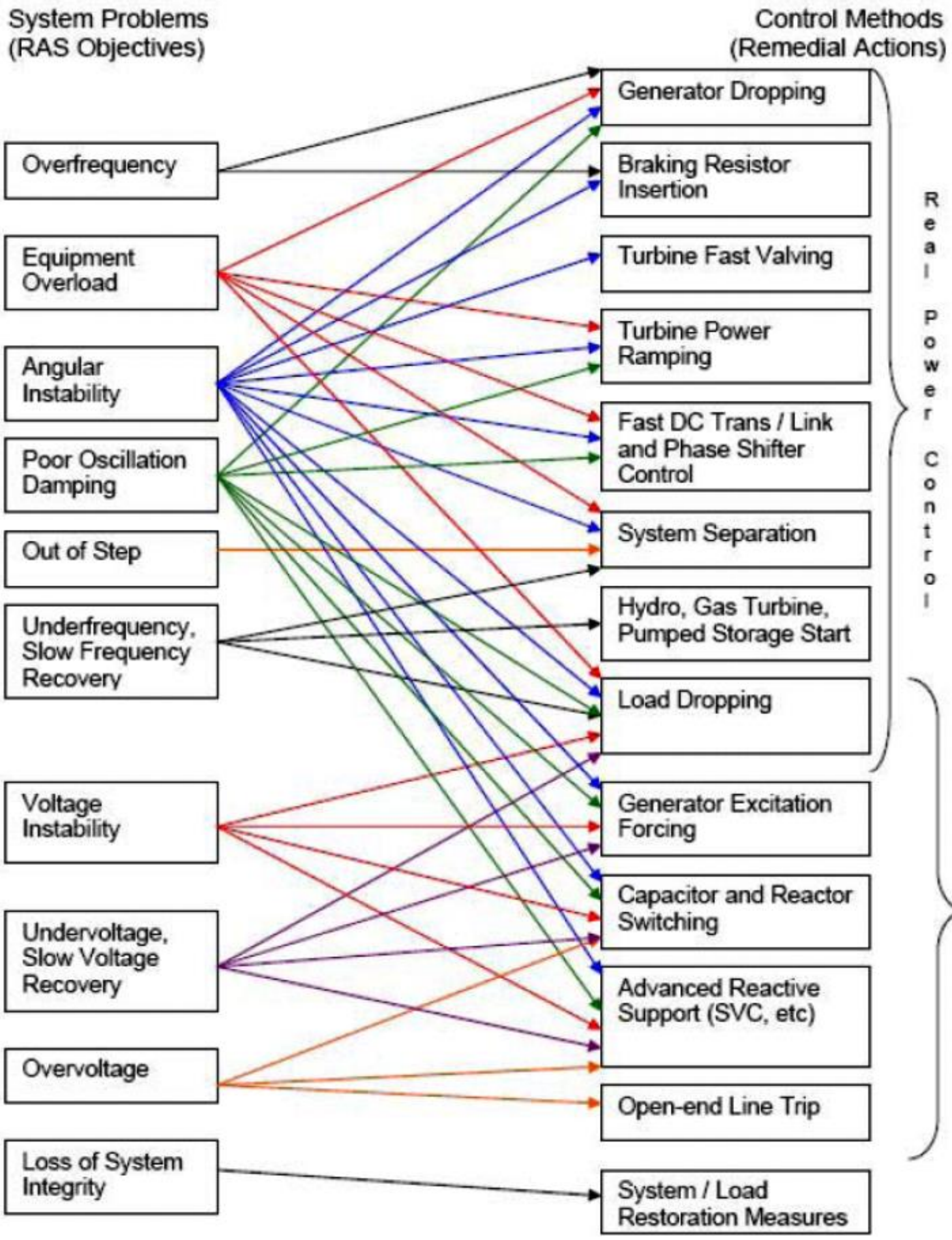


Figure 2-3. System problems and respective solutions utilized in SPS algorithms [2]

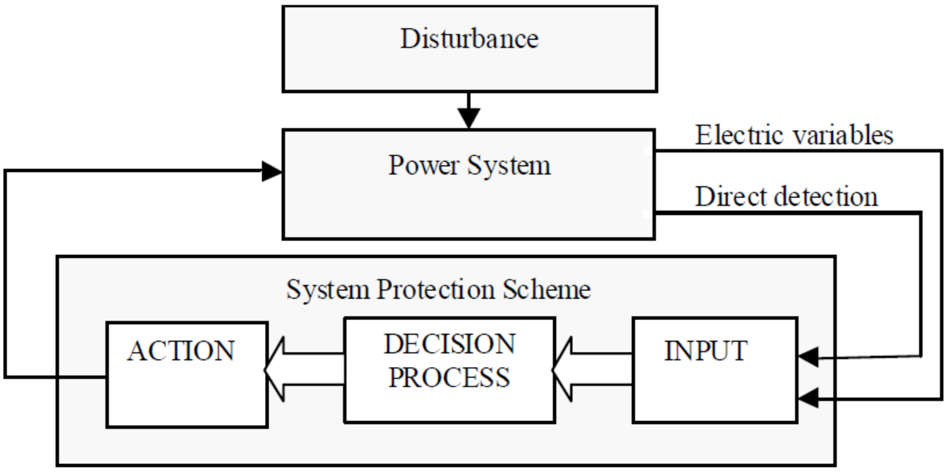


Figure 2-4. General structure of a special protection scheme [2]

2.4. Thesis Contribution

As defined in earlier chapters, requirements for intelligent protective devices to enhance power transmission capacity constitute the main motivation of this thesis study. Today, many power utilities successfully implemented these protection schemes in their grids both for capacity and security enhancement. As being a developing country, substantial growth in electricity demand may also lead other SPS installations in Turkish power system considering the slow pace of transmission investment realizations in Turkey.

The requirement for SPS stems from complex transmission problems; hence the design should be specifically tailored to fulfill these requirements. In other words, there is no on the shelf product that exists for SPS. Therefore, detailed engineering work is required to design such systems. One of the outcomes of this thesis is the development of such a new protection scheme in order to enhance security of Turkish electricity grid, thereby reduce the risk of black/brown out in congested areas via increasing the transmission capacity.

This study will also aim to develop valuable know-how in a relatively new subject for Turkish power system considering the current and future developments in the grid.

The design process involves several power system analyses that deeply investigate and examine the need for SPS in Turkish power system. In order to perform these studies, detailed regional grid model that includes static, dynamic and protection models of existing power system elements is formed. Analysis studies are then performed and requirements along with constraints are obtained.

In this perspective, a wide area measurement based special protection scheme is developed. The proposed scheme continuously monitors system variables and detects anomalies in the power system. In case of necessity, especially during abnormal conditions, the proposed scheme provides efficient countermeasures in order to prevent system security.

The scheme is based on synchronous regional system wide measurements via phase measurement units (PMU). Today, many modern power networks intend to implement PMU's in order to enhance observability in their grids. Such measurements clearly assist power utilities to understand the needs of their grids, hence increase power quality supplied to the customers. Therefore the proposed SPS is designed to utilize such PMU's in order to increase benefits. In addition, TEİAŞ has already developed and implemented a number of PMU's during National Power Quality Project. Utilization of such a domestic product is also a preferred choice in the SPS development which mutually increases the value of these products. Furthermore, considering the availability of such products and qualified engineering, it is evident that more advanced and sophisticated products can be developed. Hence, this study is thought to be a flat start for national EMS and desired to be improved in this manner.

CHAPTER 3

FUNCTIONAL REQUIREMENT ANALYSIS AND DESIGN OF WIDE AREA MEASUREMENT BASED SPS

In this chapter, grid modelling and scenario building is given for several power system analysis. After, static security analyses are conducted in order to investigate both weak points of the grid and related solutions regarding to this weak points. Further, power quality analyses are performed to identify whether HVDC operation is maintained under all grid conditions or not. This chapter also includes transient stability analysis of the network without SPS implementation which is the core of the design study. Transient stability studies indicate that the regional grid has the risk of instability even without any power import from Georgia. Finally, according to the analysis conducted, requirements of SPS are defined and step by step design process is introduced.

3.1. Analysis Scenarios and System Modelling

3.1.1. Scenario Determination

Almost every power system analysis study requires a certain degree of mathematical modelling process. Degree of the modelling is determined based on analysis requirements and application range in order to optimize the engineering work and time. Unfortunately, power system models require lots of engineering work and time since they are highly complex and considerably huge models. In SPS design study such an approach is utilized during the modelling and analysis process. In Turkey, grid planning scenarios are generally based on summer peak, winter peak and spring minimum loading conditions. Given the hydraulic conditions in the region during the spring and occurrence of recent Turkish annual peak loading in summer, the most important scenarios for Turkey in the sense of secure energy import form Georgia are envisaged to be determined by summer peak and spring minimum loading conditions. Depending on the network conditions as well as transmission line and substation investments, the analysis results of those two scenarios are assumed to provide upper and lower limits of secure power transfer from Georgia to Turkey. Given the expected in service time of the HVDC blocks is 2013 summer, the summer scenario is produced based on Summer 2013 loading conditions and the spring scenario is produced based on Spring 2014 loading conditions.

On the other hand, although generation dispatch schemes in these two scenarios are different due to the seasonal effects on water regime and loading conditions, further proliferation in generation dispatch schemes is required in order to examine all possible grid conditions that may be faced during grid operation. However, as the region includes more than 250 generators, generation dispatch schemes should be reduced to reasonable number in order to facilitate evaluation of results. Considering the effects of generation dispatch scheme in the sense of dynamic and static analyses, generation level is obviously the most important variable. In this perspective, it is wise to limit generation dispatch possibilities to the ones formed utilizing large scale generation facilities which are relatively higher effect in the analyses. This assumption reduces generation dispatch possibilities to the several combinations of generation levels for;

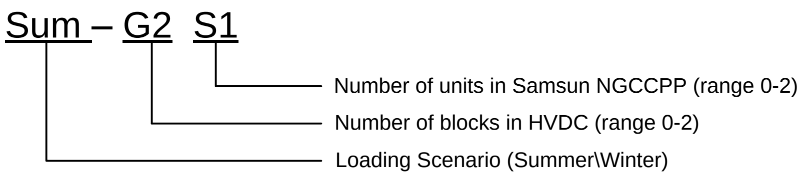
- HVDC B2B (2 x 350MW)
- Borçka HPP (2 x 150 MW)
- Deriner HPP (4x 167.5 MW)
- Samsun OMV NGCCPP (870 MW on two blocks)

Moreover, generation dispatch schemes can be further narrowed considering the dependency of hydraulic plants to the water regime which is affected by seasons. When the historical records for utilization factor of the regional hydraulic plants are investigated (which will be presented in Section 3.1.3.2 in detail), it is discovered that almost 60 - 70 % of large scale hydraulic power plants are dispatched during spring and summer loading conditions respectively. However, in order to be on the safe side, generation levels for Borçka and Deriner HPPs are set according the levels shown in Table 3-1. In the meantime, generation dispatch possibilities for Samsun NGCCPP are determined according to the summer and spring loading conditions. As given in Table 3-1, generation dispatch possibilities for Samsun NGCCPP in summer scenario are reduced to either fully dispatched or partially dispatched considering the high demand due to peak conditions. On the other hand, in spring scenarios, due to the low demand and the substantial hydraulic potential, it is assumed that Samsun NGCCPP is either partially dispatched or not dispatched. Finally, 3 power import scheme possibility for the HVDC is investigated considering the 2 block structure of the HVDC substation. As a result, total number of scenarios investigated in analysis is reduced to 12.

Table 3-1. Generation dispatch schemes considered in the analyses

Plant\Scenario	Summer Scenario	Spring Scenario
Borçka HPP	2 units (300 MW)	2 units (300 MW)
Deriner HPP	3 units (502 MW)	4 units (670 MW)
Samsun NGCCPP	1/2 blocks (435/870 MW)	0/1 blocks (0/435MW)
HVDC B2B	0/1/2 blocks (0/350/700 MW)	0/1/2 blocks (0/350/700 MW)

In the lights of the scenarios and generation dispatch schemes, the following naming convention is demonstrated in analysis results in order to ease the understanding.



3.1.2. Modelling Environment

Computer aided simulation and modelling tools are inevitable parts of the power system studies. These programs significantly reduce time and cost of the studies while offering great variety of analysis functions. There are 2 simulation programs used for modeling, namely;

- PSS\E, power system simulator program used for static load flow and SCMVA calculations
- Digsilent PF, power system simulator program used for dynamical studies and SPS modelling and analysis process.

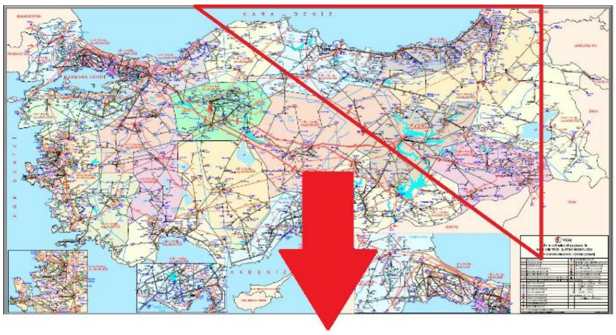
There exist several advantages and disadvantages between these two simulation programs in terms calculation and modeling capabilities, hence study benefit from utilizing two power system simulation programs.

Benefits of these tools can further be increased with the utilization of automatization codes. Using this computational power, required calculations can be conducted utilizing for loops which enable to study several scenarios within reasonable time and effort. For example, calculation of the transient stability for all branches in the region for several scenarios requires hundreds of calculations which requires considerable time and effort; however, it is important to analyze all possible conditions in SPS design analysis. Therefore automatization codes of these simulation programs, namely Python and DPL, are utilized in analysis studies.

3.1.3. Turkish Regional Grid Model

3.1.3.1. Region under Consideration

Through the analysis, the focus is given to the Black Sea and Eastern Anatolian Region of the Turkish grid given that the location of the connection is near Borçka SS. In other words, Northeastern part of the Turkish network is reduced from 400 kV Kurşunlu, Kayabaşı and Keban substations as shown in Figure 3-1. The single line diagram regarding the reduced region can also be found in Appendix A.



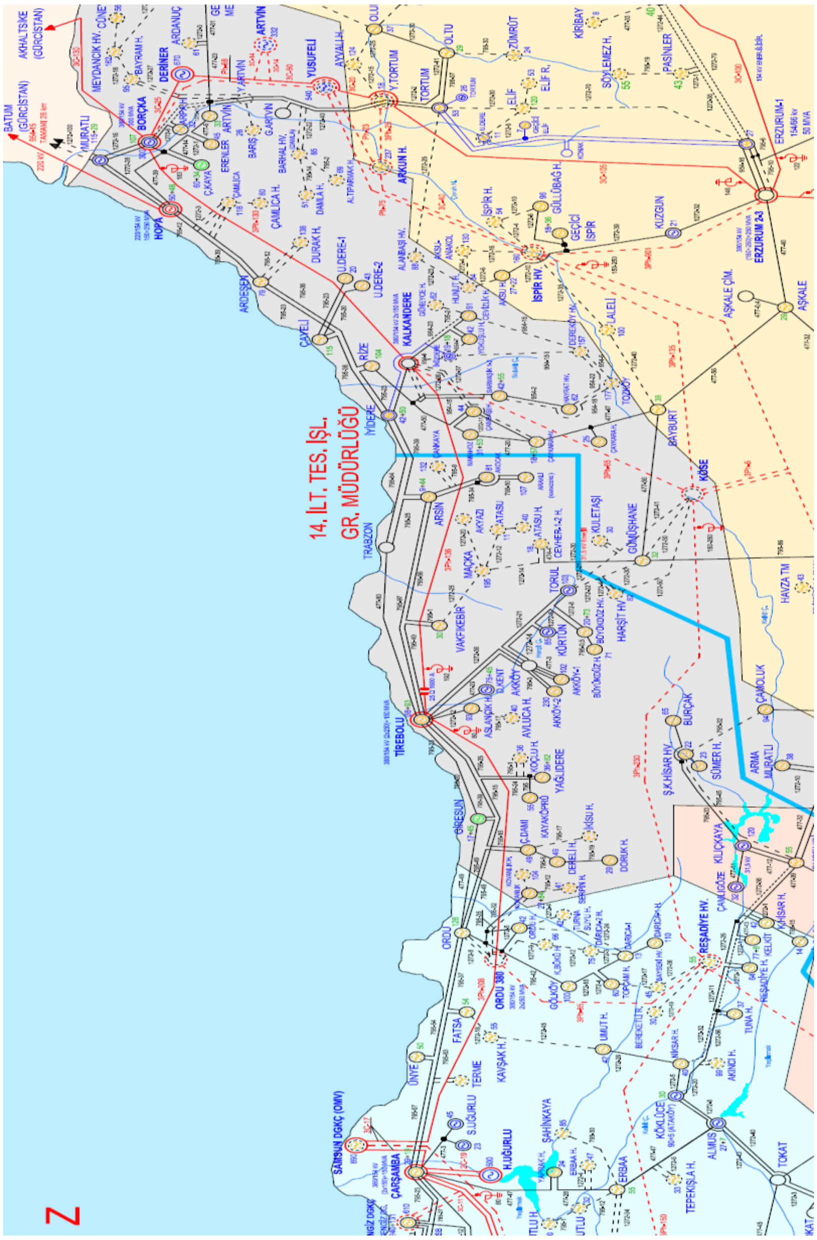


Figure 3-1. Electrification map of regional model used in design studies

3.1.3.2. Generation Profile in the Region

In Figure 3-2, the generating facilities (red circles) either in operation or construction or planned, together with the main load centers (yellow circles) and the expected main transmission routes in 2013 (black lines) related to the Georgia Interconnection, are illustrated. Given considerable amount of generation with respect to consumption of the region itself, it is essential that there is (and will be) a unidirectional power flow from the Black Sea Region to the load centers located in the Southeastern Anatolian Region, Ankara Region and the Marmara Region (Istanbul, Adapazari).

Figure 3-2: The basic transmission routes related to Georgia Interconnection (blue line: Muratli – Batumi line representation; red line: Borçka – Akhaltsikhe line representation, black lines: expected transmission highways in 2013, red circles: major generating facilities, yellow circles: major load centers).

Almost all the generators around the region are hydraulic type (many are run-of-river type), therefore, considering the water regime it is reasonable to assume that a considerable amount of generation is to be dispatched particularly during spring and initial summer periods, although dispatch of the generating units in Turkey is subjected to system security and electricity market conditions in Turkey. This assumption is further supported by historical records of generation among the region which is presented in TEİAŞ grid master plan generation scenarios report [17]. According to this report, the seasonal loading conditions of the generators in the region are summarized in Table 3-2. In addition expected growth in total small scale hydraulic electricity generation is given in Table 3-3.

Table 3-2. Utilization factor of regional generators

	Summer Scenario	**Spring Scenario**
Dam Type Hydraulic Generation (large scale HPPs)	70 %	60 %
Run of River Type Hydraulic Generation (small scale HPPs)	35 %	90 %
Other Generation Facilities	50 %	10 %

Table 3-3. Total foreseen small hydraulic generation capacity in the region [17]

Year	**Expected total small scale hydraulic electricity generation (installed) capacity**
2013	~4125 MW
2015	~5100 MW
2017	~6300 MW

3.1.3.3. Key transmission line and Substation Investments

Key transmission line and substation projects which are assumed to be completed by the corresponding years in sequence are summarized in Table 3-4. This table is based on TEİAŞ grid master plan [7].

Table 3-4. Key planned transmission system investments [7]

Realization Year	Investments
2013	Kalkandere 400 kV substation
2013	Borçka-Kalkandere 400 kV Tr. Line
2013	Kalkandere- Tirebolu Series Capacitor
2013	Borçka-Artvin and Artvin-Y. Tortum 154 kV double circuit Tr. Lines
2013	Agri-Van 400 kV Tr. Line
2014	Altınkaya-Boyabat 400 kV Tr. Line
2014	Arkun-Y. Tortum 400 kV Tr. lines
2014	Y. Tortum 400/154 kV. transformers
2014	Van-Siirt 400 kV Tr. Line
2014	Kayabaşı-Samsun NGCCPP 400 kV Tr. Line

Beyond these investments, interconnection project also includes AC transmission line investment between Borçka to Akhaltsikhe in order to complete interconnection between countries. The technical specifications regarding to this line are (see Figure 2-2);

- U_{base} = 400 kV
- Type and cross-section of conductor : 3B Cardinal 954 MCM
- Length = ~160 km effective length
- Rated current (thermal limit) = 3144 A
- Rated power (thermal limit) = 2178 MVA
- Series resistance = 0.0208 Ω/km per phase
- Series reactance = 0.266 Ω/km per phase (the line is assumed to be perfectly transposed)
- Charging susceptance = 4.31 μS/km per phase

3.1.4. Georgian Grid Model

Akhaltsikhe 500 kV SS and Batumi 220 kV SS are modeled as infinite buses to model Georgian Grid in the analysis (i.e., the security analysis are only performed for the Turkish transmission system). That is, both substations in Georgia are assumed to have a sufficient SCMVA to provide a secure power transfer from Georgian network to Turkey.

3.2. Static Security Analysis

In this chapter static security analysis results of regional Turkish grid model is introduced. These analyses consist of base case and n-1 contingency calculations in order to assess existing and expected constraints of regional grid. These calculations identify not only the constraints of the region but also give idea about reasons that cause element overloads and over/under voltages in region. In addition, solutions that are relaxing grid constraints are investigated.

Contingency analysis is an important part of the SPS design studies as the main aim of SPS is to maintain secure operation of the grid following a disturbance. For any contingency, SPS must know whether grid can withstand the related contingency or not in order to decide what action should be taken to prevent system from collapse. In addition analysis should show whether grid has any overloads or any critical voltage, angle values in case of such conditions. For this purpose contingency analysis should answer the effects and causes of any contingency in the system of interest.

3.2.1. Base Case and Contingency (n-1) Analysis

According to the Turkish grid regulations [18], Turkish power system must be designed to comply with the n-1 criterion, that is under normal operating conditions, any element of the grid should not be overloaded and grid should maintain secure operation in case of any contingency in the system. However, due to the undesired delays in transmission investments, element overloads can be observed in Turkish grid. These problems are solved in real time grid operation by re-dispatching of generating units. However, in this design study any possible constraint should be identified in order to design SPS system which ensures static security of the grid in all possible conditions.

Although element overloads have top priority and are most important indices in the assessment of static security, their evaluation is not sufficient to say that system is secure and stable. Especially in the case of long transmission lines, the angle difference between adjacent busbars is also an important and required index to evaluate static security. Where the transmission line length is above 320 km, which is the case for Turkish regional grid, transmission line limitation is due to small signal stability limit rather than its thermal limit as shown in Figure 3-3. Considering the substantial distance between Borçka and Keban (about 500 km), angle difference between these substations is also calculated in contingency analysis. Here, one may claim that these substations are not adjacent; nevertheless, busbars between these substations either are not connected or cannot capable of controlling voltage. Hence this angle difference is of importance in static security assessments.

There are also reported transmission line capacity degradation that exist in lines between Altınkaya, Kayabaşı and Çarşamba. This triangle is located in the end of the Borçka - Çarşamba 400 kV transmission corridor as shown in Figure 3-4. According to the information taken from TEİAŞ, transmission line capacity between Kayabaşı and Çarşamba is limited to 1100 MW (thermal limit is 1524 MW) due to the protection element constraints on that line. Hence the power flow on that line is also privately considered in calculations.

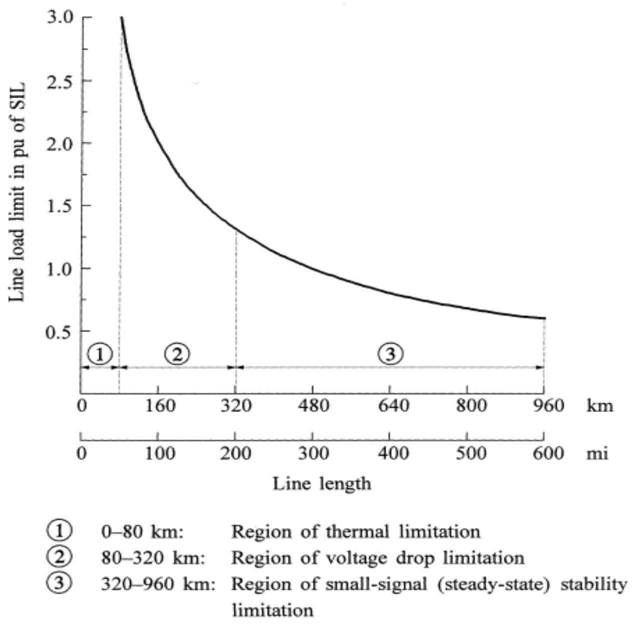


Figure 3-3. Transmission line loadability curve [19]

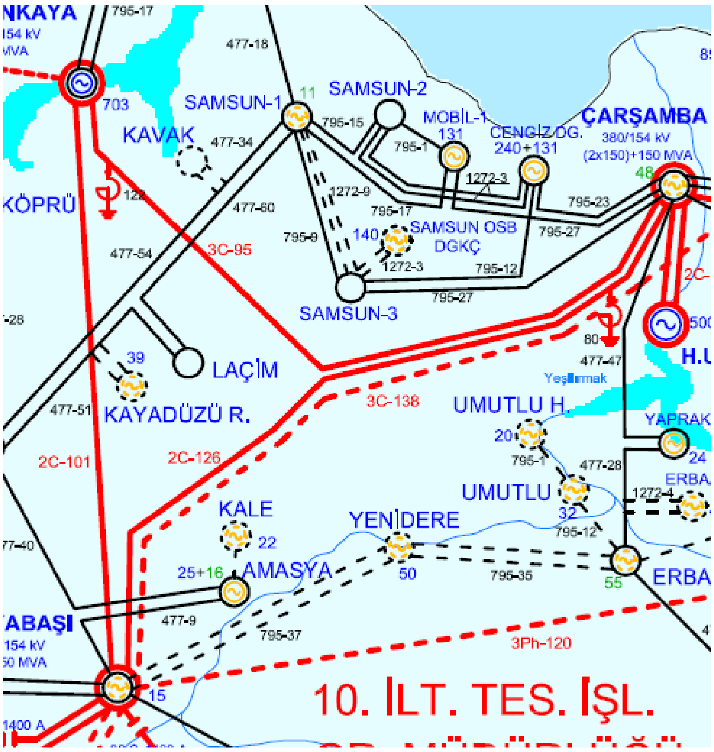


Figure 3-4. Kayabaşı – Altınkaya - Çarşamba 400 kV triangle

Under these considerations, n-1 analysis is performed for the grid model with the following assumptions;

- Dispatch of generating units in the region are adjusted according to TEİAŞ Master Plan [7].
- All existing and planned transmission lines for year 2103 are assumed to be in service.
- Since the grid model has more than 250 lines and 250 generators, contingencies are limited to 400 kV transmission line level which is 20 in total in the reduced model. The main problem of the region is the lack of sufficient transmission capacity, hence, generator outages are not considered as the loss of a generating unit relieves the system constraints.
- Although contingencies are limited to 400 kV transmission line level, 154 kV line loadings as a result of these contingencies are also considered since cascaded line opening possibility exists in 154 kV transmission lines.

In addition to the contingencies, 12 predefined solutions which are presented in Table 3-5 are also calculated for every contingency case in order to seek candidate solutions that may relive the overloading problems in the region that are originated by the related contingency. Utilization of this approach both illuminates the solutions that mitigate regional constraints and helps to envisage countermeasure alternatives which will be utilized in SPS design. Therefore, in the analysis, effects of the contingencies and predefined solutions are investigated in the same time following a defined check list type manner in order to obtain statistical results. As the number of contingencies is quiet high for manual calculation, an automated python code is developed to conduct contingency analysis. With this utilization;

- Calculation time is reduced.
- Results are shown in a compact way.
- Pre and post contingency values of selected elements can be seen easily.
- 20 contingencies and 12 predefined solutions for each scenario and each generation dispatch scheme are automatically calculated.

Table 3-5. Set of predefined solutions

		Generation Drop From				
Sol. Number	**Sol. Name**	**Altınkaya HPP**	**Borçka HPP**	**Deriner HPP**	**Samsun NGCCPP**	**HVDC**
0	Contigency	-	-	-	-	-
1	Sol. d1	-	-	1 unit (167 MW)	-	-
2	Sol. g1	-	-	-	-	1 block (350 MW)
3	Sol. g1d1	-	-	1 unit (167 MW)	-	1 block (350 MW)
4	Sol. g1d1b1	-	1 unit (150 MW)	1 unit (167 MW)	-	1 block (350 MW)
5	Sol. g2	-	-	-	-	1 blocks (700 MW)
6	Sol. g2d1	-	-	1 unit (167 MW)	-	1 blocks (700 MW)
7	Sol. g2d1b1	-	1 unit (150 MW)	1 unit (167 MW)	-	1 blocks (700 MW)
8	Sol. s1	-	-	-	1 block (435 MW)	-
9	Sol. s1a2	2 units (350 MW)	-	-	1 block (435 MW)	-
10	Sol. s1g1	-	-	-	1 block (435 MW)	1 block (350 MW)
11	Sol. s1g1a2	2 units (350 MW)	-	-	1 block (435 MW)	1 block (350 MW)
12	Sol. s1g2	-	-	-	1 block (435 MW)	1 blocks (700 MW)

The results of the python code for an example contingency condition are shown in Table 3-6. In this example case, transmission line between Borçka and Kalkandere is opened during 700 MW of power import from Georgia to Turkey. When the base case and contingency results are compared, it is clearly seen that power flow is directed to Borçka - Erzurum 400 kV corridor as the other corridor is assumed to be open. Although no overloads are observed in important 400 kV transmission lines, angle difference between Borçka to Keban is increased to 60 degrees which shows that this case is practically unacceptable. In addition, overloads in the 154 kV network are shown in Table 3-7. This table identifies that under contingency situations there are critical 154 kV transmission line overloads which may result in opening the line by overload protection relays.

The effects of the predefined solutions are also presented in Table 3-6. These calculations clearly show which predefined solution alternative is most likely to mitigate overloading problem in the regional grid after the contingency situation. As explained, these predefined solutions are developed in parallel with possible SPS countermeasures in order to give insight to SPS design. For the example case given, third solution (highlighted in green rectangle), which is dropping of a block from HVDC, is seem to resolve both angle difference and overload problems after the contingency that can be considered as stable in steady state sense; hence, this solution is accepted as possible countermeasure alternative for SPS in case of the corresponding contingency case. Utilizing this approach, the contingencies for different import conditions are examined and summarized in following sections.

Table 3-6. Example static security assessment table (contingency and predefined solutions)

Case											
ID	721111_723010_2	Borçka-Kalkandere									
	Georgia HVDC Power Transfer	700 MW									
Load Flow and Contingency Analysis Results											
Predefined Solutions >>			0	1	2	3	4	5	6	7	8
		Base Case	Contingency	Contingency + Solution d1	Contingency + Solution g1	Contingency + Solution g1d1	Contingency + Solution g1d1b1	Contingency + Solution g2d1	Contingency + Solution g2d1b1	Contingency + Solution s	Contingency + Solution sa2
Branch Flows (MW)	Borçka - Kalkandere	595.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Kalkandere - Tirebolu	559.4	220.2	189.9	155.8	125.7	97.8	90.5	60.2	31.9	254.1
	Tirebolu - Samsun	595.0	342.0	309.9	273.7	241.6	211.9	204.2	171.7	141.4	396.6
	Samsun - Çarşamba	1336.0	1088.3	1056.7	1021.0	989.3	959.9	952.3	920.1	890.0	632.5
	Çarşamba - Altınkaya	486.3	388.8	374.9	359.3	345.3	332.4	329.1	314.9	301.7	223.2
	Çarşamba - Kayabaşı	1004.3	871.2	852.3	830.9	811.9	794.1	789.6	770.1	751.9	644.8
	Altınkaya - Kayabaşı	896.5	800.0	786.3	770.8	757.0	744.2	741.0	726.9	713.8	639.6
	Borçka - Deriner	332.5	669.7	722.2	440.6	489.5	386.2	200.4	246.7	141.6	645.8
	Tortum - Erzurum	821.4	1148.3	1038.3	926.8	812.2	711.2	692.1	574.2	470.6	1125.4
	Erzurum - Agri	242.8	277.6	265.4	253.3	240.7	229.8	227.8	214.9	203.5	274.0
	Erzurum - Ozluce	561.1	764.8	686.2	603.6	519.9	444.6	429.2	341.7	263.5	732.8
	Ozluce - Keban	618.6	782.4	720.2	653.9	585.6	523.5	510.8	437.8	372.0	758.3
Angles (degree)	Borçka	71.2	88.4	80.5	71.7	64.0	56.9	55.1	47.5	40.4	80.1
	Samsun	50.2	45.7	43.5	41.1	38.8	36.7	36.2	33.8	31.6	33.0
	Çarşamba	47.1	43.2	41.1	38.8	36.5	34.5	34.0	31.7	29.5	31.5
	Deriner	70.4	86.7	78.7	70.6	62.8	56.0	54.6	46.8	40.0	78.5
	Erzurum	53.7	62.3	57.0	51.6	46.4	41.7	40.8	35.5	30.7	54.7
	Ozluce	41.7	44.8	41.8	38.5	35.3	32.4	31.7	28.3	25.3	38.2
	Keban	32.6	33.0	31.0	28.9	26.7	24.7	24.3	22.0	19.9	26.8
Angle Dif.	Borçka - Keban	38.6	55.3	49.5	42.8	37.3	32.2	30.8	25.5	20.5	53.3

Table 3-7. Example static security assessment table (line overloading)

Overloads Exist in Contingency Case

From Bus	Name	kV	Area	To Bus	Name	kV	Area	Ckt ID	loading (MW)	Rating	Loading (%)	Solution
712421	ADILCEVAZ	154.00*	71	713021	TATVAN	154	71	1	149,2	110	135,6	0
720021	ARDESEN	154.00*	72	720821	RIZE	154	72	1	217,7	153	142,3	0
720021	ARDESEN	154.00*	72	721421	CAYELI	154	72	1	199,6	153	130,4	0
720021	ARDESEN	154	72	724521	CAMLICA	154.00*	72	1	225,5	153	147,4	0
720021	ARDESEN	154	72	724521	CAMLICA	154.00*	72	2	225,5	153	147,4	0
720621	HOPA	154	72	721021	MURATLI	154.00*	72	1	247,9	206	120,4	0
720621	HOPA	154	72	721021	MURATLI	154.00*	72	3	247,9	206	120,4	0
720621	HOPA	154.00*	72	724521	CAMLICA	154	72	1	207	153	135,3	0
720621	HOPA	154.00*	72	724521	CAMLICA	154	72	2	207	153	135,3	0
720821	RIZE	154.00*	72	721221	IYIDERE	154	72	1	178,9	110	162,6	0
721110	4BORÇKA	380.00*	72	721121	BORÇKA	154	72	1	389,1	300	129,7	0
721221	IYIDERE	154	72	721421	CAYELI	154.00*	72	1	185,7	153	121,4	0
712421	ADILCEVAZ	154.00*	71	713021	TATVAN	154	71	1	138,9	110	126,2	1
720021	ARDESEN	154.00*	72	720821	RIZE	154	72	1	193,7	153	126,6	1
720021	ARDESEN	154.00*	72	721421	CAYELI	154	72	1	175,9	153	115	1
720021	ARDESEN	154	72	724521	CAMLICA	154.00*	72	1	201,6	153	131,7	1
720021	ARDESEN	154	72	724521	CAMLICA	154.00*	72	2	201,6	153	131,7	1
720621	HOPA	154.00*	72	724521	CAMLICA	154	72	1	183,8	153	120,1	1
720621	HOPA	154.00*	72	724521	CAMLICA	154	72	2	183,8	153	120,1	1
720821	RIZE	154.00*	72	721221	IYIDERE	154	72	1	153,8	110	139,8	1
721110	4BORÇKA	380.00*	72	721121	BORÇKA	154	72	1	334,1	300	111,4	1
712421	ADILCEVAZ	154.00*	71	713021	TATVAN	154	71	1	128,5	110	116,8	2
720021	ARDESEN	154	72	724521	CAMLICA	154.00*	72	1	176,1	153	115,1	2
720021	ARDESEN	154	72	724521	CAMLICA	154.00*	72	2	176,1	153	115,1	2
720821	RIZE	154.00*	72	721221	IYIDERE	154	72	1	127,9	110	116,3	2
712421	ADILCEVAZ	154.00*	71	713021	TATVAN	154	71	1	145,3	110	132,1	6
720021	ARDESEN	154.00*	72	720821	RIZE	154	72	1	227,7	153	148,8	6
720021	ARDESEN	154.00*	72	721421	CAYELI	154	72	1	213,2	153	139,4	6
720021	ARDESEN	154	72	724521	CAMLICA	154.00*	72	1	237,4	153	155,2	6

3.2.2. Summer Scenario Results

Static security assessment regarding summer scenario is given in Table 3-8. In the table, effects of contingencies for several generation dispatch schemes in summer scenario are colored in order to ease evaluation process. In this presentation examined cases are classified according to the effect of contingency on electricity transmission system security in the region. Color coding regarding to this examination is defined as follows;

- Cases marked with no convergence (red) indicate situations where solution for base case in this generation dispatch scheme can not be found. This does not mean that solution does not exists rather means that large generation re-dispatch is required.
- Cases marked with major 154 kV and 380 kV overloading (pink) indicate situations where lines operating in both voltage levels are overloaded more than 120 %.
- Cases marked with major 154 kV and minor 380 kV overloading (orange) indicate situations where lines operating in 154 kV voltage level are overloaded more than 120 % while lines operating in 380 kV voltage level are overloaded in the range of 100 - 120 %.
- Cases marked with major 154 kV overloading (yellow) indicate situations where lines operating in 154 kV voltage level are overloaded more than 120 %.
- Cases marked with major 154 kV overloading (green) indicate situations where lines operating in 154 kV voltage level are overloaded in the range of 100 – 120 %.

In addition to the color coding scheme, predefined solutions which are likely to mitigate the effect of the contingency are also presented. These solutions are based on predefined solution set which are indicated in earlier chapters (see Table 3-5). It is important to mention that solutions presented here is not optimized to any contingency and not necessarily mitigate the effect of particular contingency totally. These predefined solutions are based on possible countermeasures that may be utilized in SPS design. Therefore, investigating the comparative effects of presented solutions rather than their quantities is a much correct approach. It is also seen that in some cases, predefined solution effect is not applicable which are identified by ‘NA’. This mark does not mean that solution does not exist for this particular contingency case, rather this means predefined solutions is not effective for the particular contingency.

Results for summer scenario have shown that;

- There are element overloads exist even in the base case which should be resolved by new transmission investments.
- In case of any line loss in Altınkaya - Çarşamba - Kayabaşı 400 kV triangle, the load on the remaining lines in the triangle increases. In addition, overloading condition cannot be solved by generation shedding from Borçka region. Therefore, local solutions such as generation shedding from Altınkaya or Samsun NGCCPP should be considered. It is an important observation for the SPS design as the SPS countermeasure logic should include Çarşamba region generators.
- Most critical contingency in that scenario is the loss of line between Çarşamba and Samsun NGCCPP substations. In such a case power flow from Borçka-Çarşamba corridor is reversed. Hence, 154 kV grid close to Samsun NGCCPP is highly overloaded. As a result, predefined solution with higher generation shedding is observed.
- Loss of any line on Borçka - Erzurum corridor leads to overloading in both 154 kV grid in north to south plane. In order to resolve this problem predefined solution with higher generation shedding is observed. In addition, as can be seen from the color representation, remaining transmission corridors get much more overloaded parallel to the amount of import from Georgia.
- The effect of losing lines on Borçka - Çarşamba corridor is negligible. Similar conclusion can be made for contingencies after Erzurum substation.

Legend

No Convergence
Major 154 kV and Major 400 kV Overloading
Major 154 kV and Minor 400 kV Overloading
Major 154 kV Overloading
Minor 154 kV Overloading

Table 3-8. Transmission line overloading and predefined solution results for summer scenario

Case\Generation Dispatch Scheme	G0_S1	G1_S1	G2_S1	G0_S2	G1_S2	G2_S2
Altınkaya-Çarşamba	0	1	3	8	8	10
Altınkaya-Kayabaşı	8	9	11	9	NA	NA
Kayabaşı-Çarşamba	8	9	9	9	9	11
Çarşamba-Samsun NGCCPP	1	7	7	8	12	NA
Çarşamba-H.Uğurlu	0	0	0	0	0	1
Ordu-Tirebolu	0	0	2	0	0	2
Ordu-Samsun NGCCPP	0	0	2	0	0	2
Tirebolu- Tirebolu Series Cap.	0	0	2	0	0	1
Tirebolu Series Cap.-Kalkandere	0	0	2	0	0	1
Borçka-Kalkandere	0	0	1	0	0	1
Bocka-Deriner	0	0	0	0	0	2
Deriner-Artvin	0	4	4	1	6	6
Artvin-Yusufeli	0	4	4	1	6	6
Yusufeli-Tortum	0	4	4	1	6	6
Erzurum-Tortum	0	4	4	1	6	6
Erzurum-Özlüce	0	4	4	1	4	4
Erzurum-Horasan	0	0	0	0	0	1
Ağrı-Horasan	0	0	0	0	0	1
Ağrı-Van	0	0	0	0	0	1
Van-Başkale	0	0	0	0	0	1

3.2.3. Spring Scenario Results

Static security assessment regarding spring scenario is presented in Table 3-9. Results have shown that;

- The overall picture based on colored representation shows that the grid conditions get tougher in spring compared to summer.
- There are element overloads exist even in the base case which should be resolved by new transmission investments.
- In case of any line loss in Altınkaya – Çarşamba - Kayabaşı 400 kV triangle, the load on the remaining lines in the triangle increases. In addition, overloading condition cannot be solved by generation shedding from Borçka region. Therefore, local solutions such as generation shedding from Altınkaya or Samsun NGCCPP should be considered. It is an important observation for the SPS design as the SPS countermeasure logic should include Çarşamba region generators.
- Most critical contingency in that scenario is the loss of the line between Çarşamba and Samsun NGCCPP substations. As can be seen from the table, load flow solution cannot be attained for several loading conditions. For this contingency, power flow from Borçka - Çarşamba corridor is reversed. Hence, 154 kV grid close to Samsun NGCCPP is highly overloaded. No predefined solution seems to mitigate the effects of this contingency.
- Loss of any line on Borçka –Erzurum corridor leads to overloading in both 154 kV grid in north to south plane similar to the summer case.
- As the generation is higher in spring due to water regime in the region, 154 kV grid parallel to Borçka - Çarşamba corridor gets overloaded in case of losing any line on that corridor.
- Due to weak 154 kV network around Ağrı area, interruption of power flow from Erzurum to Van leads to overloading of lines in that area. The solution to this problem should be local as predefined solution proposals seem to be ineffective.

- 700 MW import from Georgia seems to infeasible as almost all contingency cases leads to major overloads in Turkish grid.

Legend

(red)	**No Convergence**
(pink)	**Major 154 kV and Major 400 kV Overloading**
(orange)	**Major 154 kV and Minor 400 kV Overloading**
(yellow)	**Major 154 kV Overloading**
(green)	**Minor 154 kV Overloading**

Table 3-9. Transmission line overloading and predefined solution results for spring scenario

Case\Generation Dispatch Scheme	G0_S0	G1_S0	G2_S0	G0_S1	G1_S1	G2_S1
Altınkaya-Çarşamba	8	12	12	NA	NA	NA
Altınkaya-Kayabaşı	8	9	11	NA	NA	NA
Kayabaşı-Çarşamba	7	7	9	8	9	11
Çarşamba-Samsun NGCCPP	NA	NA	NA	NA	NA	NA
Çarşamba-H.Uğurlu	0	0	0	0	4	4
Ordu-Tirebolu	7	7	7	7	7	7
Ordu-Samsun NGCCPP	7	7	7	7	7	7
Tirebolu- Tirebolu Series Cap.	0	0	2	0	0	2
Tirebolu Series Cap.-Kalkandere	0	0	2	0	0	2
Borçka-Kalkandere	0	0	1	0	0	1
Bocka-Deriner	0	0	1	0	5	5
Deriner-Artvin	0	3	4	7	7	7
Artvin-Yusufeli	0	3	4	7	7	7
Yusufeli-Tortum	0	3	4	7	7	7
Erzurum-Tortum	NA	NA	NA	NA	NA	NA
Erzurum-Özlüce	0	0	3	7	7	7
Erzurum-Horasan	NA	NA	NA	NA	NA	NA
Ağrı-Horasan	NA	NA	NA	NA	NA	NA
Ağrı-Van	NA	NA	NA	NA	NA	NA
Van-Başkale	NA	NA	NA	NA	NA	NA

3.3. Power Quality Analysis

3.3.1. HVDC Converter Station Configuration

The technical details of the AC and DC interface between two power systems at Akhaltsikhe substation are as listed below:

DC B2B Station (Structure of a Single Block: 350 MW transfer capacity):

Following information are based on either data that were provided by TEİAŞ or the assumptions (typical applications/parameters) utilized and notated by "*Assumptions*".

- Converter Transformer:
  Assumptions: (Georgian side 500 kV, Turkish side 400 kV (Yg)) / 45 kV (Y Δ), 420 MVA (U_k= 12 % at each winding) at Akhaltsikhe (Georgia) SS with on-load tap changing capability (at least 5 steps).
- Converter Blocks:
  - Twelve pulse configuration
  - Vdc_{rated} = 107 kV
  - I_{rated} =3271 A (=350 MW/107 kV)
  - DC line smoothing reactance: 2x50 mH
- Thyristor Valves:
  Assumptions: The thyristor valves to be utilized in the converter blocks are modeled with their system level equivalents, which includes the following assumptions:
  - No voltage drop on the thyristor valves (i.e., forward voltage = 0 V, both at the rectifier side and at the inverter side)
  - No switching losses in the converter

The basic configuration of the two six pulse bridges that comprise the twelve pulse converter is illustrated in Figure 3-5.

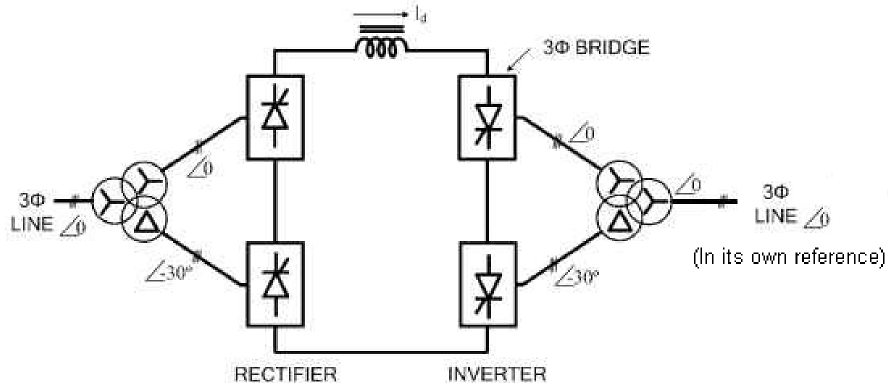


Figure 3-5: The topology of a 12 pulse B2B Substation

- Filter Blocks:

  Assumptions: 2 separate harmonic filter blocks (i.e., one for each 350 MW converter) are utilized in this study. Note that no additional power factor correction shunt capacitors are utilized. The technical details of the harmonic filters are given below:

  - 11th Harmonic Filter: Single tuned series RLC filter (band pass)
    - V_{rated} = 400 kV
    - f_{rated} = 50 Hz
    - Q_{rated} = 52.5 MVAr (for each 350 MW block)
    - f_0 = 550 Hz
    - Q (quality factor) = 300
  - 13th Harmonic Filter: Single tuned series RLC filter (band pass)
    - V_{rated} = 400 kV
    - f_{rated} = 50 Hz
    - Q_{rated} = 52.5 MVAr (for each 350 MW block)
    - f_0 = 650 Hz
    - Q (quality factor) = 100
  - 24th Harmonic Filter: High pass RLC filter

- V_{rated} = 400 kV
- f_{rated} = 50 Hz
- Q_{rated} = 52.5 MVAr (for each 350 MW block)
- f_0 = 1200 Hz
- Q (quality factor) = 3

The overall filter scheme for the harmonics is illustrated in Figure 3-6. For the sake of completeness, the determination of these filters are explained in harmonic analysis which is presented in Appendix - B.

- It has also been informed that that 3x60 MVA synchronous condensers are planned for installation in the 400 kV Akhaltsikhe swithchyard (Turkish Side). This information is approved by Georgian party although the corresponding details regarding synchronous condensers have not been provided.

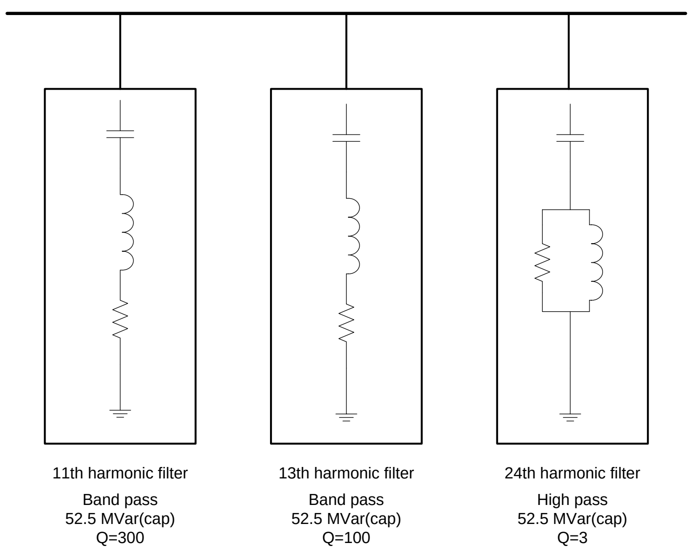


Figure 3-6. Filter scheme in the substation

Although the B2B converter enables bilateral transfer of power between both sides, since it is expected that Turkish side will generally be the importing side, the inverter side of the B2B station is assumed to be Turkey, whereas the rectifier side is assumed to be Georgia throughout the analysis.

The most crucial parameter that determines the capability of the grid to handle conventional line frequency commutated B2B stations is the strength of the AC system, which is related to the equivalent Thevenin impedance of the grid. HVDC interfaces at the weak points of AC systems may result in problems such as harmonic resonance, instability and frequent commutation failures [20].

Effective Short Circuit Ratio (ESCR) is an index for evaluating some of the complex and variable interactions between AC and DC systems, which is calculated according to the below formula:

$$ESCR = \frac{SCMVA_{grid} - S_{filter}}{P_{dc}}$$

A figure of merit for the healthy operation of conventional line frequency commuted HVDC interfaces is ESCR ≥ 2.5 [20]**.** Hence, in the following section, the feasibility of power transfer via HVDC B2B substation located at Akhaltsikhe will be analyzed for different grid topologies for the Turkish grid based on this criterion will be discussed.

3.3.2. ESCR Calculation

The maximum value of SCMVA at Borçka is expected to be 7590 MVA (in case of all expected generating units are in operation, without the synchronous condensers at Akhaltsikhe). Therefore, considering also the transmission line between Borçka and Akhaltsikhe, the maximum value of SCMVA at Akhaltsikhe end of the line is reduced to

2338 MVA due to 160 km single circuit overhead line between Borçka and Akhaltsikhe and the effect of short circuit location. However, the synchronous condensers increase the SCMVA by 610 MVA.

In addition, the harmonic filters generally produce a total reactive power at an amount of 60% of the rated DC power, which means:

11^{th} harmonic filters = 2x52.5 MVAr

13^{th} harmonic filters = 2x52.5 MVAr

24^{th} harmonic filters = 2x52.5 MVAr

Therefore, the amount of safe power transfer which will avoid dynamical over voltages (DOV) and frequent commutation failures is calculated as:

$$P_{dc\,safe} = \frac{SCMVA_{grid} - S_{filter}}{ESCR_{safe}} \approx \ 1040\ \text{MW}$$

In addition, possible grid topologies in both summer and spring scenarios that affect the SCMVA at Akhaltsikhe busbar are also considered in ESCR calculations. For this purpose, worst grid topologies that may be encountered during grid operation in the sense of influence on SCMVA at Akhaltsikhe busbar are checked. According to the results, minimum safe power transfer is found as 795 MW which is higher than HVDC capacity which 700 MW. Therefore, it is concluded that required SCMVA power for secure operation of HVDC is supplied in all conditions. As a result, no commutation failure is expected in HVDC operation.

Table 3-10. SCMVA calculations for possible grid topologies for each scenario

SCMVA at Akhaltsikhe Substation				
Grid Condition\Scenario	Summer Scenario		Spring Scenario	
	SCMVA	**P DC Safe**	**SCMVA**	**P DC Safe**
Base Case	2951	1040	3180	1132
Borçka- Kalkandere line is out of service	2677	930	2842	997
Borçka-Deriner line is out of service	2482	852	2837	995
Borçka HPP is out of service	2868	1007	3131	1112
Deriner HPP is out of service	2729	951	3029	1071
Synchronous Condenser is out of service	2338	795	2568	887
*350 Mvar filter is assumed to be connected at Akhaltsikhe SS				

3.4. Transient Stability Analysis

3.4.1. Introduction

The objective of the transient stability study is to investigate the load angle stability of the system elements after being subjected to a large disturbance. More specifically, this analysis focuses on transient changes in the rotor angles of interconnected synchronous machines of the power system. It investigates the synchronism whenever disturbance caused forces accelerate one or more machines with respect to the coherent machine group.

In order to better describe the behavior of a machine, it is wise to review the elementary principles of the rotor dynamics. The equation of motion of the machine rotor is given by

$$J\frac{d^2\theta}{dt^2} = T_m - T_e = T_a \ (N.m) \tag{3.1}$$

where

J = total moment of inertia of the rotor mass in kgm^2

θ = angular position of rotor in rad

T_m = mechanical torque supplied by the prime mover in N-m

T_e = electrical torque output of the alternator in N-m

T_a = net accelerating torque on rotor in N-m

Under steady state operation, T_m and T_e are equal; hence, there is no accelerating torque which increases or decreases the rotor mass. Under this condition, speed of the generator rotor is constant and equal to the synchronous speed of the system.

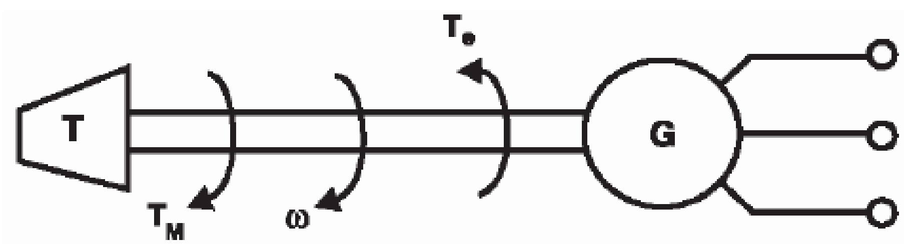


Figure 3-7. Mechanical and electrical torques on the turbine shaft

When angular position of the rotor is represented in the synchronously rotating frame and the power-torque relation is used, Equation 3.1 can further be manipulated to the well-known Swing equation (3.2), which is the fundamental differential equation used in stability analysis.

$$2\frac{H}{w_s}\frac{d^2\delta}{dt^2} = P_m - P_e = P_a\ (p.u) \qquad (3.2)$$

where;

H = inertia constant of the machine in MWsec/MVA

w_s = synchronous speed in rad/sec

w = rotor magnetic field frequency in rad/sec

δ = load angle in rad

P_m = mechanical power input in p.u.

P_e = Electrical power crossing the air-gap in p.u.

P_a = Accelerating power in p.u.

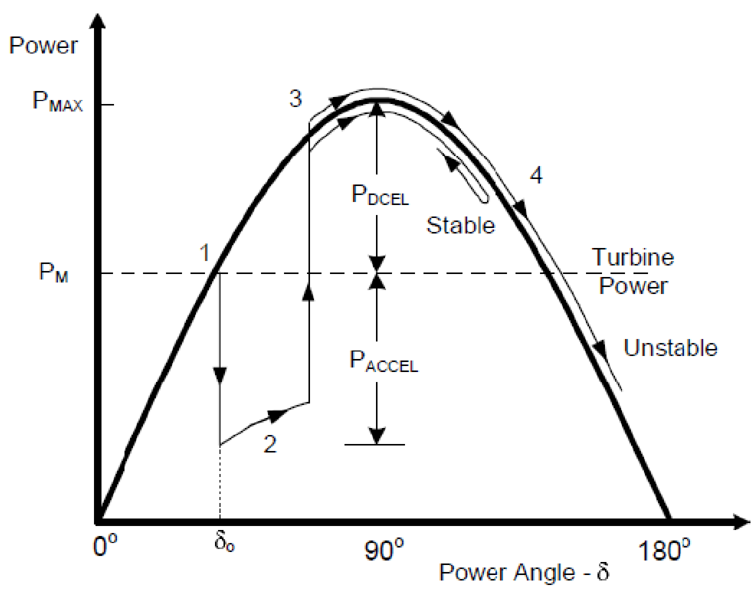


Figure 3-8. Power angle curve illustrating transient stability [21]

The behavior of the machine following a disturbance is depicted by the thin line in Figure 3-8. Initially, machine is operating in steady state where its mechanical power is equal to the electrical power and the corresponding machine angle is δ_0. As the fault occurs, operating point suddenly changes from 1 to 2 due to the change in electrical power output of the machine. However, due to the machine inertia, mechanical power, hence the load angle, does not change instantly. Therefore, the difference between mechanical and electrical power is stored as the kinetic energy in the machine which results in acceleration of the rotor. Due to the acceleration, the load angle starts to increase until fault clearance. When fault is cleared, the electrical power is restored and operating point suddenly jumps to the point 3 assuming that the system reactance is not changed during disturbance. In other words, system returns to its initial power-angle characteristics after the fault clearance. Nevertheless, restored electrical power is larger than the mechanical power which reverses the acceleration to deceleration. Although rotor starts to decelerate, rotor speed is still greater than the system speed. Therefore, load angle continues to increase until stored kinetic energy transferred to the system which is shown as movement through point 3 to 4. If sufficient retarding torque (i.e., P_m-P_e) exists, load angle decreases and the machine eventually returns to its initial operating point. In that case, machine is assessed as transiently stable.

Generally, power-angle curve of the machine changes according to the change in system reactance after a severe disturbance. Therefore, equal area criterion is utilized to assess the transient stability. This criterion is based on energy transfer between the machine and the system during acceleration and deceleration. The energy can be calculated as;

$$E_1 = \int_{\delta_0}^{\delta_{fc}} (P_m - P_e) d\delta = Acceleration\ Energy = Area\ 1 \qquad (3.3)$$

$$E_2 = \int_{\delta_{fc}}^{\delta_{max}} (P_e - P_m) d\delta = Deceleration\ Energy = Area\ 2 \qquad (3.4)$$

In order to ensure that the unit remains in synchronism, deceleration energy should be greater than the acceleration energy. Critical clearing angle is defined as the maximum fault clearing angle which satisfies the equal area criterion at the boundary (i.e., $E_1 = E_2$). In the same manner, critical clearing time is defined as the time corresponding to reach critical clearing angle. These definitions are illustrated in Figure 3-9.

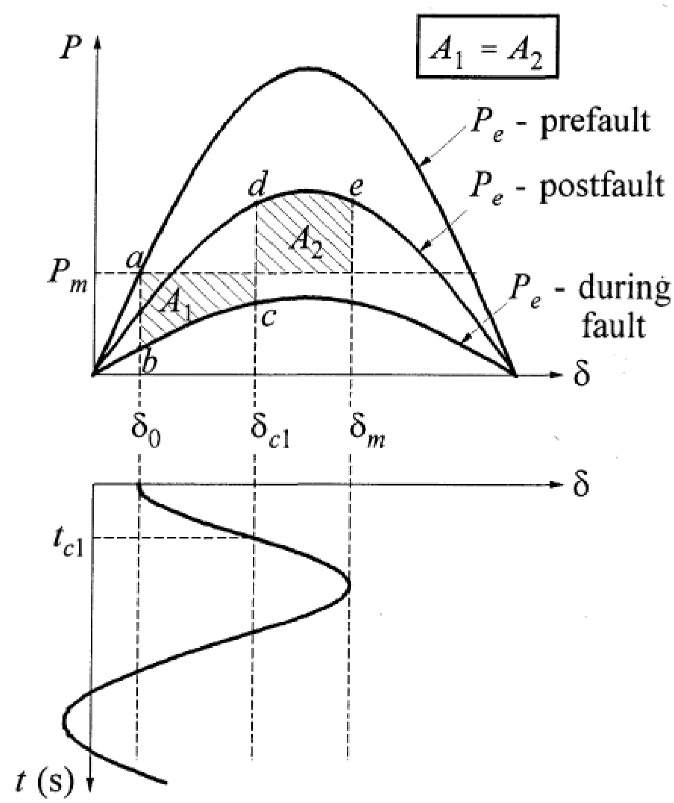


Figure 3-9. Transient stability phenomenon [19]

As SPSs are designed to secure system operation in case of a fault, transient stability studies constitute the core of the SPS design. In order to design such a protection system, the designer should be aware of;

- Under which conditions should the system operate?
- What is the maximum operation time?
- How to determine countermeasures?
- What will be the resultant system after SPS operation?

The answers regarding to these questions are all revealed after the transient stability analysis. Therefore, detailed transient stability studies with correct modelling approach and reasonable number of analysis cases are required. These subjects are all covered in the following sections.

3.4.2. Regional Grid Dynamical Model

Transient stability analysis requires computation of large set of differential and algebraic equations in order to represent nonlinear dynamic behavior of the power system elements. As the severe disturbances are of interest, linearization is not possible and detailed representation of the power system elements is necessary. Figure 3-10 shows the overall picture of required models for transient stability analysis.

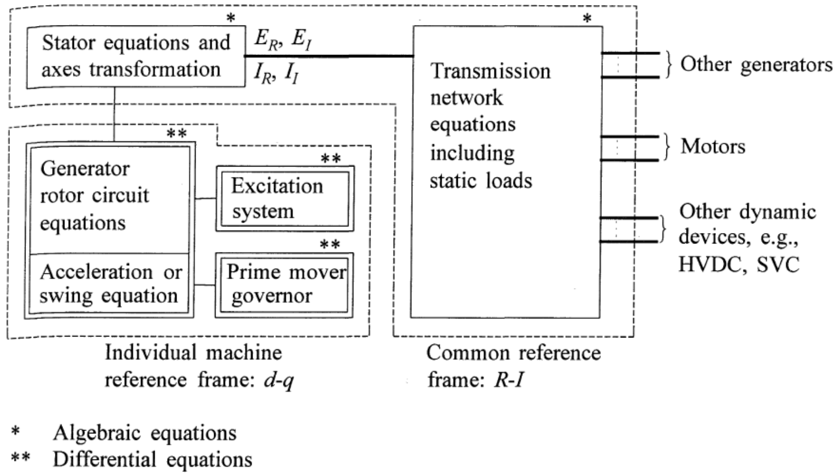


Figure 3-10. Power system model for transient stability analysis [19]

3.4.2.1. Synchronous Machine Models

Rotor dynamics and electrical circuits have significant effect on the synchronous machine behavior in the transient stability. Hence, dynamic models of the generators utilized in this analysis are capable to represent subtransient, transient and steady state behavior of the synchronous machines. The equations regarding to the synchronous machines can be derived for all states utilizing the dq model with reasonable assumptions.

During the steady state operation, field winding and damper winding currents are constant which effectively means that the dq axis voltages are solely dependent to the direct and quadrature axis reactances. The governing equations can be written as

$$v_d = -R_d i_d - X_q i_q \tag{3.5}$$

$$v_q = -R_q i_q - X_d i_d + wkM_f i_f \tag{3.6}$$

In the transient state, as the damper winding currents have decayed, effect of damper windings can be neglected. However, opposing currents are induced on the field winding which can be modeled by short circuiting field winding and setting its resistance to zero. This effectively represents the current changes occurring in the field winding in order to maintain flux linkage of this winding constant [22]. Synchronous inductances and impedances in the transient state are given in (3.7) - (3.12)

$$L_d' = L_d - L_{fd}^2 / L_f \tag{3.7}$$

$$X_d' = wL_d' \tag{3.8}$$

$$L_q' = L_q \quad for\ salient\ pole\ machines \tag{3.9}$$

$$L_q' = L_q - L_{fq}^2 / L_f \quad for\ round\ rotor \tag{3.10}$$

$$X_q' = wL_q' \tag{3.12}$$

Moreover, related time constants that represent the decay of induced currents are

$$T_{do}' = L_f / R_f \tag{3.13}$$

$$T_d' = (L_f - \frac{L_{fd}^2}{L_d}) \frac{1}{R_f} = T_{do}' \frac{L_d'}{L_d} \tag{3.14}$$

In this regard, voltage equations governing the transient behavior can be written as

$$v_d = -R_d i_d - X_q{}' i_q \tag{3.15}$$

$$v_q = -R_q i_q - X_d' i_d + e_q{}' \tag{3.16}$$

$$v_f = \dot{\psi}_f + \frac{R_f}{L_f}\psi_f - R_f \frac{kM_f}{L_f} i_d \tag{3.17}$$

$$e_q{}' = \frac{kM_f}{L_f} i_d \tag{3.18}$$

During the subtransient state, opposing currents are induced in damper windings while no current is induced in the field winding during this small time period. However, due to small time constants of damper windings, subtransient currents quickly decay. The equations governing the subtransient state are as given in (3.19) - (3.21)

$$v_d = -R_d i_d - X_q'' i_q + e_d{}'' \tag{3.19}$$

$$v_q = -R_q i_q - X_d' i_d + e_q{}'' \tag{3.20}$$

where

$$e_q'' = w\left(\left(\frac{kM_f L_D - kM_D L_{fD}}{L_f L_D - L_{fD}^2}\right)\psi_f - \left(\frac{kM_D L_f - kM_f L_{fD}}{L_f L_D - L_{fD}^2}\right)\psi_D\right) \tag{3.21}$$

Further manipulation of equations (3.5) - (3.21) and addition of the swing equation will lead to a 6th order machine model which is utilized in this study. This model is commonly utilized in the transient stability analysis due to its accuracy to represent actual synchronous machine dynamics. Hence, 6th order machine models are used in large scale generation facilities in the regional model.

In addition, 2nd order classical machine model is also utilized for relatively small sized power plants in the region in order to simplify both data preparation and analysis for transient stability analysis. 2nd order machine models are commonly used for generators far from area of interest [22]. In a similar manner, due to their negligible effects in the analysis, small sized power plants are modeled in reduced order. Governing equations regarding classical generator model is given in (3.22) - (3.24).

$$M\Delta\dot{w} = P_m - P_e - D\Delta w \tag{3.22}$$

$$\dot{\delta} = \Delta w \tag{3.23}$$

$$V = E - jX_d{}'I \tag{3.24}$$

3.4.2.2. Excitation System Models

Representation of field dynamics and excitation system is another essential topic in transient stability analysis [23]. Excitation systems are aiding the transient stability of the machine by boosting the machine voltage during transients. This action exerts a restraining torque on the rotor; hence, decreases initial rotor angle swing.

Although there are different excitation systems that exist in practice, most of the modern excitation systems are static exciters. Hence, models of this type of exciters are utilized in transient stability studies. Similar to machine modeling approach, excitation system modeling is limited to large scale power plants in the region, considering quality and simplicity of analysis. For this purpose, dynamical models of the regional plants are obtained from TEİAŞ. An example excitation model used is given in Figure 3-11.

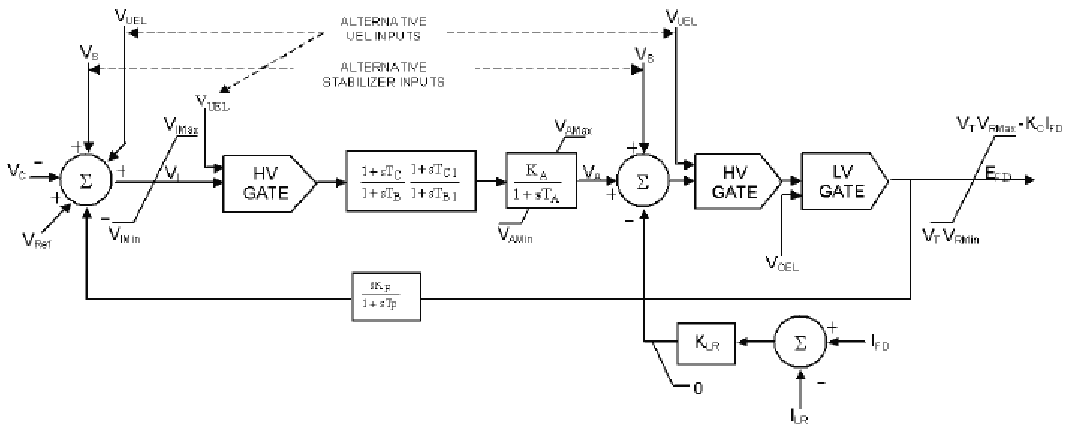


Figure 3-11. IEEE Type ST1A excitation system model [24]

3.4.3. Grid Protection Model

Being one of the essential part of the power systems, protection systems ensure secure and continuous operation of the grid. The devices under protection system continuously monitor system variables such as current, voltage, etc. in order to detect any abnormal condition in the power system. In case of an abnormal condition such as a fault, these devices disconnect problematic elements from the rest of the power system in order to preserve both malfunctioning element and the rest of the power grid.

There are several protection equipment exist in a power system depending on protected element and protection purpose. For example transmission lines are protected via overcurrent and distance relays while generators are protected via more than ten different types of relays.

Modelling the protection system in transient stability analysis is not a common practice; however, due to lack of n-1 security in the region, even transiently stable conditions may end up with overloads in grid elements that may lead to cascaded operation of protection elements. As a result, transiently stable condition may undergo instability which should also be taken into consideration in SPS design. Possibility of such situation is especially higher in 154 kV network due to weak transmission lines in the region. In order to examine secure operation of grid, overcurrent protection relays in 154 kV transmission lines are modeled in this study.

This approach is beyond the time frame of interest of transient stability analysis. Nonetheless, any possibility of instability should be investigated in SPS design as these systems are responsible for securing power system operation at all conditions.

In this regard, 154 kV overcurrent protection in transmission lines are implemented based on actual protection device settings taken from TEİAŞ. However, as the regional system under consideration is extremely large, abundant number of protective devices exist in great variety. In order to ease protection modeling process, common overcurrent relay model is utilized for whole 154 kV grid. Moreover, examination of protection settings has shown that pickup current and time setting are very similar through the region. Therefore, all protection relays in 154 kV network are adjusted to the same setting, that is, relays are adjusted so as to open at 1.3 times of nominal capacity if overloading observed for at least 5 seconds period. Inverse time protection setting is shown in Figure 3-12. In addition, according to the information obtained from TEİAŞ, all protection devices have power swing detection functionality which means that undesired operation in power swings after fault clearance is not expected.

It should also be noted that similar to the actual case, this modeling is limited with 154 kV network since loadings in 400 kV network in the region are far from their respective protection settings.

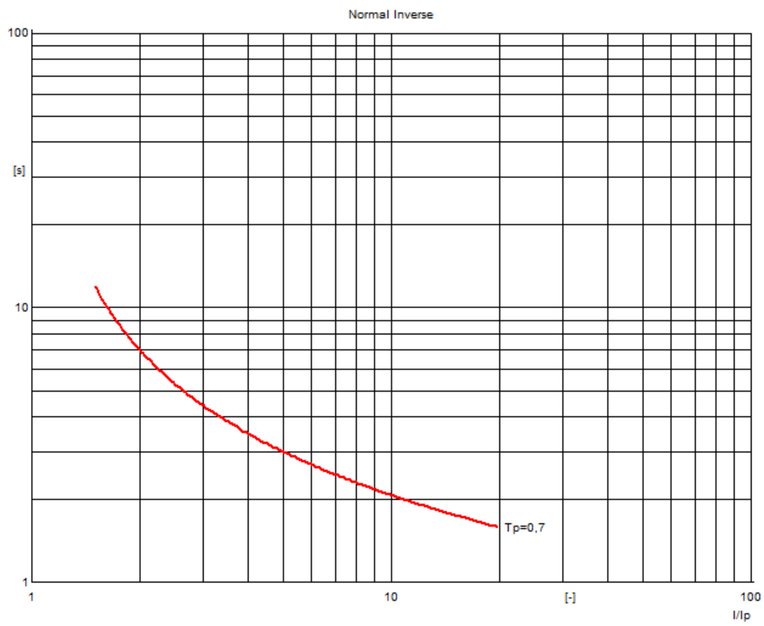


Figure 3-12. Time-current characteristic of applied protection setting

3.4.4. Dynamical model of HVDC B2B

The de facto control philosophy of HVDC B2B stations is as follows [1]:

- The inverter side controls the DC bus voltage (on D-F line in Figure 3-13)
- The rectifier side controls the DC bus current (on B-C line in Figure 3-13)
- The normal operating point of HVDC B2B convertor is shown in point E in Figure 3-13
- Controller structures of the bridge convertors are of discrete PI type (together with limiters and mode selection logic, etc.)

However, accurate modelling of the controller may not be possible due to their complexity and non-standard design. As the actual design of HVDC to be built on Georgia-Turkey interconnection cannot be obtained, several literature models are examined in order to obtain at least a generic HVDC controller structure in order to assess its transient stability behavior. PSSE library includes several HVDC models that can be utilized. Among these models, CDC4T model is selected due to its capability to represent transient behavior of an HVDC (blocking, commutation, etc.) along with steady state control.

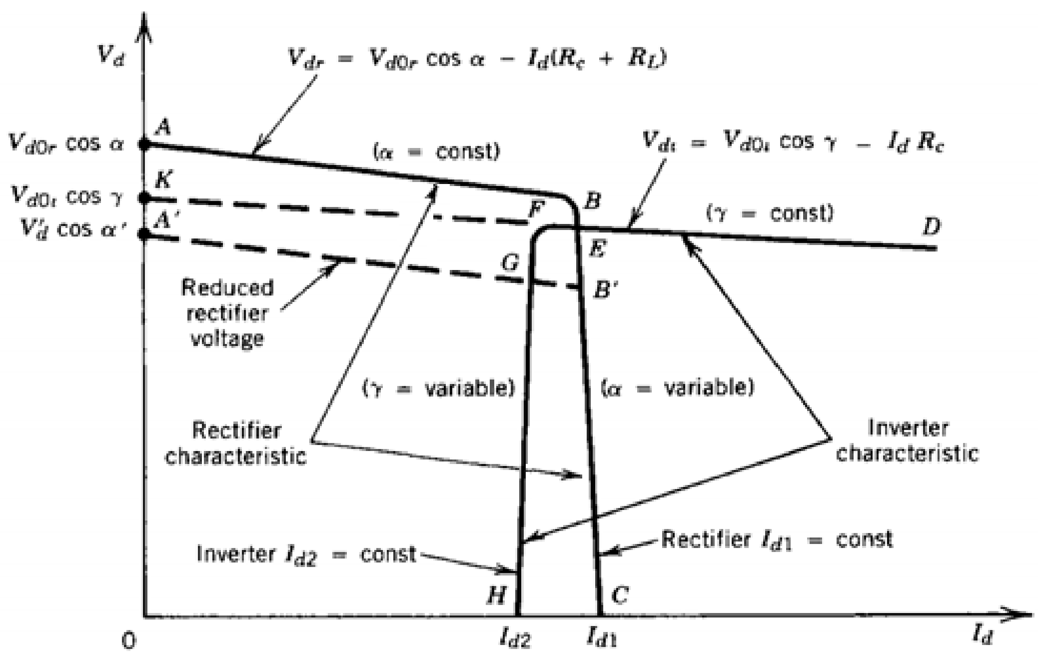


Figure 3-13. Operating curves of B2B convertor stations [1]

Transient stability investigation of this generic model is shown in Figure 3-14. In this pre-examination of the model, a three phase short circuit fault close to the HVDC block is simulated. In the simulation, a fault at t=5 sec is applied and is cleared after 150 msec, considering that the protective device operates in 150 msec period. This simulation has shown that, during short circuit, HVDC blocks power transfer (represented as red line in figure) and return quickly to the service with a fast ramp rate when the fault is cleared. The response obtained in this simulation is similar to the behavior of the HVDC control during transient state which is explained in Figure 3-15 in detail.

As it is seen from both figures, transient response of HVDC is highly related to its controller settings (blocking time, ramp rate etc.). Considering the lack of knowledge regarding to the HVDC control scheme and dynamic model, it can be assumed that this generic model can be utilized in studies. In addition, in order to be on the safe side, blocking time is assumed to be equal to the fault clearing time and reestablishment of power injection is assumed to be immediate (i.e., infinite ramp rate). That is, HVDC acts as a constant power injection point. Under these circumstances, the transient behavior of HVDC is very similar with the behavior of a constant power load whose behavior to the same fault case simulation as in HVDC B2B is given in Figure 3-16.

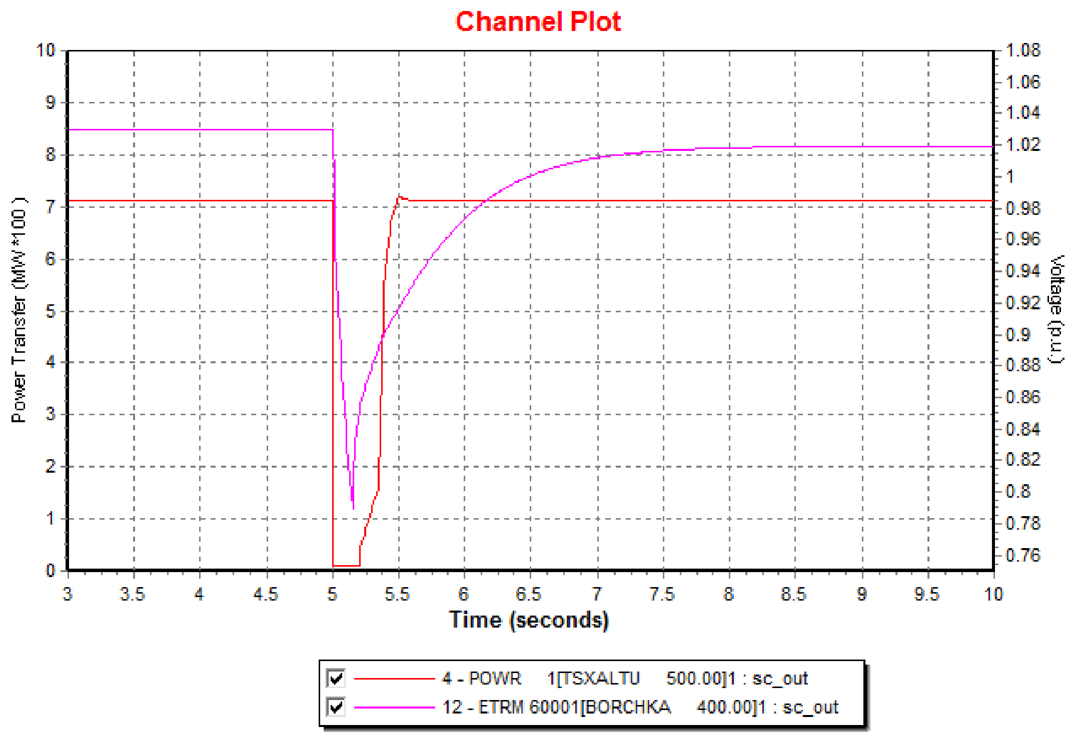


Figure 3-14. Transient response of the simulated generic HVDC model

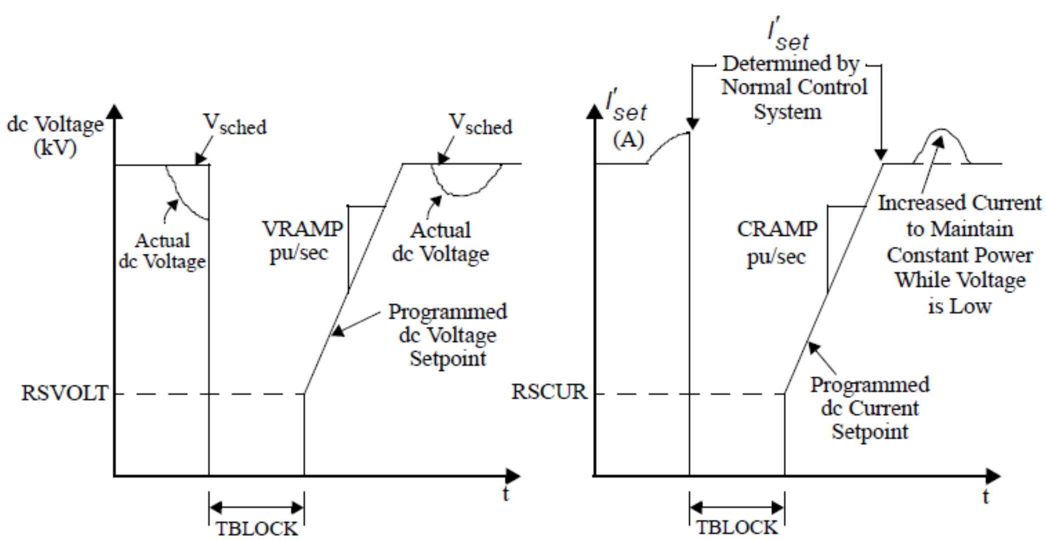


Figure 3-15. Behaviour of the HVDC B2B model during transient

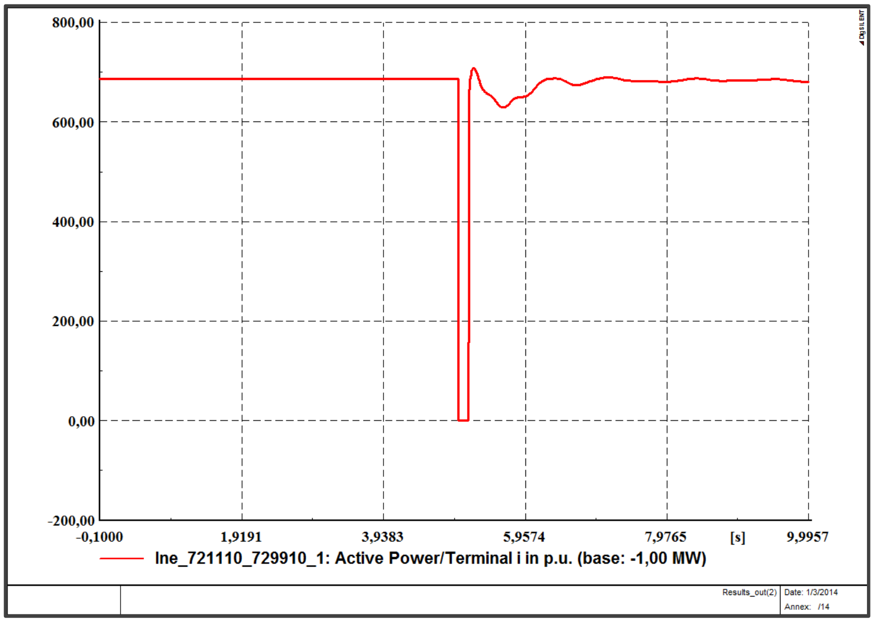


Figure 3-16. Transient behavior of constant power load model

Comparison of Figure 3-14 and Figure 3-16 shows that the dynamic behavior of HVDC can be approximated as a constant power load. Due to the lack of voltage control, small oscillations after the fault clearance is observed in active power output of the constant power load. However, these small oscillations can be neglected as the effect of these oscillations in a regional system is negligible. In that respect, HVDC model can be simplified as a negative constant power load through the analysis assuming that no commutation failure occurs. As explained in the power quality section, adequate short circuit MVA is supplied to HVDC in all conditions, therefore commutation failure risk due to Turkish grid is not expected. Hence, negative constant power load modeling approach is feasible and utilized through the transient stability analysis.

3.4.5. Transient Stability Assessment of Regional Model

3.4.5.1. Cases Considered

As explained, the backbone of the region consists of two main 400 kV transmission corridors that are connecting regional electricity production to the demand centers. These two 400 kV transmission corridors form a giant ring in the region which covers 21 busses at 400 kV level, some of which have 154 kV connections.

Considering the distributed small scale hydraulic generation in the region which are connected through 154/400 kV substations, it is evaluated that the effect of disturbance in different locations on the 400 kV ring definitely affects transient stability calculations. Therefore, for the sake of completeness, transient stability analysis is conducted at each line segment connecting these 400 kV substations. In other words, 20 contingency cases are investigated in transient stability calculations. Considering also the 2 scenarios and 6 generation dispatch schemes for each scenario, total number of cases examined reaches 240. Such abundant number of transient stability cases is handled via utilization of automatization codes. Digsilent PF, which is a powerful power system analysis software, utilized in transient stability calculations, enables automatization through Digsilent Programming Language (DPL) codes.

On the other hand, calculation of transient stability for every case is one side of the story. Study also requires evaluation of huge number of results. In order to complete the transient stability assessment, an interactive MATLAB code is developed. This interface code takes the result of each case simulated as an input and presents some important parameters that are specific for assessing regional grid stability, such that the user can evaluate the stability condition in each case easily.

An example figure related to MATLAB interface is given in Figure 3-17. As illustrated, this representation not only includes the transmission corridor flows and the busbar angles but also shows the flows over reported degradated transmission lines on

Altınkaya, Kayabaşı and Çarşamba triangle, so that user can check different constraints and assess transient stability in a case by case manner.

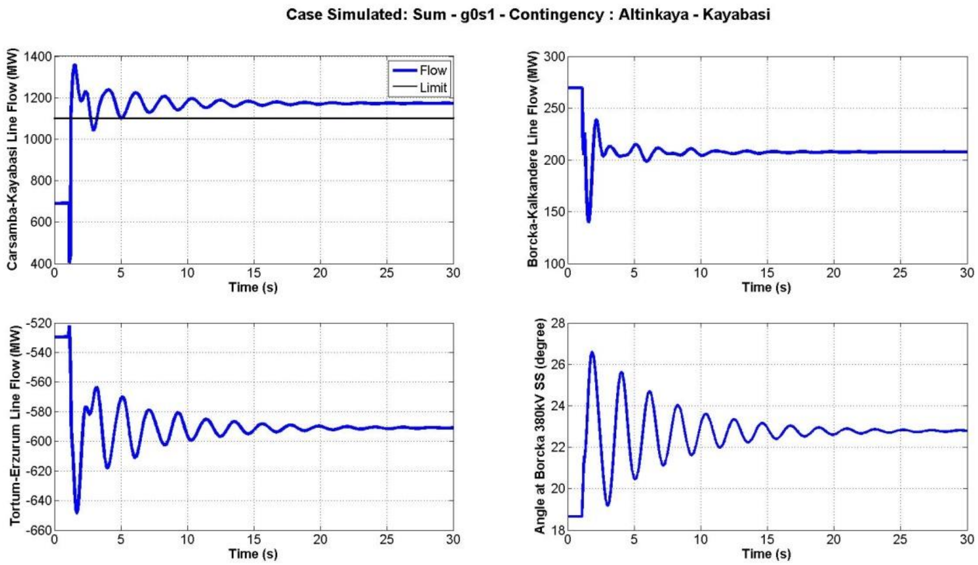


Figure 3-17. Example transient stability assessment interface on MATLAB

In the following sections, transient stability analysis results for spring and summer scenarios are given. In all cases, a three phase fault at t=1 sec is applied at the middle of the transmission line of interest. The fault clearing time, which is the sum of relay pickup and CB interruption time, is selected as 120 msec considering that the fault interruption time in high voltage transmission lines that is between 2-5 cycles.

Finally, it is important to note again that examined scenarios for summer and spring differ for Samsun NGCCP generation. In the summer scenario, it is expected that all generators are dispatched as much as possible due to the increase in the demand (i.e., peak season). Therefore, in generation dispatch schemes for the summer scenario, Samsun NGCCPP is either fully dispatched or partially dispatched. On the other hand, in generation dispatch schemes for the spring scenario, due to the low demand and the substantial hydraulic potential, it is assumed that Samsun NGCCPP is either partially dispatched or not dispatched. This seems to be a reasonable assumption considering also the results of the static security analysis for the spring season. Indeed, full dispatch of Samsun NGCCPP in the spring scenario obviously causes instability problems.

3.4.5.2. Transient Stability Analysis Results for Summer Scenario

As indicated, North Black Sea region is one of the net exporter regions in Turkey. Although there is a significant generation potential in the region, the power grid in the region, both 400 kV backbone and 154 kV grid, is weak for transmitting generation to the load centers. In addition, lengths of the transmission lines are relatively long due to the geographic conditions in the region. Consequently, regional transmission system can be regarded as highly vulnerable to instability conditions. Hence, transient stability analysis for the summer scenario yields significant results regarding to the dynamic security of the grid.

It is observed that even without Georgia interconnection, instability condition may be attained according to the generation level of regional high capacity generation facilities. Case illustrated in Figure 3-18 shows this mentioned situation. In this case, Borçka HPP, Deriner HPP and Samsun NGCCPP are almost fully operational. This situation leads to significant power flow over Borçka - Çarşamba transmission corridor. Being placed in the outlet of this long corridor, Samsun NGCCP - Çarşamba line is the most overloaded and most significant transmission line in the region. Hence, transient stability analysis has shown that any fault on this line leads to loss of synchronism in several power plants in the region as shown in Figure 3-18 which may end up with regional collapse.

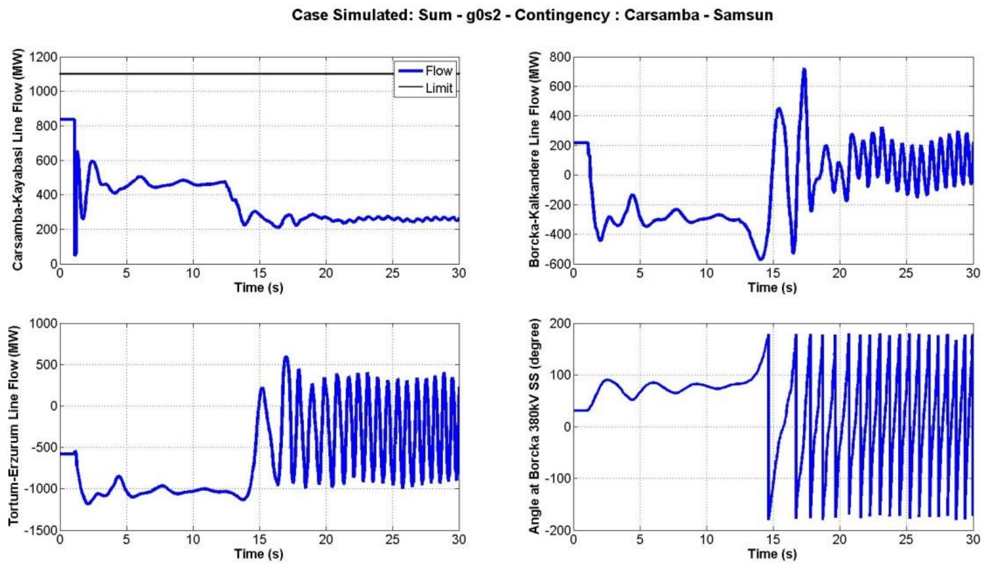


Figure 3-18. Transiently unstable condition without Georgia interconnection

As indicated in previous sections, the capacity of the transmission line between Çarşamba and Kayabaşı is limited, lower than its thermal capacity due to degraded protection elements installed on this line. Transient stability analysis has shown that, in most of the generation dispatch schemes, this transmission line is loaded more than its allowed limit in case of loss of any transmission line in Kayabaşı – Çarşamba - Altınkaya triangle. It should also be noted that this case is observed even energy import from Georgia is zero. This special condition is taken into consideration in all cases similar to the examples shown in Figure 3-19 and Figure 3-20.

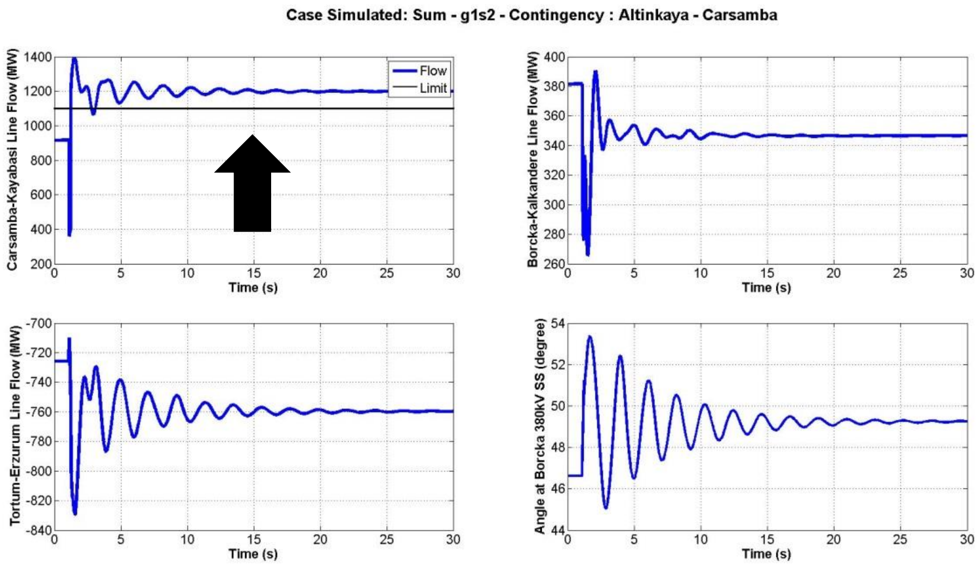


Figure 3-19. Kayabaşı - Çarşamba transmission line loading problem in case of loss of Altınkaya – Çarşamba line (case with 350 MW import from Georgia)

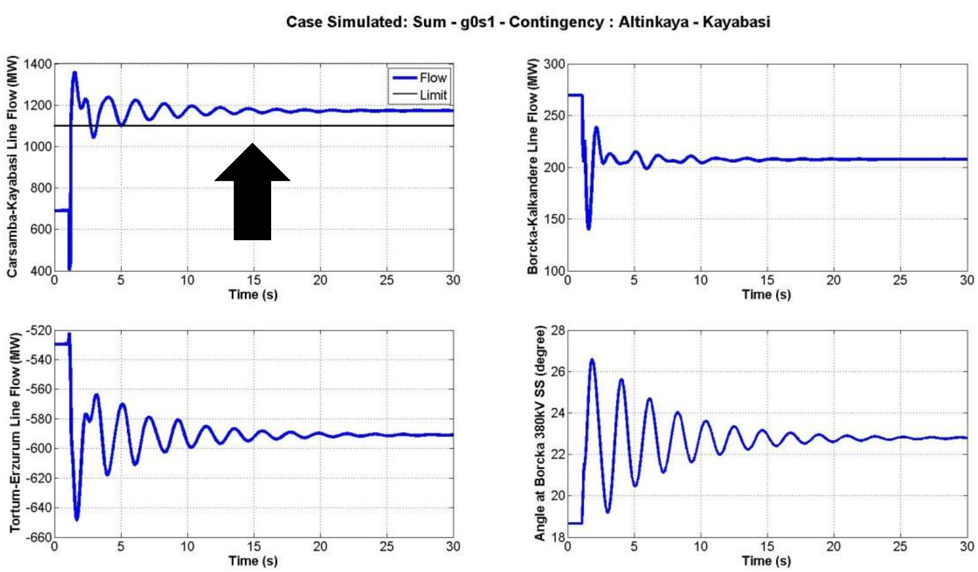


Figure 3-20. Kayabaşı - Çarşamba transmission line loading problem in case of loss of Altınkaya – Kayabaşı line (case without import from Georgia)

When 350 MW energy import cases are investigated, it is observed that some contingency cases over transmission corridor connecting Borçka to Erzurum will lead to instability conditions as well as the Çarşamba-Samsun transmission line. In Figure 3-21, transient stability results can be seen for a fault occurring on Deriner - Artvin transmission line. Although the system seems to stay stable after the fault clearance as seen from flow and angle graphs in Figure 3-21, overloading condition on 154 kV transmission lines will lead to cascaded overcurrent relay operations which can be observed in 9 sec. after the fault clearance in Figure 3-21. As a result, system becomes unstable as seen in Figure 3-21. Similar to the cases with 350 MW import, same problem is also expected and observed in cases with 700 MW import as well. The relevant graph for the case with 700 MW import is given in Figure 3-22 in which the transmission line connecting Yusufeli and Tortum is opened. Therefore, overloading problem in 154 kV should also be closely examined during SPS design process.

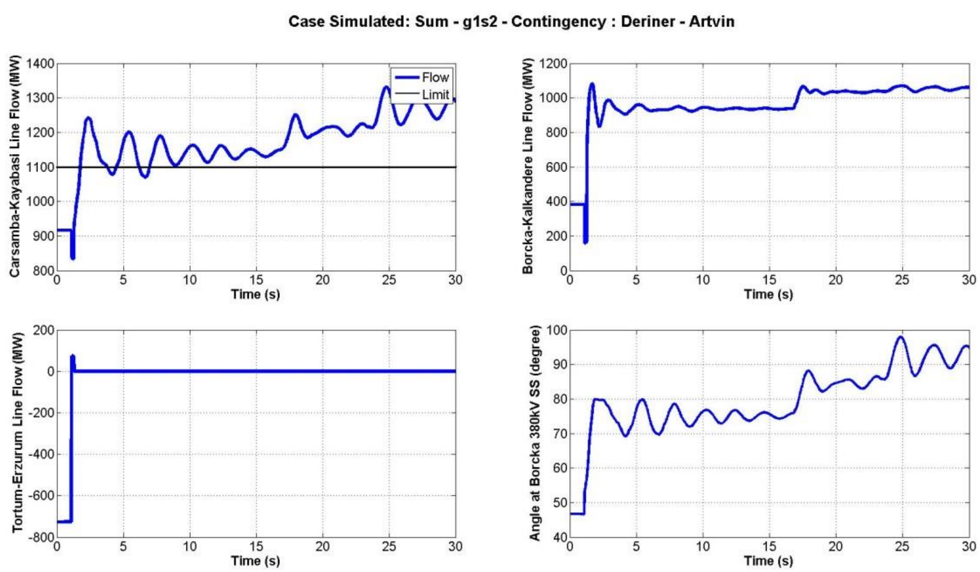


Figure 3-21. Transient instability as a result of cascaded 154 kV line opening (case with 350 MW import)

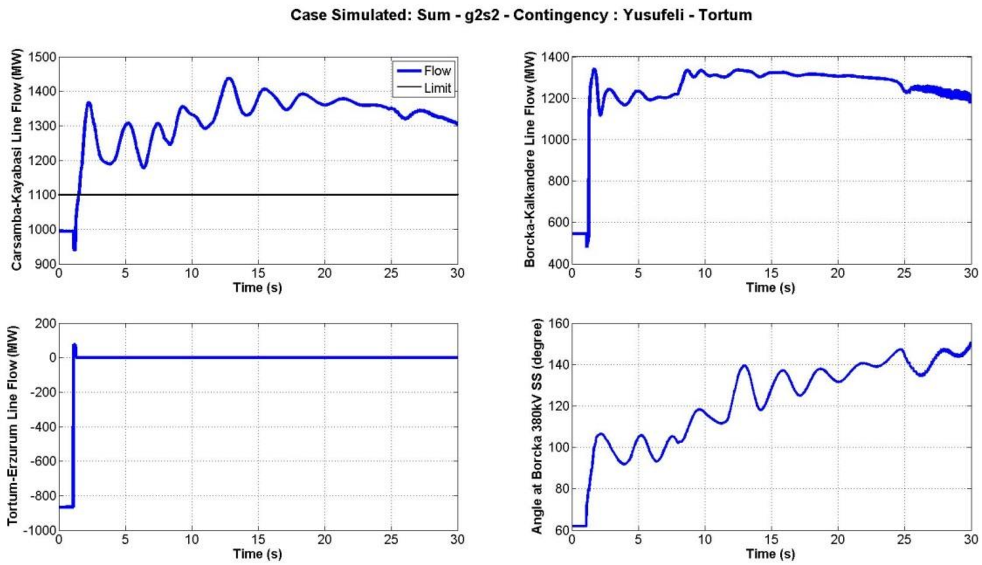


Figure 3-22. Transient instability as a result of cascaded 154 kV line opening (case with 700 MW import)

In addition, cases including 700 MW import from Georgia are also investigated. Due to increase in regional loading with the increase in the amount of import, the region becomes even more vulnerable to instability condition as expected.

The overall evaluation of all simulated cases is given in Table 3-11. In the table, stable cases are shown with green ticks while unstable cases are shown with red cross. In addition, cases that should be considered in terms of degraded lines are identified with yellow exclamation marks. Evaluation of several cases has shown that;

- Transmission line between Çarşamba and Samsun NGCCPP is the most critical line in the region and it is shown that there may be transient stability problems even without any power import from Georgia.
- Risk of instability increases with the amount of power import from Georgia as expected.

- Generation level of Samsun NGCCPP is also an important factor in transient stability as it directly affects the Borçka – Çarşamba 400 kV transmission corridor.
- Loss of the transmission line between Çarşamba and Samsun NGCCPP reverses the power flow direction in Borçka - Çarşamba 400 kV corridor. Hence power flow shifts to 154 kV lines and that situation leads to significant overloading problem among 154 kV regional transmission system.
- Loss of the transmission corridor between Borçka and Erzurum clearly increases the power flow on both remaining 400 kV corridor and 154 kV transmission in north to south plane. Hence, cascaded operation of 154 kV lines due to overcurrent protection is observed. This cascaded operation causes instability as well.

Table 3-11. Transient stability results table for summer scenario

Case \ Generation Dispatch Scheme	G0_S1	G0_S2	G1_S1	G1_S2	G2_S1	G2_S2
Altınkaya-Çarşamba	✓	✓	✓	✓	✓	!
Altınkaya-Kayabaşı	✓	!	!	!	!	!
Kayabaşı-Çarşamba	!	!	!	!	!	!
Çarşamba-Samsun NGCCPP	✓	✗	✗	✗	✗	✗
Çarşamba-H.Uğurlu	✓	✓	✓	✓	✓	✓
Ordu-Tirebolu	✓	✓	✓	✓	✗	✗
Ordu-Samsun NGCCPP	✓	✓	✓	✓	✗	✗
Tirebolu- Tirebolu Series Cap.	✓	✓	✓	✓	✓	✓
Tirebolu Series Cap.-Kalkandere	✓	✓	✓	✓	✓	✓
Borcka-Kalkandere	✓	✓	✓	✓	✓	✓
Bocka-Deriner	✓	✓	✓	✓	✓	✓
Deriner-Artvin	✓	✓	✓	✗	✗	✗
Artvin-Yusufeli	✓	✓	✓	✗	✗	✗
Yusufeli-Tortum	✓	✓	✓	✗	✗	✗
Erzurum-Tortum	✓	✓	✓	✗	✗	✗
Erzurum-Özlüce	✓	✓	✓	✓	✗	✗
Erzurum-Horasan	✓	✓	✓	✓	✓	✓
Ağrı-Horasan	✓	✓	✓	✓	✓	✓
Ağrı-Van	✓	✓	✓	✓	✓	✓
Van-Başkale	✓	✓	✓	✓	✓	✓

3.4.5.3. Transient Stability Analysis Results for Spring Scenario

As indicated, power generation in the region is dominated by hydraulic type power plants. Due to the water regime in the spring season, generation level in the region significantly increases. As a result, transmission lines in the region become even more loaded compared to summer scenario. Hence, the risk of transient instability increases in the region.

In addition, realization of Altınkaya - Boyabat 400 kV transmission line creates parallel transmission way to load centers in west part of the Turkey. However, this also increases loading over Borçka – Çarşamba corridor as the regional transmission merely depend on this corridor.

The overall evaluations regarding to the simulated cases are given in Table 3-12. Again, in the table, stable cases are shown with green ticks while unstable cases are shown with red crosses. In addition, cases that should be considered in terms of degraded lines are identified with yellow exclamation marks parallel to the representation shown in summer scenario results. Evaluation of several cases in the spring scenario has shown that;

- As most of the small scale hydraulic generation is connected to the 400 kV network over Borçka - Çarşamba transmission corridor, increase in power flow on that line increases the transient instability risk in the spring season. Hence, the number of unstable cases increases for disturbance over Borçka – Çarşamba transmission corridor.
- Transmission line between Çarşamba and Samsun NGCCPP is the most critical line in the region and it is shown that there may be transient stability problems even without any power import from Georgia.
- Realization of Tortum 400/154 kV connections and new 154 kV transmission investments relieves the Borçka - Erzurum 400 kV transmission corridor, especially the Borçka - Tortum part, significantly. As a result, transient

instability problem significantly reduces for disturbances on Borçka – Tortum part of the Borçka - Erzurum 400 kV transmission corridor. However, it should be noted that the power flow on that corridor merely depends on Tortum - Erzurum transmission line.

Table 3-12. Transient stability results table for spring scenario

Case \ Generation Dispatch Scheme	G0_S0	G0_S1	G1_S0	G1_S1	G2_S0	G2_S1
Altınkaya-Çarşamba	✓	✓	✓	!	✓	!
Altınkaya-Kayabaşı	✓	✓	✓	✓	✓	!
Kayabaşı-Çarşamba	✓	✓	✓	✓	✓	✓
Çarşamba-Samsun NGCCPP	✓	✗	✗	✗	✗	✗
Çarşamba-H.Uğurlu	✓	✓	✓	✓	✓	✓
Ordu-Tirebolu	✓	✓	✗	✗	✗	✗
Ordu-Samsun NGCCPP	✓	✓	✗	✗	✗	✗
Tirebolu- Tirebolu Series Cap.	✓	✓	✓	✓	✗	✗
Tirebolu Series Cap.-Kalkandere	✓	✓	✓	✓	✗	✗
Borcka-Kalkandere	✓	✓	✓	✓	✗	✗
Bocka-Deriner	✓	✓	✓	✓	✓	✓
Deriner-Artvin	✓	✓	✓	✓	✓	✓
Artvin-Yusufeli	✓	✓	✓	✓	✓	✓
Yusufeli-Tortum	✓	✓	✓	✓	✓	✓
Erzurum-Tortum	✓	✓	✓	✓	✗	✗
Erzurum-Özlüce	✓	✓	✓	✓	✓	✓
Erzurum-Horasan	✓	✓	✓	✓	✓	✓
Ağrı-Horasan	✓	✓	✓	✓	✓	✓
Ağrı-Van	✓	✓	✓	✓	✓	✓
Van-Başkale	✓	✓	✓	✓	✓	✓

3.5. SPS Design Studies

Previous sections have shown that energy import from Georgia via HVDC leads to transmission overloading and instability problems in the Turkish grid. Therefore, an intelligent protection scheme that monitors the system dynamics and coordinates the grid after disturbances in the region via utilizing some countermeasures is definitely required. In this section, a special protection scheme that is aimed to resolve the problems identified in previous sections is introduced.

3.5.1. Requirement Summary

Any deficiency in SPS design may lead to catastrophic results for the region that SPS developed for. Therefore, in order to design a protection scheme for the region, requirements and expectations should be cautiously examined in detail. In the perspective of studies conducted in previous sections, following conclusions can be made;

- Static load flow and contingency analyses have shown that almost every contingency in the region leads to overloading problems especially during spring season. Due to overcurrent protections, loading level of these lines should be limited up to a certain degree. Hence, the designed SPS should eliminate the overload in transmission lines in order not to evoke cascaded line openings.
- The overloading problem in Altınkaya – Kayabaşı - Çarşamba transmission triangle should be locally solved as the effect of countermeasures in Borçka region to this triangle is minimum. Hence separate logic required for this area.
- As identified by power quality studies, HVDC operation (i.e., commutation schedule) is not effected by grid changes in Turkish side due to synchronous condensers installed in Akhaltsikhe substation. Hence, countermeasures are practically unlimited in terms of secure HVDC operation.
- As the instability and overload problems stem from high generation, the primary focus in countermeasures should be given to generation shedding.
- Amount of generation drop is limited to maximum disturbance can the Turkish grid withstand without losing synchronous operation with ENTSO\E.
- Minimum operation time for SPS to interact disturbances is less than 700 msec. according to the transient stability calculations.

In addition to the specific grid requirements, common design necessities should also be considered in the SPS design. These are;

- 8760 hours of secure operation is aimed with the SPS utilization. Hence, SPS should be successful for any loading condition. In other words, design should be loading independent.
- As the annual growth rate of Turkish grid is around 7 %, several grid investments are realized in each year in order to meet the demand. Hence, grid topology is changing year by year and this situation forces SPS design to be modular and quickly adaptable to the changing grid environment.
- SPS must be fully automated and should be operated without human interaction.

3.5.2. Solution Space

As indicated in the previous section, primary focus in countermeasure determination is given to generation shedding, since the main problem stems from the high generation in the region. The results of static security analysis have shown that solutions that relieve the system following a disturbance can be classified into 3 main groups according to the fault location.

<u>Çarşamba - Kayabaşı countermeasure group</u>

Since no alternative 400 kV transmission corridor connecting northeastern region generation to main load centers exists, huge amounts of power flow occur on lines connected to Kayabaşı substation. This situation leads to overloading on these lines even without any contingency. Therefore, loss of any line in Kayabaşı – Çarşamba - Altınkaya triangle leads to overloading and loading dependent instability problems. The obvious candidate that resolves this problem is the generation shedding. However, static security analysis identified that the generation shedding from Borçka area is not as effective as local the generation shedding. In order to minimize the generation shedding and to maximize the effect of risk mitigation, local candidates such as Altınkaya HPP, H. Ugurlu HPP and Samsun NGCCPP should be preferred. Hence, this countermeasure group includes generation shedding from Altınkaya and H. Uğurlu HPPs. As a result, in case of any disturbance that is occurred on Kayabaşı - Altınkaya - Çarşamba 400 kV triangle, primarily Çarşamba - Kayabaşı countermeasure group is utilized.

Borçka countermeasure group

This group is dedicated for disturbances that may occur in between Borçka - Samsun NGCCP and Borçka - Erzurum substations. As the power flow on these lines are primarily affected by regional generation, the effect of generation shedding from Borçka area is significant. Hence, this countermeasure group includes generation shedding from Borçka HPP, Deriner HPP and power import reduction from HVDC. Moreover, disturbances on Erzurum - Keban corridor can also be compensated utilizing this countermeasure group.

Samsun Countermeasure Group

This group is specific to possible disturbances that may occur on Samsun NGCCP - Çarşamba line. In case of losing this line, the power flow reversal in Borçka - Çarşamba corridor leads to several 154 kV related problems that may result in instability. Hence, this specific countermeasure group is dedicated to Samsun NGCCPP - Çarşamba line and is also operated in coordination with Borçka countermeasure group.

3.5.3. Monitoring Location Determination

In order to detect the changes in the power system, SPS can either observe on/off state of breakers in the regional system or measure power system variables such as voltage power etc. Considering the size of the region of interest, detection via breaker position signal is not selected, as this type of implementation require lots of signals to be transmitted to the deciding center. Such an approach reduces both modularity and reliability of the design. Therefore, latter approach is preferred and the system is monitored via PMU measurements. However, PMU based design rises an important question regarding to the monitoring locations. Therefore, design studies started with identifying monitoring locations that are sufficient for SPS design. In general, this determination process is based on step-by-step optimization of cost and design requirement. Considering the Turkish regional network, the initial point is trivial. As Northeastern region of Turkey consists two intersecting 400 kV corridors, 3 PMU measurements one at intersecting point and remaining two at the ends of the 400 kV corridors are selected as initial starting point. In the design process, it turns out that this selection is the minimum measurement requirement for SPS logic in order to determine grid states in the region.

3.5.4. Instability Pattern

Like any protection element, SPS should operate correctly when needed and should not intervene the system operation in cases where protection is not necessary. In order to reveal these necessities, careful and detailed calculations are performed in SPS design study.

In order to determine the variables that reveal a pattern for detecting instability conditions, several simulations are conducted. As the main problem that affects regional system stability is the loading of transmission lines, the analyses first focused on detecting instability pattern based on active power flows. However, the meshed structure of the regional system yield no clear pattern, especially due to the 154 kV network. In addition, it is not possible to determine a single pattern on power flows for different loading conditions. Therefore study proceeded on finding an instability pattern on several power system variables.

It is known that the measured variables from PMU devices are limited to voltages and currents. As a result, the PMU based SPS design should focus on these variables and variables derived from PMU measurements. Literature survey study on wide area measurement based SPS applications has shown that, positive sequence voltage angle and variations based on angles are common variables that are used in SPS design. Hence, SPS design study focused on determining an instability pattern based on busbar angles, angle deviations and derived variables based busbar angles.

Considering the transmission structure in the region, it is obvious that any disturbance on one of the two main transmission corridors results in significant power flow and angle deviation in the remaining transmission corridor. In this regard, deviations in angles and power flow in PMU measurement points located on remaining transmission corridor are investigated.

Transient stability analysis results for the summer scenario have shown that angle difference between Borçka and Çarşamba substatitions yields a clear instability pattern for disturbances occurring on Borçka - Erzurum transmission corridor. When stable and unstable cases following a disturbance are classified, it has been found out that, the system stays in a stable state if the angle difference between Borçka and Çarşamba substations is lower than 40 degrees as shown in Figure 3-23. Hence, for stable cases, transient change in the angle difference after the fault should not exceed 40 degrees limit. In a similar manner, it is also observed that angle difference between Borçka and Çarşamba for the unstable cases, represented as green curves in Figure 3-23, exceed the 40 degree limit and increases boundlessly.

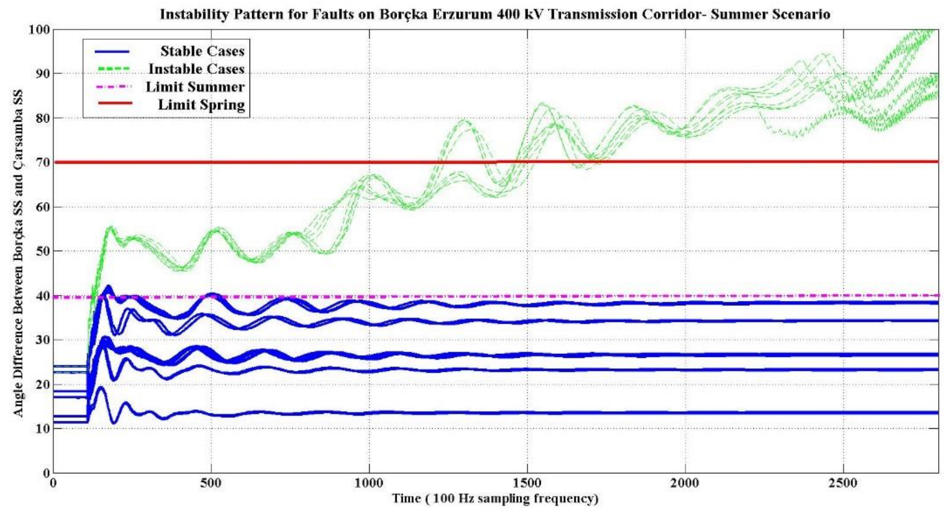


Figure 3-23. Instability pattern for faults on Borçka – Erzurum transmission corridor (summer scenario)

Same analysis for the spring scenario is given in Figure 3-24. It has been found out that same limit for stable cases in the spring scenario changes to 70 degrees. Actually, although different limits complicate the SPS logic determination, it is an expected result due to topological changes in Borçka - Erzurum corridor between years analyzed in summer and spring scenarios that is 2013 and 2014 respectively. These changes are identified in Table 3-4 of the Section 3.1.3.

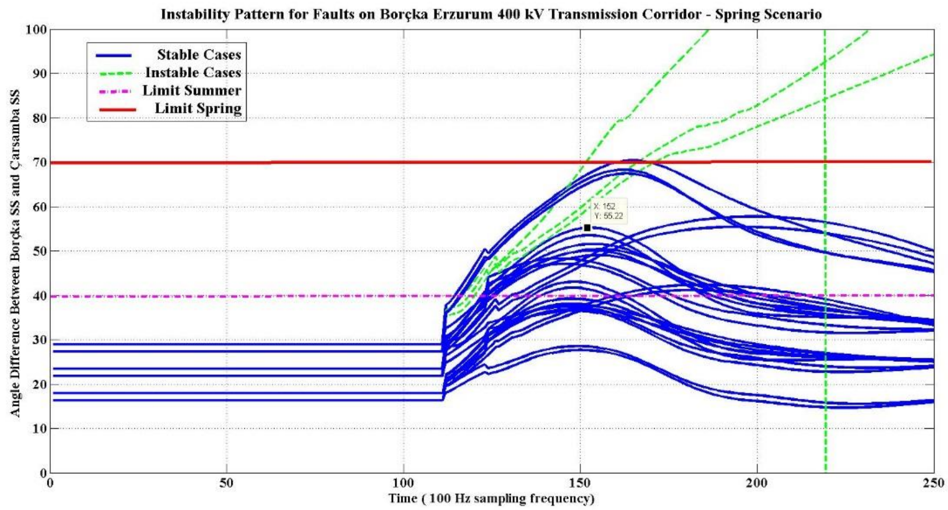


Figure 3-24. Instability pattern for faults on Borçka – Erzurum transmission corridor (spring scenario)

On the other hand, same calculations for faults on Borçka - Çarşamba corridor did not give any clear pattern as in the other case due to the meshed structure of Borçka - Çarşamba corridor with 154 kV regional network. Therefore angle difference pattern is further processed with angle difference deviation. Angle difference deviation variable shows nothing but how fast the angle difference changes according to the fault. With this utilization, severity of disturbance is further taken into consideration. When stable and unstable cases in transient stability analysis are investigated, it is discovered that created combined parameter, which is angle difference multiplied with angle difference deviation, yield a clear pattern for stability determination. Hence, combined parameter is investigated utilizing transient stability analysis results for the summer scenario for the cases having disturbance on Borçka – Çarşamba transmission corridor. Analysis of mentioned combined parameter for summer scenario has shown that grid stay in stable state if that combined parameter is lower than 40 degrees as shown in Figure 3-25.

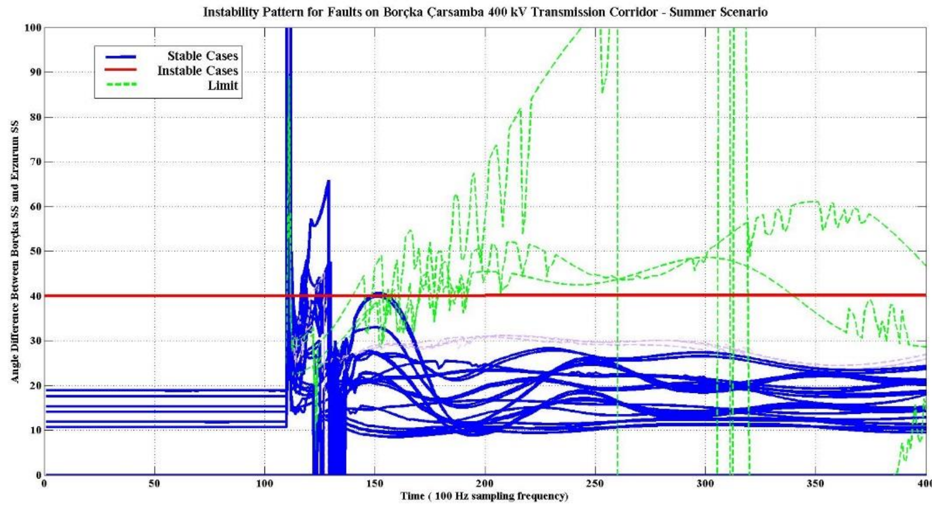


Figure 3-25. Instability pattern for faults on Borçka – Çarşamba transmission corridor (summer scenario)

Same analysis for the spring scenario also shows the mentioned 40 degree limit for combined stability parameter. The regarding pattern for the spring is given in Figure 3-26. As Borçka - Çarşamba transmission corridor in summer and spring scenarios is almost same for 2013 and 2014 in terms of grid topology, limit values are found same in each case.

In addition, most severe disturbance in transient stability analysis (fault on Çarşamba-Samsun NGCCPP line) is also shown in Figure 3-26 as black dotted line. Examination of the behavior of that disturbance, revealed another important information regarding to the SPS logic design that is maximum SPS intervention time. It is clear from the figure that, in worst contingency, system loses synchronism 700 msec. after fault clearance. Therefore it can be concluded that SPS should react within maximum 700 msec. Actually, it should react much less than 700 msec. in order to create sufficient retarding torque that forces machines to stay stable.

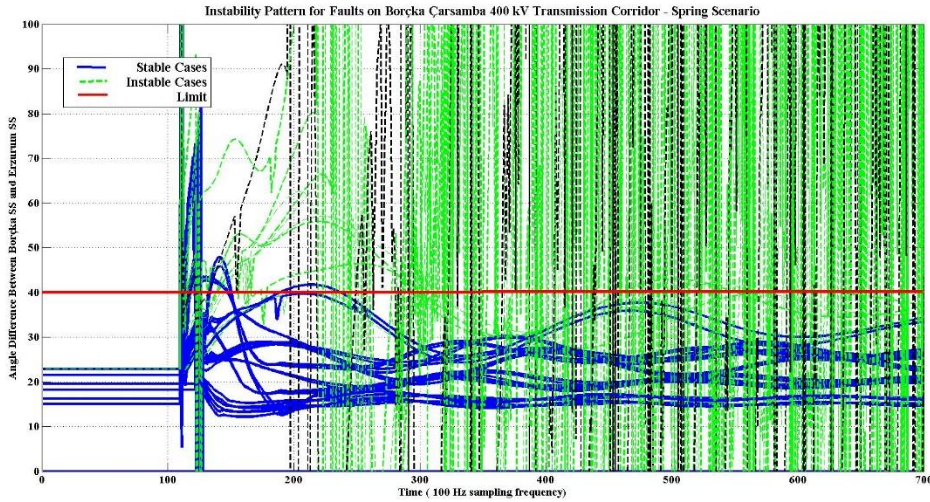


Figure 3-26. Instability pattern for faults on Borçka – Çarşamba transmission corridor (spring scenario)

3.5.5. Development of SPS Logic

Results of numerous simulations, as presented in previous sections have answered some basic questions like when, why and how to operate regarding to SPS design. Given the requirements and design related analysis results, the only remaining part is the logic interpretation. This is simply interpreting the behavior of the power system during disturbances and the interaction of SPS. In this section several functions of SPS logic are introduced.

3.5.5.1. Fault Related Detection Functions

When a severe disturbance such as a short circuit fault in a system, power flows on the transmission lines show abrupt changes and voltages on busbars that are close to the faulty element reduce significantly. Roughly, it can be said that the fault drives the power system to a state where almost all variables in the power system show quick deviations. This is the starting point of the SPS logic design as it should detect correct time to activate.

In SPS logic, power flow deviations at measurement points are utilized in order to determine the fault in the regional system. This is a preferable selection as any fault in the region, surely changes power flow on the transmission lines which are constantly observed by PMU's placed. As a consequence, significant change in flow is detected at least two out of three PMUs. Hence, for the fault detection, dP/dt values in each PMU are constantly calculated based on measurements taken from PMUs.

During normal operation, at least 500 MW power flows are observed at the end points of each the transmission corridor. Based on this observation, threshold level for fault detection on power flow deviation is selected as 300 MW considering the parallel 154 kV power flows. In other words, if the power flow deviates more than 300 MWs in 3 consecutive measurement periods in any PMU, the SPS logic determines that a fault has occurred in the region.

Measurements taken from PMUs during the fault condition are useless for the SPS due to anomalies in variables. Hence, determination of the system stability based on these variables is not preferred. Rather, change in system variables after the fault clearance is waited in order to assess the effect of disturbance. As a result, fault clear determination function is also implemented in the SPS logic. The implementation is based on voltage levels measured from PMUs, considering the busbar voltages are significantly low during the fault and rapidly increase after the fault clearance.

Furthermore, the location information regarding the fault also yields valuable information for the SPS logic. As determined in static security and transient stability chapters, the instability pattern changes according to the location of fault. For this reason, fault location determination holds crucial importance.

In order to detect the fault location, both directions of power flow and angle values at measurement points are constantly observed. In case of fault occurrence in the system, mentioned angle and power flow variables before and after fault conditions are recorded. Then the fault location determination logic decides the location of the fault via decision tree shown in Figure 3-27.

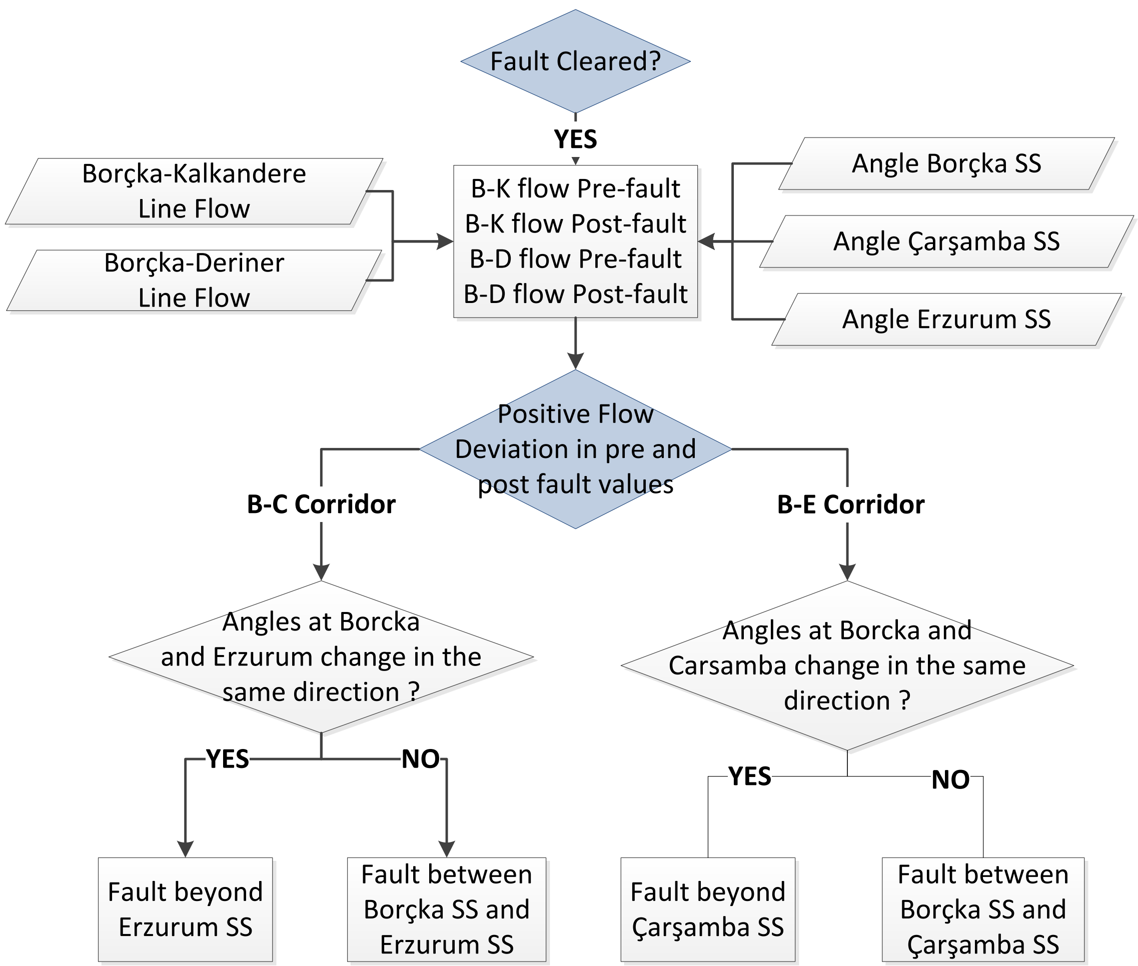


Figure 3-27. Fault location detection logic

3.5.5.2. Countermeasure Activation Logic

Candidate countermeasures that mitigate the effect of disturbance in the region according to the location of the disturbance have already been defined in previous sections. Therefore, given the effect and the location of disturbance, SPS logic already knows which countermeasure group to activate. However, determination of the magnitude of countermeasure that relieves the system after disturbance heavily depends on the initial grid loading condition prior to the disturbance. So, it is difficult to design a logic that exactly determines the required countermeasures online. Rather, the activation of predetermined countermeasures in a step by step fashion till stability is ensured, is preferred in this design.

Given that the instability pattern of the several contingencies, designed SPS logic inherently has the information regarding stability limits. Hence, in case of a violation exists in a contingency case, the logic should activate countermeasures step-by-step until violation condition is averted. In order to realize this idea, 3 discrete countermeasure activation steps that depend on different activation levels are created in the SPS logic. As a result, activation of countermeasures is optimized so as to use minimum required countermeasures.

In addition, for the disturbances that occur in Çarşamba - Kayabaşı - Altınkaya triangle, where instability is not the only concern due to line capacity degradation, limitation on line flows are applied. According to the information taken from TEİAŞ, transmission lines between Çarşamba to Kayabaşı and Altınkaya to Kayabaşı can loaded up to 1100 MW. Hence, in case of losing any line in this triangle, countermeasures are activated directly upon the violation of the mentioned limit value.

3.5.5.3. Available Countermeasure Search Logic

Up to this point, the implemented SPS functions have identified the existance fault and activated the regarding countermeasures. In addition, the logic also indicates the magnitude of countermeasure that is required rather than specifically determining the exact action. It is a reasonable approach as the grid condition, especially the availability of countermeasures, that is the countermeasure is online or offline during actual operation, is unknown for the SPS. Therefore, countermeasure search algorithm is implemented for the SPS design.

The search algorithm starts with determining online countermeasure candidates in the grid. Then, discrete countermeasure steps are formed among these candidate groups regarding to the unit size. This simple routine is calculated continuously in the logic such that there is always a countermeasure in the system. As a result, the lack of countermeasure or the wrong countermeasure selection is prevented and countermeasures always stay armed during SPS operation.

3.5.5.4. Combined Logic Scheme

Combination of aforementioned logics and functions are formed in a controller block in Digsilent software to test and simulate the SPS in several grid conditions. The implemented SPS logic is shown in Figure 3-28. Simulation results regarding to the operation of SPS logic are given in the next chapter.

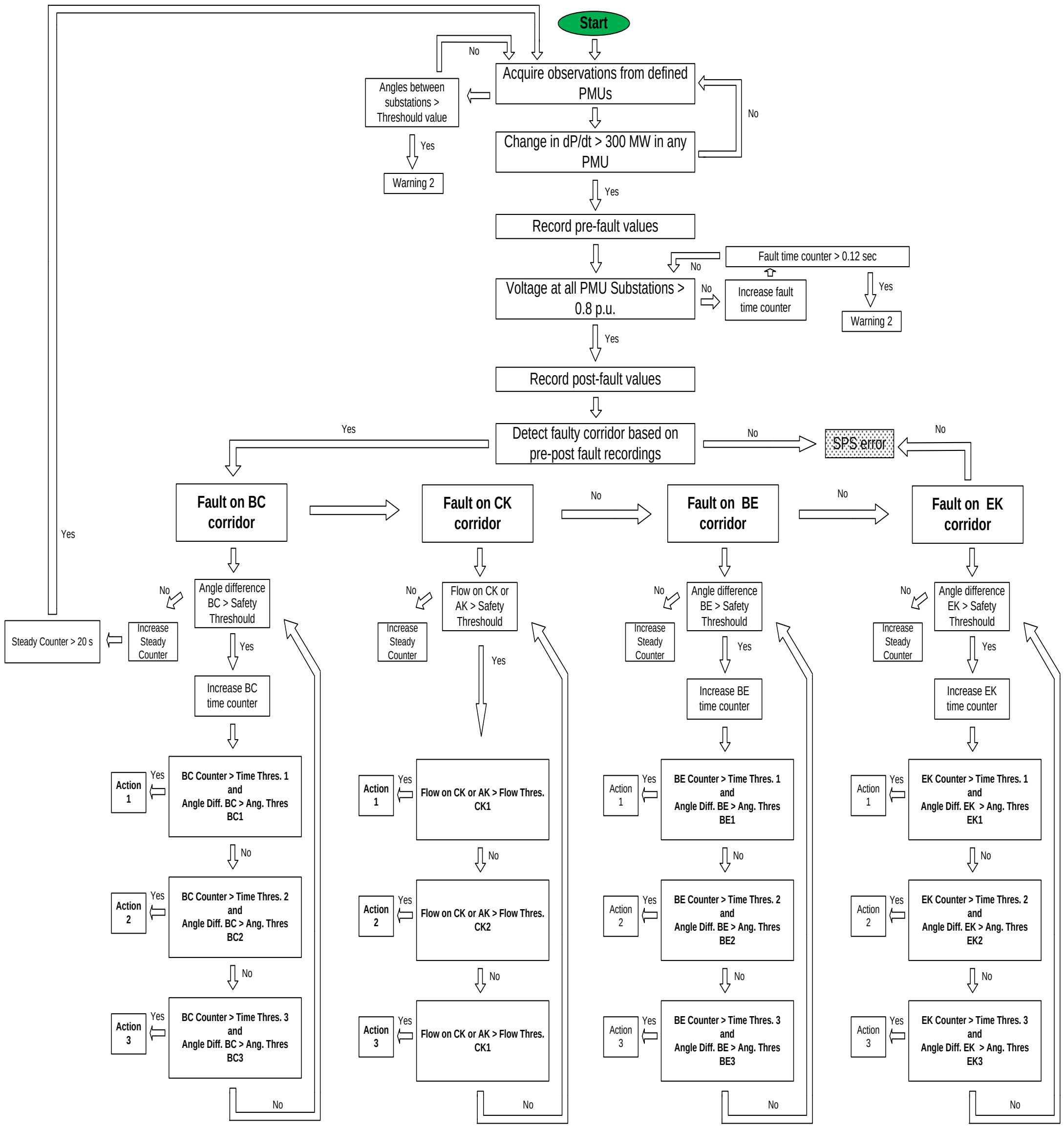


Figure 3-28. SPS logic flowchart

CHAPTER 4

SIMULATION RESULTS AND DISCUSSION

Up to this point, detailed analysis studies have been conducted in order to define requirements for the design of SPS. As a result of these analyses, an algorithm that monitors certain electrical variables in the system and assesses changes in the system operating point by following the dynamics during post contingency period and eventually decides on a preventive action is created. As a next step, implementation and testing of designed algorithm on a simulation environment is required. Hence, in this part of the study, implementation of the developed SPS logic on a simulation environment and performance tests are presented.

Reliability is the most important title for a protective element. However, being a reliable element requires several testing procedures that examine stability, accuracy, dependability etc. SPSs are also classified as intelligent protective elements. Hence, the SPS design must be reliable in order to be used in a power system. Therefore, detailed testing is performed to complement the SPS design study. In this chapter, time domain simulation (i.e. transient stability) results with SPS implementation are given.

4.1. Implementation of Designed Logic on Simulation Environment

After being determining the logic of the SPS system, the structural requirements of the design become much clearer. During the logic design process, it is concluded that 3 main PMU measurements are sufficient to observe the system dynamics in the sense of SPS algorithm. In addition to this, SPS logic utilizes several countermeasures, which are actually generators in the region. Hence information flow between SPS logic and generators in counter measures is required. As a result, PMUs and generators in counter measures are main peripherals that must be connected to the SPS logic.

After identifying the requirements and peripherals for the SPS implementation, SPS is constructed as a custom controller on Digsilent software. The implementation of the SPS logic and its peripherals are illustrated in Figure 4-1. As illustrated in implementation figure, signals expected from PMU's and dispatch information from power plants, which are utilized as countermeasures, are gathered.

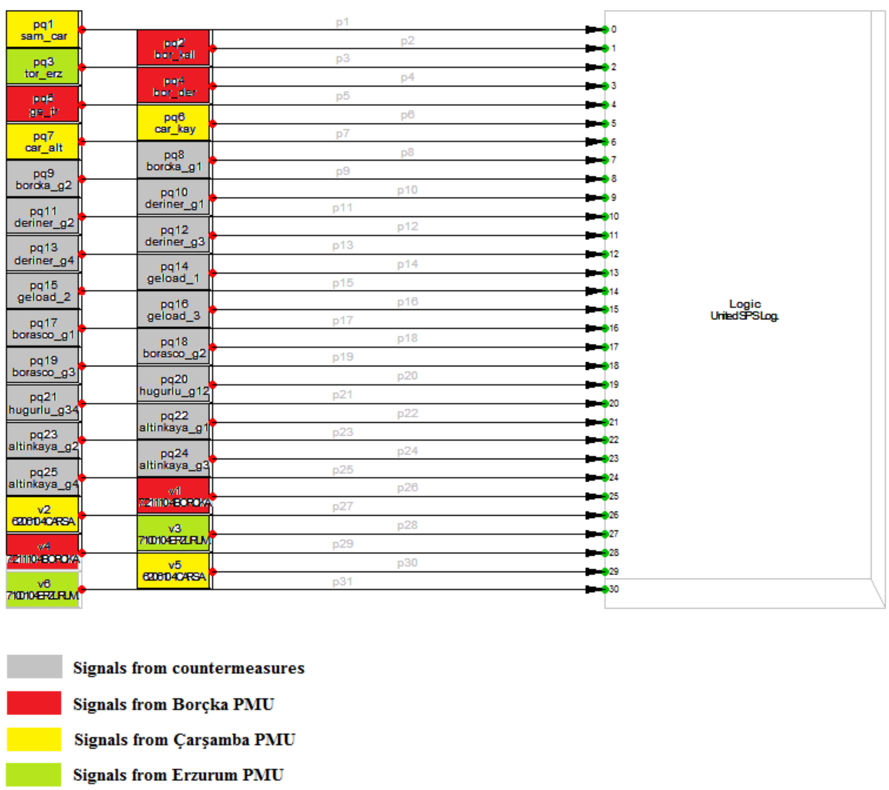


Figure 4-1. SPS implementation in Digsilent software

4.2. Transient Stability Results for Summer Scenario under SPS Supervision

As indicated in the previous transient stability analysis section, regional power system is suffering transient stability problems even without power import from Georgia. The results illustrated in Figure 3-18 indicate the current situation, which clearly shows both the importance and the requirement of SPS in the region. There are also several contingency cases that have transient instability risk depending on the generation dispatch scheme of the region.

The main aim of SPS is to decide on a preventive action that ensures regional system stability and reliability in all possible grid conditions. Hence, the main expectation from SPS is to eliminate mentioned instability conditions. In order to assess how successful does the SPS in these tasks, studies conducted in transient stability section are performed again with the supervision of the implemented SPS algorithm.

Figures between 4-2 to 4-5 show the effect of SPS on some of the instable cases in transient stability study for summer scenario. In addition, transient stability results before SPS implementation are also drawn on the same figure in order to ease the understanding.

As indicated, fault occurring on Çarşamba - Samsun NGCCPP line is the worst contingency in the region. This contingency causes instability in almost all generation dispatch schemes regarding to both scenarios. However, transient stability calculation under SPS supervision for this contingency has shown that, implemented SPS system successfully eliminates the risk of instability for all grid conditions. In the case shown in Figure 4-2, that is the generation dispatch scheme with lowest generation dispatch in which worst contingency leads instability, SPS detects abnormal system conditions (i.e., line fault and disconnection of line) and reacts in a sufficient time period to eliminate instability risk by dropping generation from Samsun NGCCPP. In that case, approximately 400 MW generation is shed which relieves the system constraints. It is clear from the figure that the power flows and angles in blue colored lines, that is the case under SPS supervision, reached steady state condition after SPS intervention while the case without SPS in red dashed lines is not.

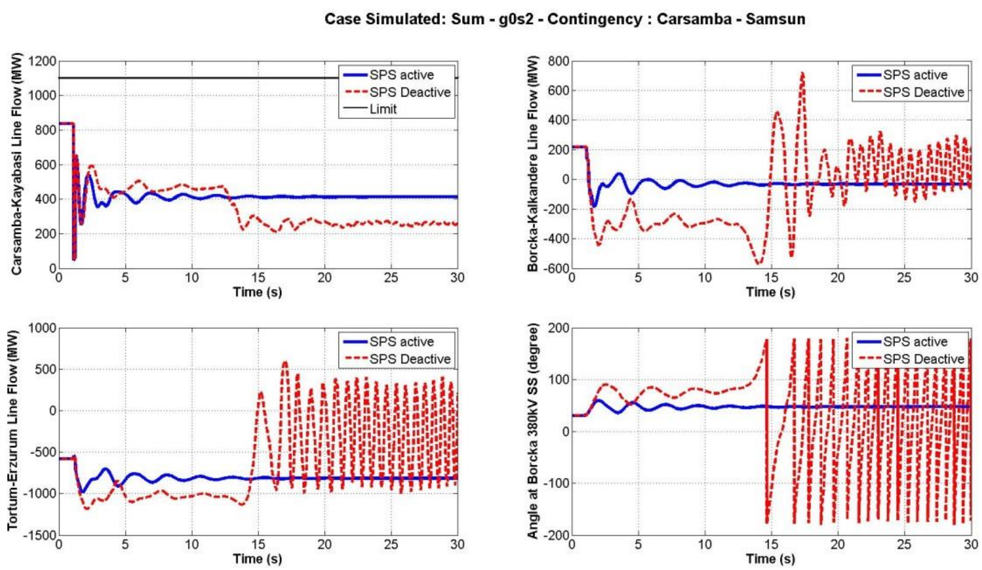


Figure 4-2. Effect of SPS during loss of the line between Çarşamba and Samsun (summer scenario)

Another critical case that needs to be investigated is the case with cascaded operation of overcurrent relays. In some of the cases, although system is transiently stable, cascaded openings of 154 kV transmission lines due to the overcurrent protection cause instability in the region. However, in the case of SPS supervision the risk is eliminated as SPS detects and reacts to the abnormal system conditions quickly. In the case shown in Figure 4-3, contingency that is occurring on Deriner - Artvin 400 kV line, triggers the SPS such that it react and shed approximately ~650 MW of generation around the region in order to preserve stability. This action also satisfies the special condition regarding the degraded Çarşamba - Kayabaşı 400 kV transmission line and load on that line is reduced until overloaded vanishes, as illustrated in Figure 4-3.

In addition, SPS also considers the load on degraded transmission lines in cases where contingency occurs on Altınkaya – Çarşamba – Kayabaşı triangle. In Figure 4-4, it is obvious that in case of losing Altınkaya - Kayabaşı 400 kV line, overloading on Çarşamba - Kayabaşı line is controlled such that the loading on that line is dropped until safe loading condition is attained.

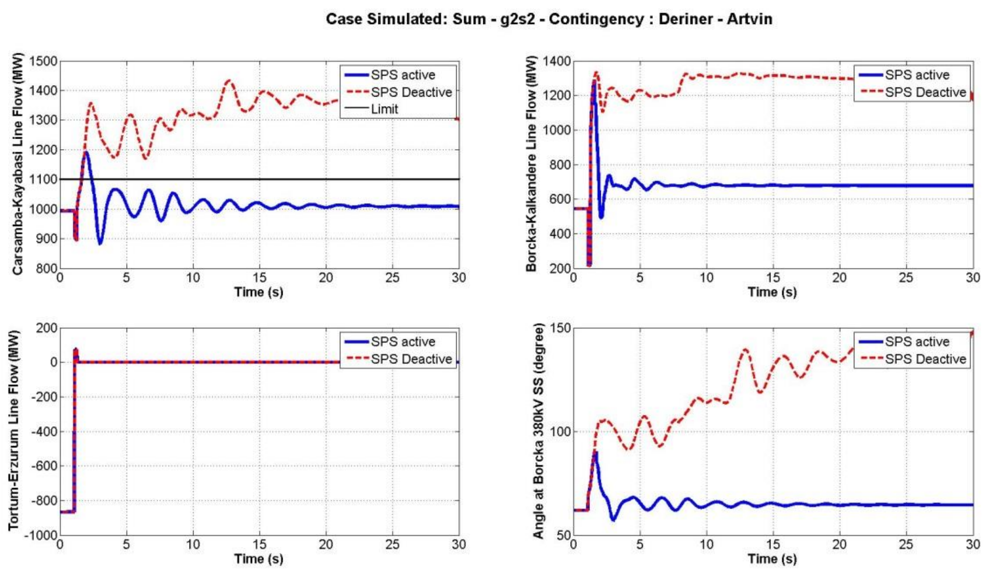


Figure 4-3. Effect of SPS in case of cascaded line openings (summer scenario)

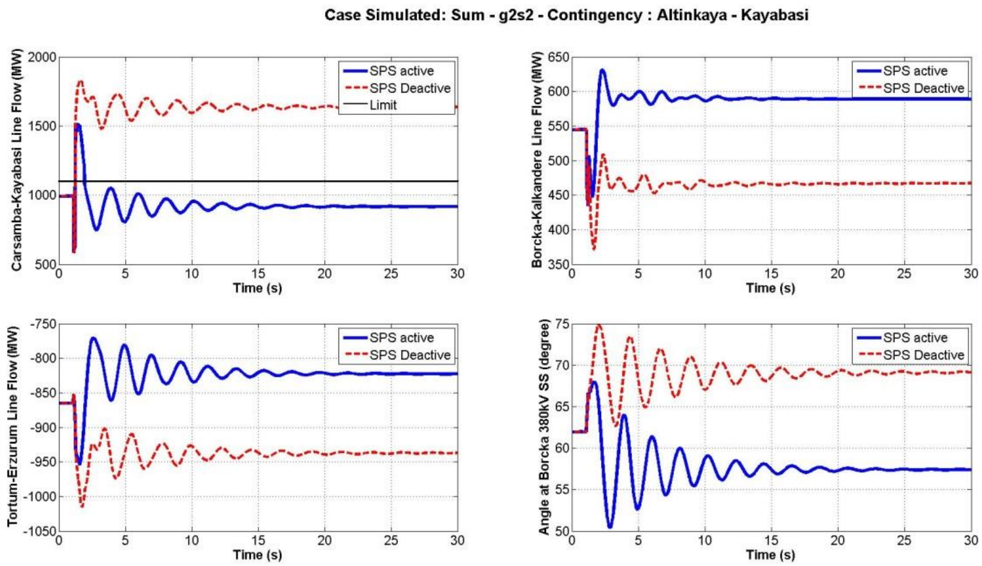


Figure 4-4. Effect of SPS in case of degraded transmission lines (summer scenario)

Like any protection equipment, SPS should not intervene the system operation where it is not required. Such an example case for this condition is shown in Figure 4-5. This figure clearly illustrates that the power system response is same for both SPS active and inactive cases. There are lots of cases where SPS intervention is not needed. Therefore, it is important to limit SPS action to the cases where necessary.

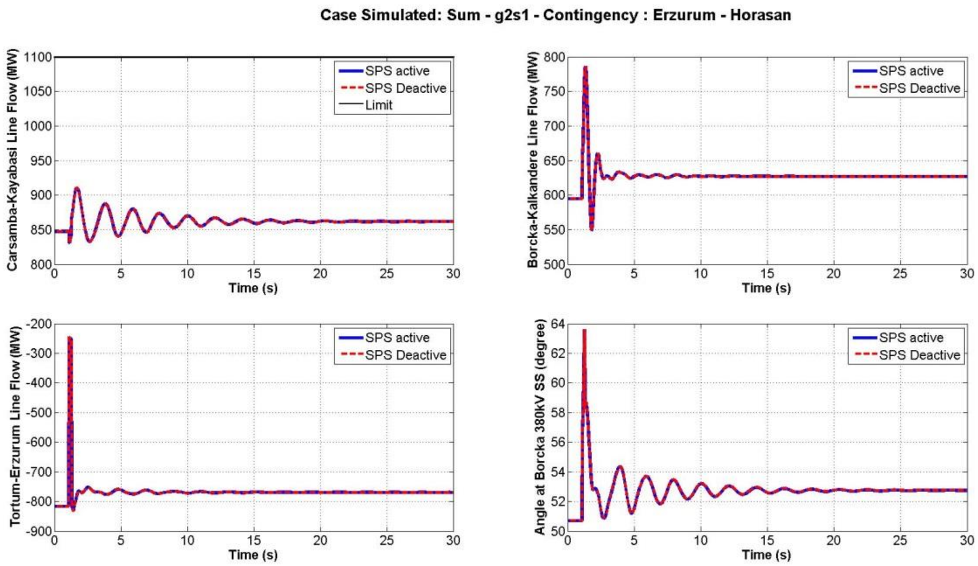


Figure 4-5. Effect of SPS in case where no action needed (summer scenario)

Moreover, an example to a voltage collapse case is given in Figure 4-6. As seen from the figure, in case of lack of synchronizing torque, system slowly proceeds to instability condition. This special instability condition cannot be detected by SPS due to the slowly changing grid dynamics. However, these cases are not evaluated as problematic cases since dynamical model utilized in this study does not contain automatic voltage regulators for generators in 154kV system where voltage problem mains. It is considered that the voltage collapse problem should primarily be solved by automatic voltage regulators in the system, rather than SPS action. Moreover, it is not reasonable to solve these types of problems via SPS action. Otherwise, strict protective SPS setting is required and these strict settings may lead to unnecessary countermeasure activation in stable cases which is not desired.

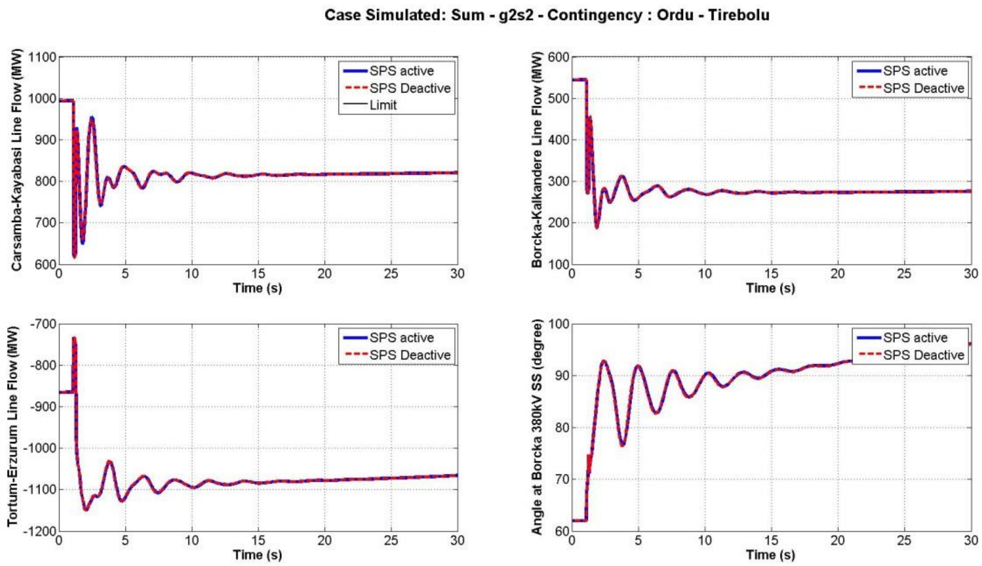


Figure 4-6. Effect of SPS in case of voltage collapse (summer scenario)

Summary of the analysis results under SPS supervision is given in Table 4-1. In the table, stable cases are shown with green ticks and cases that should be considered in terms of voltage collapse are identified with yellow exclamation marks. Results have shown that SPS ensures secure operation of the grid under all conditions except for the voltage collapse cases.

In order to clearly describe the SPS operation in all analysis cases, SPS actions on every case are summarized in Table 4-2. According to the results given in Table 4-2, it is obvious that SPS is acting only on conditions where intervention is necessary. In addition, most severe generation shed order given by SPS happens in case where transmission line between Çarşamba to Samsun NGCCPP is lost. In that case, SPS orders a total of 1350 MW of generation shedding which is quite a large value as the interconnection between Turkey and ENTSO\E may be affected. However, it is reported that SPS in Thrace region was successfully handled 1300 MW loss of generation in

Istanbul region. Nevertheless, this case should be investigated in detail in order to ensure safe operation of Turkish power system as a whole.

Table 4-1. Transient stability results for summer scenario under the SPS supervision

Case \ Generation Dispatch Scheme	G0_S1	G0_S2	G1_S1	G1_S2	G2_S1	G2_S2
Altınkaya-Çarşamba	✓	✓	✓	✓	✓	✓
Altınkaya-Kayabaşı	✓	✓	✓	✓	✓	✓
Kayabaşı-Çarşamba	✓	✓	✓	✓	✓	✓
Çarşamba-Samsun NGCCPP	✓	✓	✓	✓	✓	✓
Çarşamba-H.Uğurlu	✓	✓	✓	✓	✓	✓
Ordu-Tirebolu	✓	✓	✓	✓	!	!
Ordu-Samsun NGCCPP	✓	✓	✓	✓	!	!
Tirebolu- Tirebolu Series Cap.	✓	✓	✓	✓	✓	✓
Tirebolu Series Cap.-Kalkandere	✓	✓	✓	✓	✓	✓
Borcka-Kalkandere	✓	✓	✓	✓	✓	✓
Bocka-Deriner	✓	✓	✓	✓	✓	✓
Deriner-Artvin	✓	✓	✓	✓	✓	✓
Artvin-Yusufeli	✓	✓	✓	✓	✓	✓
Yusufeli-Tortum	✓	✓	✓	✓	✓	✓
Erzurum-Tortum	✓	✓	✓	✓	✓	✓
Erzurum-Özlüce	✓	✓	✓	✓	✓	✓
Erzurum-Horasan	✓	✓	✓	✓	✓	✓
Ağrı-Horasan	✓	✓	✓	✓	✓	✓
Ağrı-Van	✓	✓	✓	✓	✓	✓
Van-Başkale	✓	✓	✓	✓	✓	✓

Table 4-2. The amount of generation shed order given by SPS for all simulated cases in summer scenario

Case \ Generation Dispatch Scheme	G0_S1	G0_S2	G1_S1	G1_S2	G2_S1	G2_S2
Altınkaya-Çarşamba	0 MW	0 MW	0 MW	0 MW	0 MW	500 MW
Altınkaya-Kayabaşı	0 MW	500 MW	500 MW	700 MW	500 MW	700 MW
Kayabaşı-Çarşamba	180 MW	550 MW	550 MW	900 MW	550 MW	900 MW
Çarşamba-Samsun NGCCPP	0 MW	370 MW	500 MW	1050 MW	850 MW	1350 MW
Çarşamba-H.Uğurlu	0 MW	0 MW	0 MW	0 MW	0 MW	0 MW
Ordu-Tirebolu	0 MW	0 MW	0 MW	0 MW	0 MW	0 MW
Ordu-Samsun NGCCPP	0 MW	0 MW	0 MW	0 MW	0 MW	0 MW
Tirebolu- Tirebolu Series Cap.	0 MW	0 MW	0 MW	0 MW	0 MW	0 MW
Tirebolu Series Cap.-Kalkandere	0 MW	0 MW	0 MW	0 MW	0 MW	0 MW
Borcka-Kalkandere	0 MW	0 MW	0 MW	0 MW	0 MW	0 MW
Bocka-Deriner	0 MW	0 MW	0 MW	0 MW	0 MW	0 MW
Deriner-Artvin	0 MW	0 MW	0 MW	320 MW	670 MW	670 MW
Artvin-Yusufeli	0 MW	0 MW	0 MW	320 MW	670 MW	670 MW
Yusufeli-Tortum	0 MW	0 MW	0 MW	320 MW	670 MW	670 MW
Erzurum-Tortum	0 MW	0 MW	0 MW	320 MW	670 MW	670 MW
Erzurum-Özlüce	0 MW	0 MW	0 MW	0 MW	320 MW	670 MW
Erzurum-Horasan	0 MW	0 MW	0 MW	0 MW	0 MW	0 MW
Ağrı-Horasan	0 MW	0 MW	0 MW	0 MW	0 MW	0 MW
Ağrı-Van	0 MW	0 MW	0 MW	0 MW	0 MW	0 MW
Van-Başkale	0 MW	0 MW	0 MW	0 MW	0 MW	0 MW

4.3. Transient Stability Results for Spring Scenario under SPS Supervision

As indicated, the Northeastern region of the Turkey has a significant hydraulic potential. Due to the water regime during spring season, generation level in the region significantly increases. Consequently, transmission lines in the region become even more loaded compared to summer scenario. Hence, the risk of transient instability increases in the region.

When the regional generation distribution is investigated it can be observed that many run of river type generators are densely populated close to the Borçka - Çarşamba 400 kV transmission corridor. Therefore, instability conditions are widely seen especially for Borçka - Çarşamba 400 kV corridor contingencies.

In addition, transmission investments on Borçka - Erzurum corridor relive the loading through this corridor. Hence, transient stability studies in the spring season mainly focuses on Borçka - Çarşamba 400 kV transmission corridor.

Figures 4-7 to 4-12 show the effect of SPS on some of the instable cases in transient stability studies for the spring scenario. In addition, transient stability results without SPS implementation is also drawn on the same figure in order to ease the understanding.

Loss of transmission line between Çarşamba to Samsun NGCCPP again appears as the worst contingency in the region. Similar to the summer scenario, this contingency causes instability in almost all generation dispatch schemes. However, SPS implementation resolves the problem in the region regarding to that contingency as illustrated in Figure 4-7.

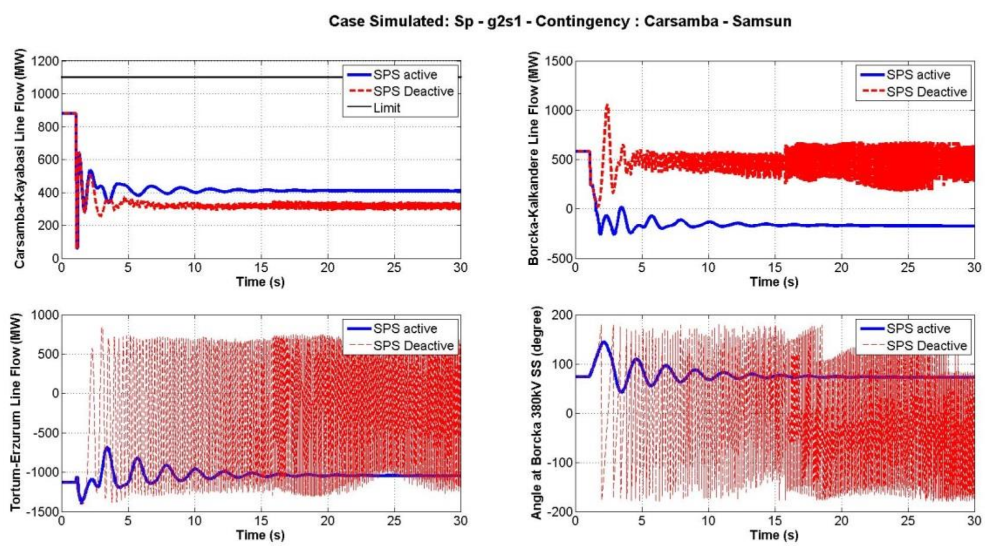


Figure 4-7. Effect of SPS during loss of the line between Çarşamba and Samsun (spring scenario)

As indicated in the transient stability analysis section for the spring scenario, increase in the power flow on Borçka - Çarşamba transmission corridor due to small hydraulic generation connected to that line, increases the transient instability risk. Therefore SPS undertakes an important duty especially in the spring season. However, SPS successfully reacts and resolves the disturbances along this corridor and maintains the regional system stability in all analyzed cases. The relevant cases which show the contingencies on Borçka - Çarşamba transmission corridor are illustrated between Figures 4-8 to 4-10.

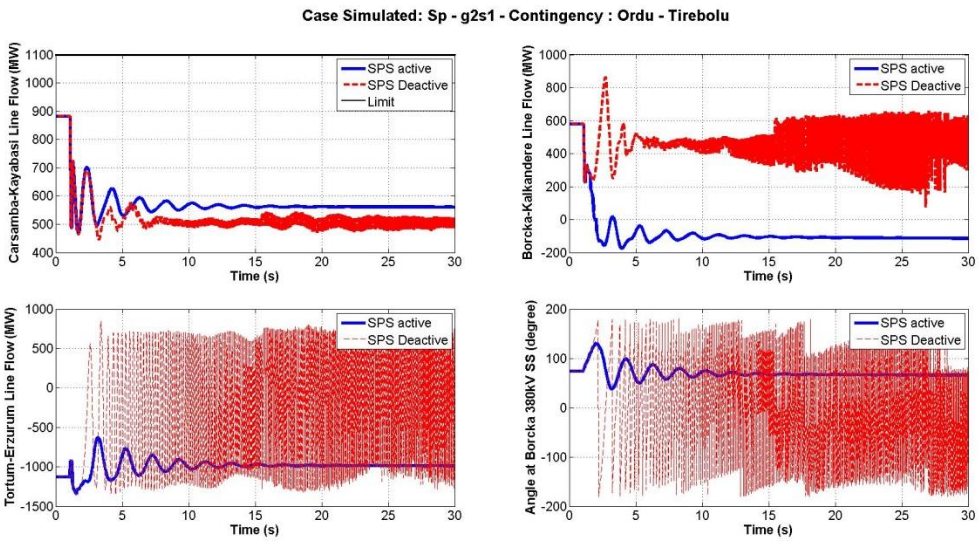


Figure 4-8. Effect of SPS during loss of the line between Ordu and Tirebolu (spring scenario)

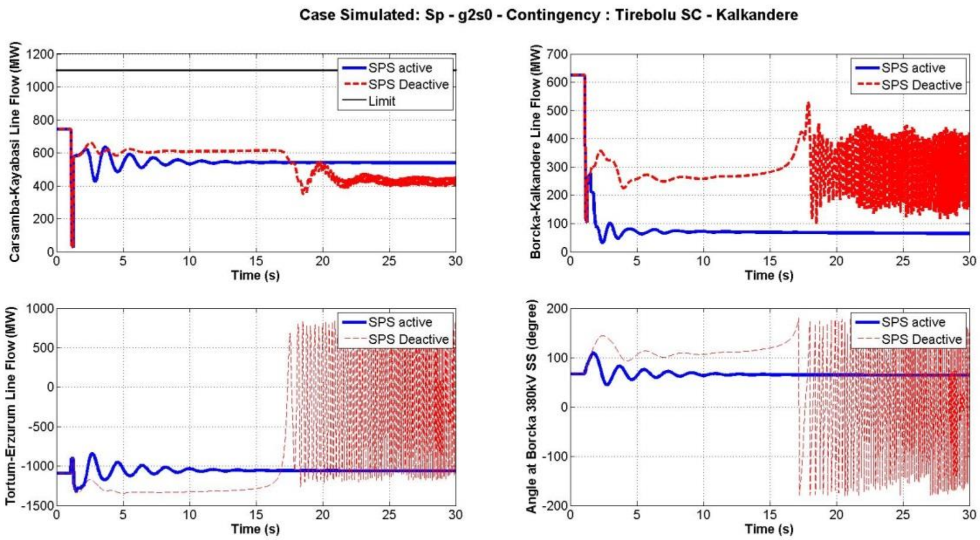


Figure 4-9. Effect of SPS during loss of the line between Tirebolu and Kalkandere (spring scenario)

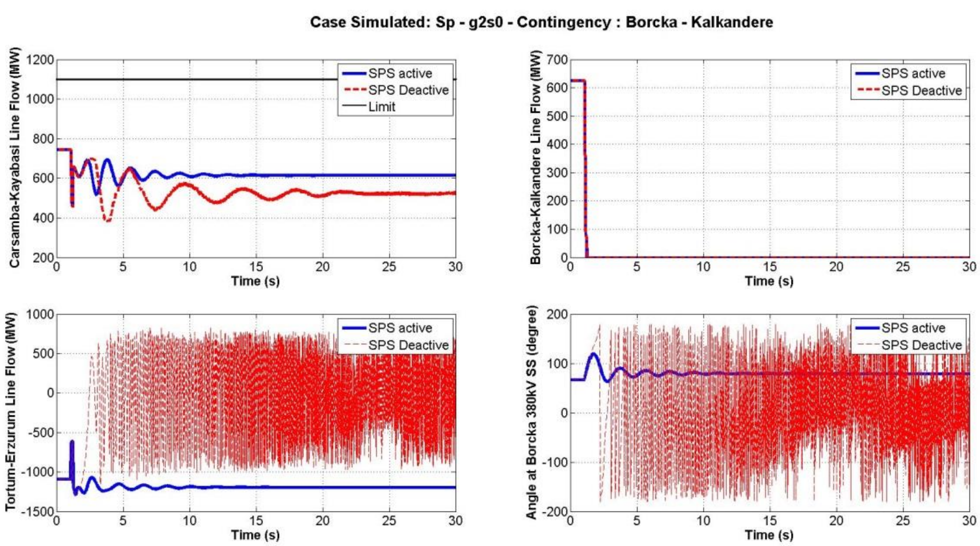


Figure 4-10. Effect of SPS during loss of the line between Kalkandere and Borçka (spring scenario)

Similar to the summer scenario, SPS action in the spring scenario is limited to the cases where SPS action is necessary as shown in Figure 4-11. In this figure, it is illustrated that the system dynamics during the contingency is same in both SPS active and deactive cases, which means that the SPS does not react to the contingency as it is not required.

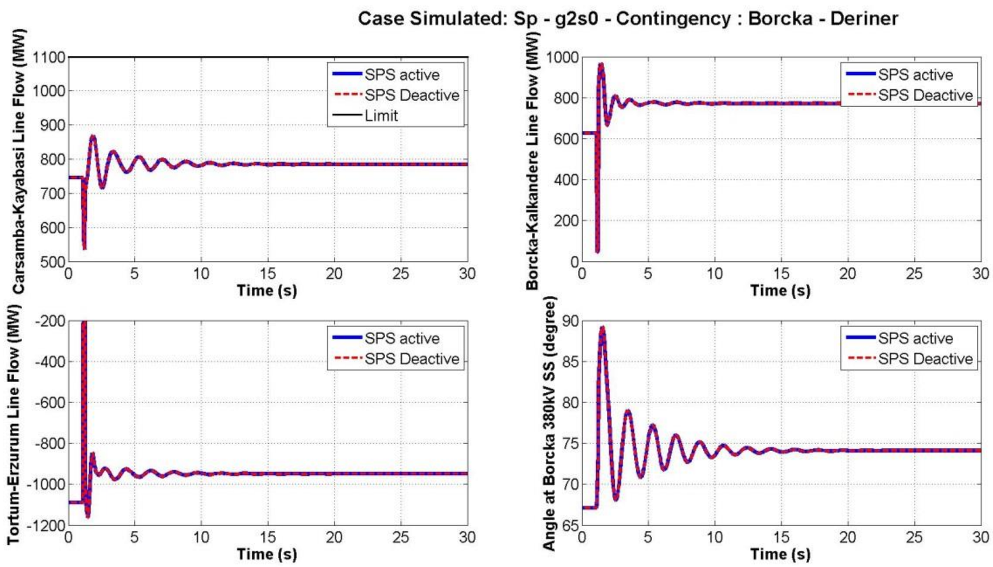


Figure 4-11. Effect of SPS in case where no action needed (spring scenario)

Finally, for the contingencies on Borçka – Erzurum transmission corridor, SPS successfully maintains the system stability in cases where SPS action is necessary. Transient stability results for the spring scenario revealed that transmission investments along this corridor significantly reduce the instability risk. The only remaining contingency that may lead to instability is the case in the which transmission line between Erzurum and Özlüce is lost. However, the instability risk in this case is also eliminated with SPS action as shown in Figure 4-12.

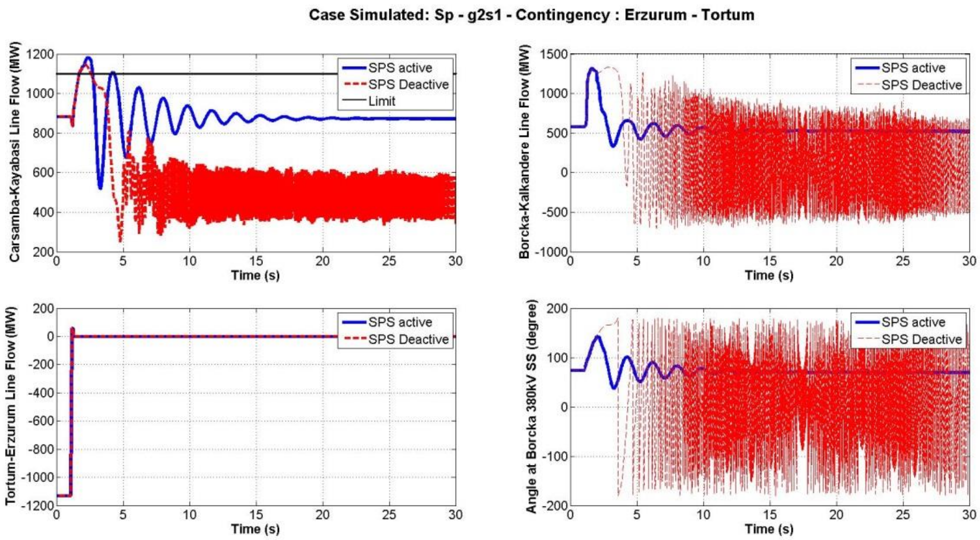


Figure 4-12. Effect of SPS during loss of the line between Erzurum and Özlüce (spring scenario)

Summary of the analysis results for spring scenario under SPS supervision is given in Table 4-3. Results have shown that SPS ensures secure operation of the grid under all conditions. In addition, SPS actions on every case are summarized in Table 4-4. According to the results given in Table 4-4, it is obvious that SPS is acting only on conditions where intervention is necessary.

Table 4-3. Transient stability results table for spring scenario under the SPS supervision

Case \ Generation Dispatch Scheme	G0_S0	G0_S1	G1_S0	G1_S1	G2_S0	G2_S1
Altınkaya-Çarşamba	✓	✓	✓	✓	✓	✓
Altınkaya-Kayabaşı	✓	✓	✓	✓	✓	✓
Kayabaşı-Çarşamba	✓	✓	✓	✓	✓	✓
Çarşamba-Samsun NGCCPP	✓	✓	✓	✓	✓	✓
Çarşamba-H.Uğurlu	✓	✓	✓	✓	✓	✓
Ordu-Tirebolu	✓	✓	✓	✓	✓	✓
Ordu-Samsun NGCCPP	✓	✓	✓	✓	✓	✓
Tirebolu- Tirebolu Series Cap.	✓	✓	✓	✓	✓	✓
Tirebolu Series Cap.-Kalkandere	✓	✓	✓	✓	✓	✓
Borcka-Kalkandere	✓	✓	✓	✓	✓	✓
Bocka-Deriner	✓	✓	✓	✓	✓	✓
Deriner-Artvin	✓	✓	✓	✓	✓	✓
Artvin-Yusufeli	✓	✓	✓	✓	✓	✓
Yusufeli-Tortum	✓	✓	✓	✓	✓	✓
Erzurum-Tortum	✓	✓	✓	✓	✓	✓
Erzurum-Özlüce	✓	✓	✓	✓	✓	✓
Erzurum-Horasan	✓	✓	✓	✓	✓	✓
Ağrı-Horasan	✓	✓	✓	✓	✓	✓
Ağrı-Van	✓	✓	✓	✓	✓	✓
Van-Başkale	✓	✓	✓	✓	✓	✓

Table 4-4. The amount of generation shed order given by SPS for all simulated cases in spring scenario

Case \ Generation Dispatch Scheme	G0_S0	G0_S1	G1_S0	G1_S1	G2_S0	G2_S1
Altınkaya-Çarşamba	0 MW	0 MW	0 MW	200 MW	0 MW	200 MW
Altınkaya-Kayabaşı	0 MW	0 MW	0 MW	0 MW	0 MW	0 MW
Kayabaşı-Çarşamba	200 MW	440 MW	200 MW	440 MW	200 MW	440 MW
Çarşamba-Samsun NGCCPP	0 MW	320 MW	320 MW	670 MW	670 MW	1070 MW
Çarşamba-H.Uğurlu	0 MW	0 MW	0 MW	0 MW	0 MW	0 MW
Ordu-Tirebolu	0 MW	0 MW	320 MW	320 MW	1070 MW	1070 MW
Ordu-Samsun NGCCPP	0 MW	0 MW	320 MW	670 MW	670 MW	1070 MW
Tirebolu- Tirebolu Series Cap.	0 MW	0 MW	0 MW	0 MW	320 MW	320 MW
Tirebolu Series Cap.-Kalkandere	0 MW	0 MW	0 MW	0 MW	670 MW	670 MW
Borcka-Kalkandere	0 MW	0 MW	0 MW	0 MW	320 MW	320 MW
Bocka-Deriner	0 MW	0 MW	0 MW	0 MW	0 MW	0 MW
Deriner-Artvin	0 MW	0 MW	0 MW	0 MW	0 MW	0 MW
Artvin-Yusufeli	0 MW	0 MW	0 MW	0 MW	0 MW	0 MW
Yusufeli-Tortum	0 MW	0 MW	0 MW	0 MW	0 MW	0 MW
Erzurum-Tortum	0 MW	0 MW	0 MW	0 MW	1070 MW	1070 MW
Erzurum-Özlüce	0 MW	0 MW	0 MW	0 MW	0 MW	0 MW
Erzurum-Horasan	0 MW	0 MW	0 MW	0 MW	0 MW	0 MW
Ağrı-Horasan	0 MW	0 MW	0 MW	0 MW	0 MW	0 MW
Ağrı-Van	0 MW	0 MW	0 MW	0 MW	0 MW	0 MW
Van-Başkale	0 MW	0 MW	0 MW	0 MW	0 MW	0 MW

CHAPTER 5

CONCLUSION

Asynchronous interconnection between Georgia and Turkey via line commutated back to back (B2B) HVDC through one of the most congested transmission corridors in Turkey is operational since November 2013. Previous feasibility studies regarding to this project have shown that depending on the amount of power transfer between parties and loading conditions, there might be transmission bottlenecks and problems in Turkish power system. This constitutes a serious problem as the net transfer capacity between both parties is zero during the spring season and it may be the case for other seasons as well due to n-1 security concerns. From economical point of view, zero exchange will be a huge burden for both investors and electricity traders who desire to benefit from this investment. In this regard, expansion in the transmission capacity of current infrastructure by using intelligent protective system seems to be the only viable solution. Hence, this study focused on the design of a special protection scheme that ensures power system security and sustainability. The main idea behind SPS implementation is to coordinate the outages in the Northeastern region of Turkish electricity system along with some countermeasures. However, implementation of such protection scheme requires detailed power system analyses including static and dynamic stability calculations in order to understand the regional system requirements and weak points.

For this purpose, this study first deals with system modelling issues that accurately represent the regional grid. As the region under consideration is significantly large, several assumptions are made through modelling process. These assumptions enable to reduce time required to model the area without losing the accuracy of calculations.

After completing the modelling study, static security analysis that investigates the existing and expected constraints of the regional grid is performed for several scenarios and loading conditions to identify not only the constraints of the region but also to give idea about reasons that cause element overloads and over/under voltages in the region. The following conclusions are drawn from static security studies;

- Overloads in the regional grid exist even in the base case (i.e., no contingency) both in summer and spring scenarios. These problems should be resolved by new transmission investments. This result also reflects that the n-1 security criterion is not satisfied for the region, hence, increases the vulnerability of the region to the disturbances and line losses.
- In case of loss of any line in Altınkaya - Çarşamba-Kayabaşı 400 kV triangle, the loading level of the remaining lines in the triangle increases. The lines Altınkaya - Kayabaşı and Çarşamba – Kayabaşı are reported as operated under their nominal capacities due to degraded protection elements. Hence, overloading on these lines should be controlled and decreased immediately in order to prevent the line from being out of service.
- Most critical contingency in all scenarios is the loss of line between Çarşamba and Samsun NGCCPP substations. In this contingency, the direction of the power flow from Borçka- Çarşamba corridor is reversed. Hence, 154 kV grid close to Samsun NGCCPP becomes highly overloaded.
- Loss of any line on Borçka – Erzurum corridor leads to overloading in 154 kV grid from north to south plane for both summer and spring scenarios.
- The effect of losing any line on Borçka - Çarşamba corridor has negligible effect on stability in summer scenario. On the contrary, in spring scenario, 154 kV grid parallel to Borçka-Çarşamba 400 kV corridor gets overloaded due to high generation regime. It should be noted that hydraulic potential in the region is significant and considerable amount of generation is expected in the spring season as a result of water regime.

- 700 MW power import from Georgia seems to infeasible for the spring season as almost all contingency cases lead to major overloads in Turkish grid.

Static security analyses have shown that the region itself has n-1 concerns even without any power import from Georgia. It is clear from the results that constraints in the region are mainly due to transmission inadequacy. Unfortunately, the issue cannot be resolved until new transmission investments are realized. Hence, generation shedding seems to be most promising solution where rapid mitigation of contingency effect is required. Therefore, predefined solutions to the contingencies in the region are calculated in static security analyses in order to understand and examine the place and the amount of generation shedding that is required to resolve transmission overloading. This study also illuminates the possible SPS countermeasures.

Following, power quality analyses are conducted to examine the adequacy of the grid to support conventional line commutated HVDC operation. It should be noted that, line commutated HVDC requires certain amount of reactive power and SCMVA during its operation in order not to face with commutation failures. Hence, the HVDC operational requirements are checked for possible grid topologies in both summer and spring scenarios that affect the SCMVA. Results of power quality analyses have shown that secure HVDC operation is maintained for all possible grid topologies. It is identified that 700 MW power import, which is the capacity of the HVDC, can be maintained without interruption due to commutation failure. This assessment also implies that no constraint exists on SPS countermeasure selection; in other words, generation drop in the region does not cause any problem for HVDC operation.

Static security and power quality analyses have given important results for regional system examination. However, their results cover information regarding to steady state of the power system. In order to investigate stability regarding state transition of the regional system, transient stability analyses have also been performed in this study. Transient stability analyses, which are inevitable part of system examination in SPS studies, definitely clarify grid dynamics and system stability. However, this study requires the computation of large set of differential and algebraic equations which necessitate detailed modelling. Hence, for high capacity generation facilities detailed dynamical models are created while small sized plants are represented with simple mechanical models. Moreover, due to the lack of n-1 criterion in the region, overcurrent protection relays are added in 154 kV transmission lines in order to examine cascaded transmission line opening threat in 154 kV network. Utilizing the mentioned grid dynamic and protection model, transient stability analyses are performed for several scenarios and contingencies. The analysis results can be summarized as;

- Transmission line between Çarşamba and Samsun NGCCPP is the most critical line in the region. Results have shown that, any fault occurring on that line may lead to instability problems even without any power import from Georgia.
- Risk of instability increases proportionally with the amount of power import from Georgia, as expected.
- Generation level of Samsun NGCCPP is also an important factor in transient stability, as it directly affects the Borçka – Çarşamba 400 kV transmission corridor.
- In the summer scenario, it is observed that the regional system may become unstable in case of losing any line that is connecting Deriner to Erzurum which are the parts of Borçka-Erzurum 400 kV transmission corridor. Surely the instability situation changes depending on loading level of the region and the risk of instability proportional with loading level.
- In the spring scenario, due to the generation regime in Black Sea region, instability risk becomes evident in case of losing any line forming Borçka-Çarşamba 400 kV transmission corridor. Again, the instability situation changes depending on generation dispatch scheme of the region and the risk of instability increases proportionally with generation level.

Transient stability analyses also identify the behavior of power system elements and their related variables which are used to detect instability pattern in the region. Specifically, angle differences and deviations are utilized for SPS logic design.

Based on the results of these three main analyses, a PMU based special protection scheme is developed for the region. Considering the transmission structure in the region, that includes a giant ring which consists of 2 main 400 kV transmission corridors intersecting on the substation of interconnection, 3 PMU points are selected for system observation. These PMUs are located on end points of main 400 kV transmission corridors and on the intersection point (i.e., Borçka). With this placement, required degree of system observation is obtained.

After determining the measurement points and variables that are required to form SPS logic, design study is focused on logic interpretation. For this purpose, first, fault and fault location detection functions are developed. These functions clarify the activation point of the proposed SPS. Following the activation, SPS determines the magnitude of required countermeasures that mitigate the effect of that contingency. In the determination process, 3 different threshold levels and time dials are utilized in order to optimize system preventive actions. Hence, a step- by-step countermeasure activation approach is suggested for implementation. Additionally, due to the uncertainty in the availability of countermeasures, which are actually generators in the region, available online countermeasure detection function is included in the SPS.

Finally, the proposed scheme is formed in a simulation environment in order to examine its reliability and dependability. All scenarios, loading conditions and contingencies simulated in transiently stability analysis are repeated for testing and evaluation. Results have shown that proposed special protection scheme successfully manages all possible contingencies in the region and eliminates the risk of instability without endangering the remaining Turkish power system.

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APPENDIX - A

SINGLE LINE DIAGRAM OF THE REGION

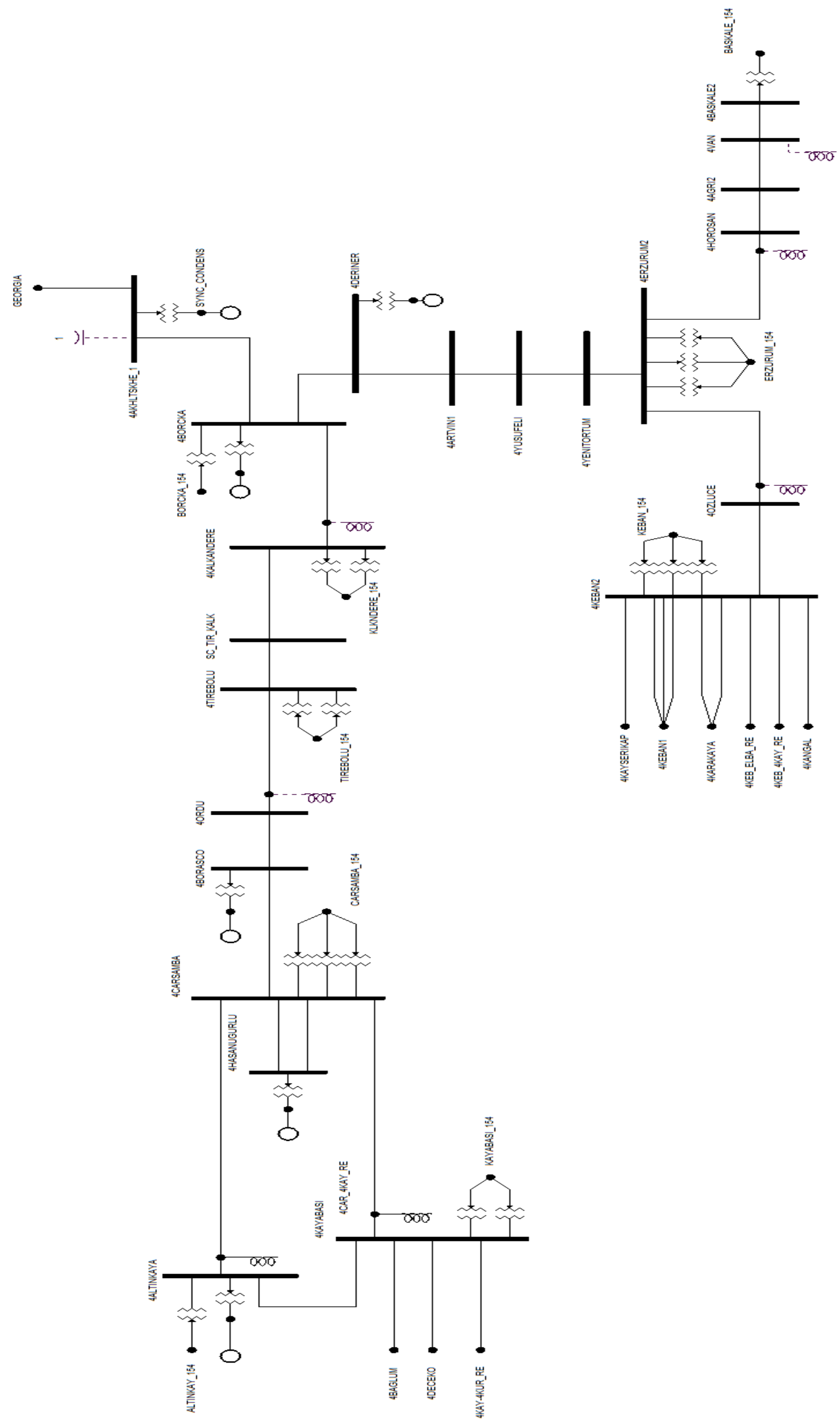

Figure A-1. Single Line Diagram of the Region

APPENDIX – B

HARMONIC ANALYSIS REGARDING HVDC B2B INTERCONNECTION

It is known that any nonlinear load is a harmonic current source and hence should be sufficiently compensated in order not to overload the electrical equipment with excessive reactive power that has no practical use. Since a group of customers are interconnected to the power system at a specific node (Point of Common Coupling, PCC), the transmission system operator is responsible from maintaining an acceptable sinusoidal voltage wave shape for the quality of supply.

Any B2B converter is, similarly, a source of harmonic currents and hence should be compensated adequately so as to maintain the power quality standards defined in the Turkish Grid Code [18]. In order to analyze whether this standart is satisfied in Borçka substation after connection with HVDC B2B substation or not, the worst case in the sense of harmonics, that is 700 MW power transfer from Georgia, is analyzed considering the inverter side of this interconnection is Turkey. The time domain simulation results of the B2B converter is illustrated in Figure B-1.

One can immediately see the distortion on the voltage wave shape at Borçka substation, due to the nonlinear nature of the inverter. The harmonic spectrum of the inverter current is illustrated in Figure B-2.

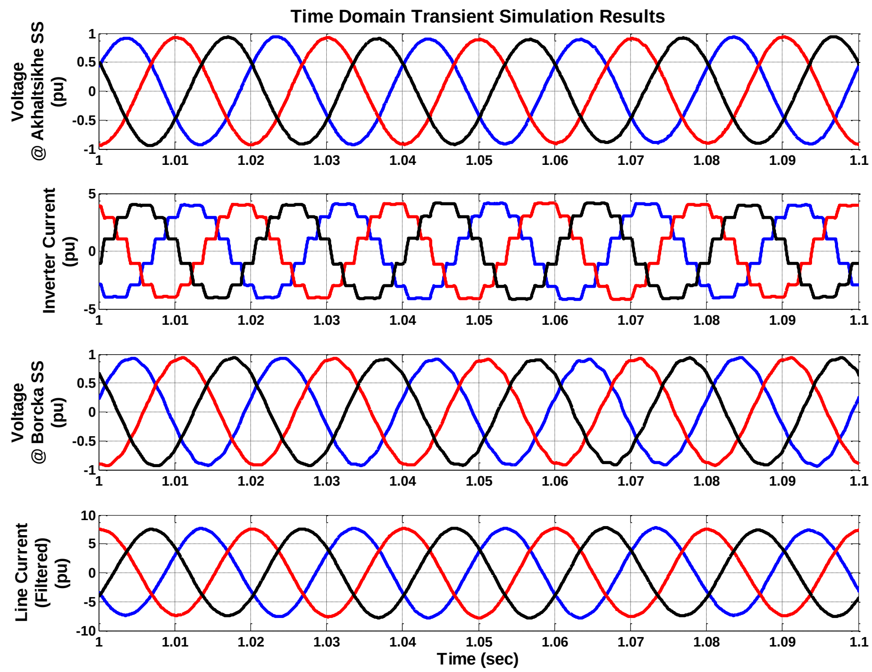

Figure B-1. Time domain transient switching results of the B2B converter

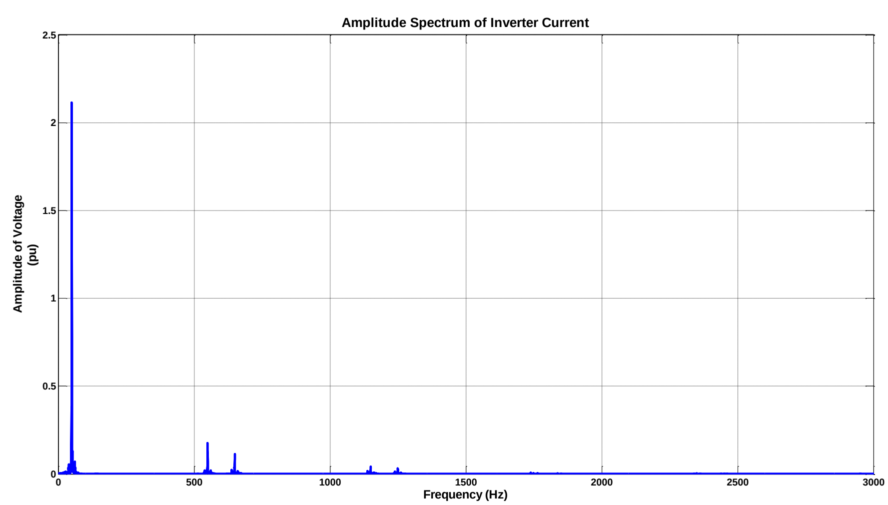

Figure B-2. The harmonic spectrum of inverter current

As can be readily seen in Figure B-2, the most dominant harmonic of the inverter current is the 11th harmonic. This verifies the necessity of the harmonic filters that should be tuned as mentioned in the Section 3.3 of this study. It should be noted that in most applications, the 11th and 13th harmonic filters are tuned with a quality factor of 100.

The harmonic spectrum of line current at the receiving end of the transmission line (i.e., Borçka substation) is illustrated in Figure B-3. It can be observed that the problematic harmonic components are eliminated by analyzing Figure B-1 and Figure B-3 together.

The harmonic spectrum of voltage at Borçka substation is illustrated in Figure B-4. The comparison of the harmonic components of the voltage waveform illustrated in Figure B-1 and Figure B-4 are listed in Table B-1. Table B-1 clearly expresses that all requirements of the grid code are satisfied.

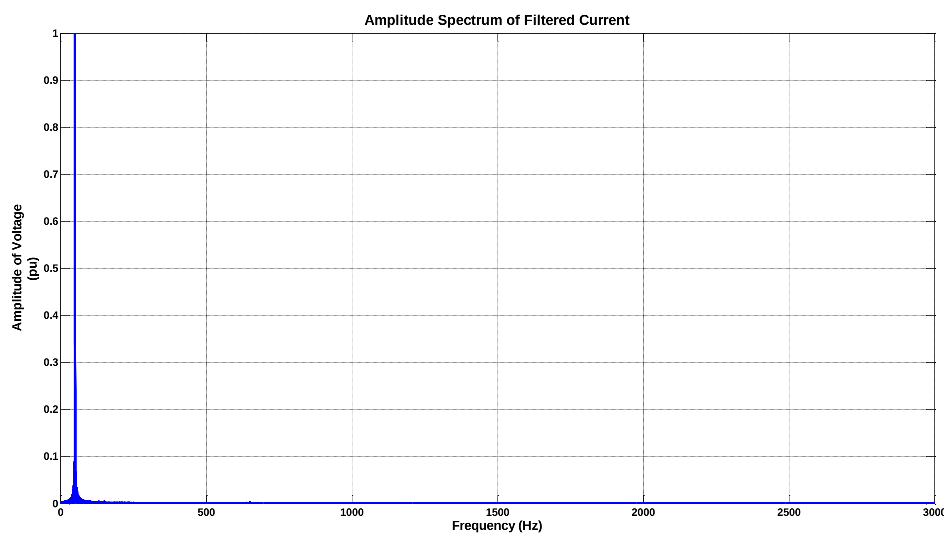

Figure B-3. The harmonic spectrum of the current at the receiving end (Borçka substation) of the transmission line

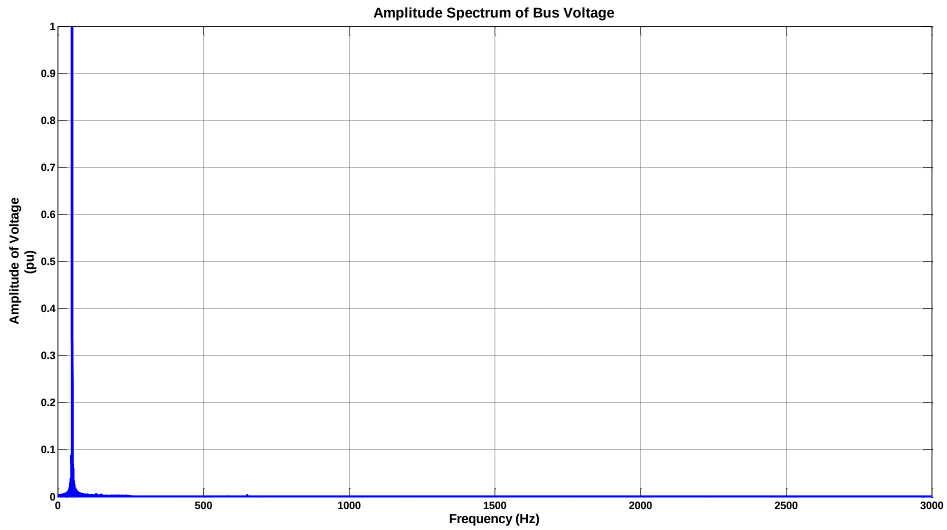

Figure B-4. The harmonic spectrum of the voltage at Borçka substation

Table B-1: The comparison of the voltage harmonics related to the B2B converter and Turkish grid code requirements

Odd Harmonics (Non multiples of 3)			Odd Harmonics (Multiples of 3)			Even Harmonics		
Harmonic Number	Harmonic Voltage (%)	Simulation Results (%)	Harmonic Number	Harmonic Voltage (%)	Simulation Results (%)	Harmonic Number	Harmonic Voltage (%)	Simulation Results (%)
5	1.25	0.1468	3	1	0.5145	2	0.75	0.4
7	1	0.0391	9	0.4	0.0654	4	0.6	0.1543
11	0.7	0.6106	15	0.2	0.0594	6	0.4	0.0045
13	0.7	0.0348	21	0.2	0.023	8	0.4	0.0724
17	0.4	0.0873	>21	0.2	OK	10	0.4	0.0579
19	0.4	0.0109				12	0.2	0.1136
23	0.4	0.0399				>12	0.2	OK
25	0.4	0.0386						
>25	0.2+0.2 (25/h)	OK						
THD < % 2								